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Sediment Transport and Water Quality During Reservoir Drawdown Operations: Howard Hanson Dam and the Green River, 2007

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1 INTRODUCTION

Howard Hanson Dam was completed in 1962 and sediments began accumulating shortly thereafter resulting in the minimum winter operating pool (referred to as the "turbidity pool") elevation to rise from about 1038 ft to near 1073 ft. The stored sediments may have impacted the downstream ecosystem by reducing the amount of fine grained material in the aquatic and riparian environments, and interrupting the movement of spawning gravels. The higher pool elevation interferes with the inspection, maintenance, and repair of the regulating outlet structure, stop-logs, and trash-rack. Additionally, the current construction of a downstream fish passage facility (FPF) and expected operation as early as 2010 also requires a change from the historic practice of accumulating sediment behind HHD.

The Seattle District Corps of Engineers (COE) completed a Reservoir Operations and Sediment Management Plan for water year 2008 which outlined a series of five (5) goals that could be implemented over the next 1 to 10 years to progressively reduce the amount of sediment stored behind Howard Hanson Dam (U.S. COE 2007). One major objective was to investigate sedimentation processes in the reservoir and the downstream transport of suspended sediments and turbidity in the Green River below Howard Hanson Dam. To accomplish this goal, the COE proposed a series of up to five (5) experimental reservoir drawdowns to about elevation 1065 ft to intentionally erode deposited sediments within the reservoir to occur from November 2007 through February 2008. The Water Year 2008 Reservoir and Sediment Management Plan (U.S. COE 2007) described the flow and water quality conditions necessary for implementing an experimental drawdown. There was one period during WY 2008 where conditions were met and a drawdown was performed.

The Washington State Department of Ecology (WDOE) issued a Temporary Short Term Modification of Water Quality Standards (Ecology 2007) to the turbidity standard during reservoir drawdown operations. A condition of the water quality modification was for the COE to monitor water quality upstream and downstream of Howard Hanson Dam during each drawdown.

1.1 Purpose and Objective

The goal of the water quality monitoring program is to ensure that the reservoir drawdown operations meet the criteria set forth in the Temporary Short Term Modification of Water Quality Standards and to support the overall goals of the project. The objective of the monitoring program is to measure downstream turbidity and sediment transport during reservoir drawdown operations to better characterize the fate and transport of turbidity and suspended sediments during reservoir drawdowns. The turbidity and sediment data will ultimately be used to explore feasibility of and implement proposed future operations that may include 1) annually pass the incoming sediment load, 2) erode a portion of the sediment stored behind HHD and lower the winter operating pool to about elevation 1055 ft, and 3) erode the remainder of the sediment deposits to about elevation 1035 ft and have near run-of-river conditions

2 METHODS AND MATERIALS

2.1 Site Characterization

Howard Hanson Dam is located on the Green River at river mile 64.5, about 45 miles southeast of Seattle (**Figures 1 and 2**). The Green River basin drains about 483 square miles in Western Washington of which about 221 square miles are located above the dam site. Elevations in the watershed range from about 1,000 feet at the dam to over 5,000 feet in the Cascade Mountains. The watershed is characterized by forested north-south trending mountain slopes and steep river valleys. Extensive logging operations occur in the watershed resulting in a patchwork of forested and clear cut slopes.

Sediments have been accumulating behind Howard Hanson Dam since the project was completed in 1962. The sediment accumulation has caused the minimum winter operating pool (referred to as the turbidity pool) to rise from about 1038 feet to 1073 feet, resulting in interferences with inspection, maintenance, and repair of the outlet structures as well as reduced flexibility in operating the reservoir. Additionally, the build up of sediments behind the dam has altered the downstream ecosystem by blocking the movement of sediments from the upper watershed to the lower watershed.

2.2 Reservoir Drawdown Operations

For the 2008 water year, the COE proposed a series of up to five drawdowns of the reservoir to elevation 1065 ft to investigate sediment erosion and transport in the reservoir, and turbidity and suspended sediment transport downstream of Howard Hanson Dam (U.S. COE 2007). Hydrologic and weather conditions during the water year allowed for one drawdown to be conducted from December 4 to 6, 2007. **Figure 3** shows the inflow, outflow, and forebay elevations measured during the drawdown. The drawdown began at 0900 hours on December 4, 2007 when forebay elevations were lowered below elevation 1070 feet and lasted until 0400 hours on December 6 when elevations rose above 1070 feet for a drawdown duration of about 43 hours. The maximum drawdown elevation reached was 1066 feet at 1100 hours on December 5, 2007. Inflows to and outflows from the reservoir during the drawdown ranged from about 2500 cfs to 4000 cfs.

2.3 Water Quality Criteria

The Washington Department of Ecology (WDOE) determines water quality criteria for the Green River at Howard Hanson Dam. The 2003 WDOE standards classified the Green River above and below Howard Hanson Dam as a Core Summer Salmonid Habitat water body. Core Summer Salmonid Habitat water quality standards for turbidity, temperature, dissolved oxygen and pH are presented in **Table 1**.

A Temporary Short Term Modification of Water Quality Standards (Order No. 4898) was issued by WDOE in August 2007 for reservoir drawdown operations at Howard Hanson Dam and the Green River (Ecology 2007). The temporary modification allowed for the exceedance of the turbidity standard in the Green River during reservoir drawdowns conducted between November 1, 2007 and February 15, 2008. As a condition of the modification, limits were set on the allowable turbidity values measured downstream during the drawdowns as outlined below.

Each allowable drawdown shall last no longer than two days. At any time during the drawdowns, when discharge is greater than 1,500 cfs, and the turbidity values recorded at the downstream tailwater monitoring point (RM 63.8) reach 500 NTU for two consecutive hourly readings, the COE shall raise the pool one foot and hold it at that level for four hours. If turbidity does not exceed 500 NTU for four consecutive hours, the drawdown will continue. If the turbidity exceeds 500 NTU for four consecutive hours, the COE shall cease the drawdown operation and raise the pool depth to 1070 feet. Any time during the drawdowns, when the discharge is between 500 and 1500 cfs, turbidity will not exceed 100 NTU at RM 63.8 for two consecutive hourly readings. If at any point during any of the drawdowns, the turbidity values recorded at the downstream monitoring point (RM 63.8) reaches 600 NTU, drawdown activity shall cease immediately and the pool depth will be raised to 1070 feet. All other water quality standards (**see Table 1**) must be met.

2.4 Sampling Design and Data Collection Locations

Water quality monitoring was designed to (1) meet the requirements set forth in the Temporary Short Term Modification of Water Quality Standards (Order No. 4898) and (2) determine the fate and transport of suspended sediments downstream of the project. To meet both these requirements water quality monitoring was conducted at four (4) stations located upstream and downstream of Howard Hanson Dam during reservoir drawdown operations (**Figures 1 and 2**). The upstream station (HAQW) was located at about RM 70.0 near Railroad Bridge 71, approximately 5.5 miles upstream from the dam. The first downstream station (HAHW) was located at RM 63.8 about 0.7 miles downstream of the dam at the site of the existing USGS Green River below Howard Hanson Dam gaging station (No. 12105900). The second downstream station (GRAH) was located at about RM 60.3 about 4 miles downstream of the dam at the site of the existing USGS Green River at Purification Plant near Palmer gaging station (No. 12106700). The third downstream station (AUBW) was located at about RM 32.0 about 32.5 miles downstream of the dam at an existing bridge crossing of the Green River located about 1000 feet downstream of the existing USGS Green River near Auburn gaging station (No. 12113000). Water quality parameters, analytical methods and detection limits for the drawdown study are presented in **Table 2**.

2.4.1 Water Quality Standard Conditions Monitoring

Water quality standard conditions monitoring consisted of collecting manual grab water samples at stations HAQW, HAHW and GRAH twice daily (morning and afternoon) during the drawdown, with one additional sample collected 12 hours after the drawdown ceased. Automated samplers collected hourly turbidity measurements upstream of the dam (HAQW) and downstream of the dam (HAHW) during the drawdown and for 24-hours after the drawdown. Because the automated turbidity probe can be difficult to maintain a calibration at high turbidity levels, hourly manual grab samples were collected downstream of the dam (HAHW) as a check on the automated probe. Each manual sample was analyzed for the following parameters:

- Turbidity (field parameter)
- Temperature (field parameter)
- pH (field parameter)
- Conductivity(field parameter)

- Dissolved oxygen (field parameter)
- Total Suspended Sediment (lab parameter)

Manual grab samples were collected from as near to the center of the stream channel as possible by submerging laboratory-cleaned, prelabled sample containers below the water surface at mid-depth. Sample containers were rinsed once prior to filling, oriented upstream during filling, capped with headspace for mixing, and immediately placed on ice in a cooler. Measurements of turbidity were performed in the field using a Hach 2100P turbidimeter while measurements of all other field parameters (noted above) were performed in situ using a Hydrolab MiniSonde 4a multiprobe coupled with a Surveyor 4 surface display and recording unit. Samples intended for total suspended sediment analysis were delivered to the appropriate laboratory following proper chain of custody procedures.

Automated turbidity measurements were collected using a Hydrolab MiniSonde 5 water quality probe, a Geomation 2380 data collection platform (DCP), a radio transmitter, and a power source. Measurements were made every hour and the data was transmitted via radio directly to the Seattle District's HEC-DSS water quality database. At the downstream station (HAHW) the water quality probe was placed on an anchored pulley-ramp-track system that extended into the river to about the center of the channel approximately 1 foot off of the bottom of the river. At the upstream station (HAQW) the probe was placed inside an anchored, perforated PVC pipe that extended into the river to about the center of the channel approximately 1 foot off of the bottom of the river.

2.4.2 Suspended Sediments Monitoring

A comprehensive suspended sediments monitoring study was conducted during the drawdown event at downstream stations HAHW and AUBW to determine the fate and transport of sediments in the Green River (**see Figures 1 and 2**). The study consisted of collecting (1) cross sectional depth integrated manual suspended sediment samples at station AUBW, (2) automated point sample suspended sediment samples at station HAHW and (3) automated *in situ* suspended sediment concentrations and particle sizes at station HAHW. The original sampling plan outlined collecting cross sectional depth integrated samples at station HAHW and not point samples. However, storm damage to the USGS cableway at station HAHW prohibited the use of the cableway during the drawdown and necessitated the change in the sampling plan. Each suspended sediment sample was analyzed for the following parameters:

- Total Suspended Sediment (lab parameter/field parameter)
- Particle Size (lab parameter/field parameter)
- Turbidity (field parameter)

2.4.2.1 Cross Sectional Depth Integrated Sediment Sampling

Cross sectional depth integrated suspended sediment sampling was performed at the AUBW station by two field technicians using the isokinetic, equal-discharge-increment (EDI) method (Edwards and Glysson 1999). The objective of the EDI method is to use an isokinetic device (a sampler that allows water to enter without changing its velocity relative to the stream) to collect a series of discharge-weighted samples passing through a cross section, with each sample

representing equal volumes of river discharge. Suspended sediment samples were collected with a Depth-Integrating Hand Line Type Model US DH-76 sampler from a bridge at station AUBW according to the following procedures:

- Determine the location of the centroid of flow within each flow increment and mark this location on the bridge. The centroids will correspond to locations of 10, 30, 50, 70, and 90 percent of the cumulative discharge along the cross section.

- Determine the sampling depth and mean stream velocity at the centroid of each equal-discharge increment.

- Determine the transit rate for each centroid that will yield subsamples with about the same volume (plus or minus 10 percent) using isokenetic transit rate tables for expected sampling depth, velocity, and nozzle size (USGS 1999). When compositing subsamples, the minimum volume for every equal-discharge increment is the minimum volume collected for the deepest vertical.

- Lower the DH-76 sampler at the predetermined transit rate until the sampler just touches the streambed. Without pausing, raise the sampler immediately at a constant rate to complete the vertical sample. The descending rate does not have to equal the ascending rate, but both rates need to be constant and within the isokinetic range of the sampler based on USGS tables (USGS 1999).

- After collecting the sample, ensure that the sample container is not overfilled or underfilled based on tables of maximum and minimum volumes for a given sampling depth, velocity, and nozzle size (USGS 1999). If a sample container is overfilled or underfilled, discard the sample and resample.

- After successful collection of a sample, move to the next centroid and sample until the entire cross section has been sampled.

- Composite each subsample into containers prepared by the analytical laboratory for the given parameters. Swirl the sample gentle while compositing to ensure that all particulates in the sampler bottle are transferred to the composite bottle.

- Sampling containers were appropriately labeled, immediately placed on ice in a cooler, and delivered to the appropriate laboratory following proper chain of custody procedures.

2.4.3 Automated Point Sample Suspended Sediment Monitoring

Automated point sample suspended sediment monitoring was conducted at station HAHW using an ISCO-6712 automatic pump sampler. The ISCO-6712 pump sampler collected a point sample at station HAHW from a location near the center of the river about 1 foot off of the bottom of the river. The pump sampler was programmed to collected hourly samples from 1000 hours to 1600 hours during the day and then collected samples every 3 to 4 hours during the night from 1700 hours to 0900 hours the following day. Samples were transferred from the ISCO-6712 bottles into containers prepared by the analytical laboratory for the given parameters by gently swirling the sample while compositing to ensure that all particulates in the sampler bottle were transferred to the laboratory bottle. All containers were appropriately labeled, immediately placed on ice in a cooler, and delivered to the appropriate laboratory following proper chain of custody procedures.

2.4.4 Automated *In Situ* Suspended Sediment Monitoring

A LISST-100X laser diffraction instrument (Laser In-Situ Scattering and Transmissometry) was deployed at Station HAHW at the same location as the ISCO-6712 pump sampler and was anchored near the center of the river channel about 1 foot off of the bottom of the river. The LISST-100X is a laser-diffraction sensor designed to measure particle size distribution and volume concentration over a size range of 2.5 to 500 microns. The LISST-100X has the ability to calculate suspended sediment concentrations over a wide range, depending on the particle size of the sediment and the laser path length of the instrument. A shorter laser path length permits higher suspended sediment concentrations to be measured by the instrument. Because high suspended sediment concentrations were expected during drawdown operations, the standard 50 mm path length of a LISST-100X was reduced to 5 mm to allow for a greater range of data measurements. The LISST-100X is able to take multiple measurements over a wide range of sampling intervals. For the drawdown, the LISST-100X was programmed to average 120 measurements over a 1 minute time period at 10 minute intervals.

2.5 Quality Assurance Procedures

Quality assurance of water quality samples followed procedures set forth in the Howard Hanson Dam Reservoir Operations and Sediment Management Plan for Water Year 2008: Water Quality Sampling and Analysis Plan Dam Ground Water Quality Monitoring Project Sample and Analysis Plan (U.S. COE 2007). Laboratory data were validated according to the sampling and analysis plan, and quality control data provided by the laboratory were combined with results of field duplicate and split analysis to check the precision and accuracy of the data.

Quality assurance of data measured by the LISST-100X followed recommended guidelines set forth by Sequoia Scientific, the manufacturer of the LISST instruments (Pottsmith 2007). Sequoia Scientific recommends that LISST-100X measurements recorded when the Optical transmission of the laser is less than 20% but greater than 10% are suspect and should be used with caution. Data measured when the optical transmission of the laser is less than 10% are suspect and in general the data should not be used. For the drawdown study, data collected when the laser transmission was less than 20% but greater than 10% were only used when the following guidelines were met:

- Time series analysis of the data showed no unusual spikes in the data from measurements collected when optical transmission was less than 20%.

- Time series analysis showed that data measured when transmission was less than 20% followed a similar trend with data collected when transmission was greater than 20%.

3 RESULTS AND DISCUSSION

3.1 Water Quality Standard Conditions Monitoring

3.1.1 Turbidity Monitoring

Hydrographs of hourly inflow, outflow, and pool elevation for the Green River at Howard Hanson Dam before, during, and after the December 4 to 6, 2007 drawdown are presented in **Figure 3**. The reservoir drawdown began at 0900 hours on December 4, 2007 when the pool was lowered below 1070 feet and was completed at 0400 hours on December 6, 2007 when the pool was raised above 1070 feet. Turbidity values measured during the drawdown are shown in **Figure 4** and presented in **Table 4**. The data show that the automated turbidity sampler at Station HAHW was consistently higher than hourly manual grab samples collected at the same location. In addition, the hourly grab samples were similar to point sample turbidity measurements using the ISCO-6712 pump sampler. The similar pattern between the automated samples and the grab/pump samples suggest that the automated sampler was working but was likely out of calibration at the higher turbidity concentrations.

Inflow turbidity values as measured at Station HAQW changed little during the drawdown event and stayed below about 35 NTU during the entire event, while outflow turbidity values increased dramatically from about 50-100 NTU to 200 NTU as the pool was drawn down from about 1072 feet to 1070 feet (**Figure 4 and Table 4**). Turbidity values increased again (from about 200 NTU to > 400 NTU) when the pool was drawn down from 1070 feet to 1069 feet, stabilized and then decreased to less than 300 NTU as the pool was slowly drawn down from about 1069 to about 1067. When the pool was lowered below 1067 ft. turbidity levels increased above 500 NTU as measured on December 5th at 0500, 1100, 1200, and 1300 hours. The reservoir drawdown was halted on December 5th at 1200 hours and the pool was raised. Turbidity values quickly dropped below 500 NTU when the pool elevation increased above 1067 feet. Turbidity values at Station HAHW were similar to background concentrations at Station HAQW at 1100 hours on December 6th, about 51 hours after the drawdown began.

3.1.2 Water Quality Monitoring

Water quality samples collected in the morning and afternoon upstream (HAQW) and downstream (HAHW and GRAH) of Howard Hanson Dam during the drawdown event as required by the Temporary Short Term Modification of Water Quality Standards (Order No. 4898) are presented in **Table 5**. Little change in dissolved oxygen, conductivity, pH, or temperature existed between the upstream and downstream samples during the drawdown. Increases in turbidity and suspended sediments were measured at the downstream stations during and after the drawdown event. These data are similar to the automated and manual grab turbidity sample data presented above in Section 3.1.1 and reflect the transport of sediments downstream in the Green River when the forebay pool is lowered below 1070 feet.

3.2 Suspended Sediment Monitoring

The LISST-100X measurements of the silt/clay fraction compared well with the point samples collected by the ISCO-6712 pump sampler while the sand fraction comparisons were more variable (**Figure 5**). Gaps in the LISST data are due to the optical transmission dropping below 10 to 20% likely the result of debris (likely a leaf or stick) on the optical lens. High flows during

the drawdown resulted in the LISST-100X getting stuck in the water and field personnel were unable to periodically remove the LISST-100X from the water to clean the lens. Consequently, the LISST-100X only sporadically collected data during the drawdown, likely when the lens was free from leaves or sticks.

When operational, the LISST-100X accurately tracked the point sampler silt/clay concentrations including the expected increase in silt/clay when the forebay pool dropped below 1070 feet and 1067 feet (**Figure 5**). Moreover, on December 5th between 0500 and 1400 when the pool was dropped below 1067 and then quickly raised back above 1067, the LISST-100X accurately tracked the increases and decreases in the silt/clay fraction as the pool fluctuated above and below 1067 feet. The LISST-100X data correlates well with the point sample ISCO-6712 data during this time period.

The LISST-100X sand fractions were more variable when compared to the point sampler sand fractions (**Figure 5**). The LISST-100X accurately tracked the increase in sand fractions when the forebay pool dropped below 1070 feet. However, the LISST-100X sand concentrations were initially less than the point sampler sand concentrations when the pool dropped below 1067 feet before increasing dramatically when the pool reached the lowest elevation of 1066.37 feet. During the maximum drawdown elevation, the LISST-100X appeared to overestimate the concentration of sand before the LISST became inoperable due to low optical transmission values. Interestingly, the LISST-100X appeared to accurately track the overall trend in sand fractions when compared to the point sampler, but the timing of the increase in sand concentrations in relation to the forebay pool elevations were slightly different between the LISST and the point sampler.

3.2.1 Silt/Clay Fractions

Time series analysis of particle sizes corresponding to silt/clay fractions are shown in **Figures 6 and 7** for both the LISST-100X and ISCO-6712 point sampler. For each silt/clay size fraction, the LISST-100X data correlates well with the ISCO-6712 point sampler data. In the silt/clay size fraction, the larger particle sizes (i.e. 8 µm, 16 µm and 31 µm) had the highest concentrations. All silt/clay fractions showed similar responses to the drawdown of the forebay pool. Concentrations increased slightly as the pool was dropped down to about 1070 feet. The initial drawdown of the forebay pool below 1070 feet at 0900 hours resulted in a rapid rise in all silt/clay fractions except the 2 µm fraction. Silt/Clay fraction concentrations stabilized and began to decrease as the pool elevation was slowly drawn down from about 1069 feet to about 1067 feet. Silt/clay fractions accurately tracked forebay pool elevation changes in the 1067 foot elevation (**Figures 6 and 7**). When the pool was drawn down below 1067 feet on December 5th at 0400 hours, silt/clay fractions rapidly increased, and when the pool was raised back above 1067 feet at 0800 hours the silt/clay fractions rapidly decreased. Similarly, when the pool was brought below 1067 feet for the second time at 1000 hours the silt/clay fraction rapidly increased with a similar rapid decrease when the pool was brought above 1067 feet at 1400 hours.

Particle size distributions and concentrations over the silt/clay size range measured by the LISST-100X are presented in **Figures 8 and 9**. The LISST-100X data show that the majority of silt/clay particles fell within the 8.65 µm to 53.5 µm size range. All silt/clay fractions (2.72 µm to 53.5 µm) followed a similar pattern during the drawdown experiment with low initial

concentrations, a sharp increase when the pool was drawn down below 1070 feet, a decrease as the pool was slowly drawn down from 1069 feet to 1067 feet, and a sharp increase when the pool was lowered below 1067 feet. Particle size distribution ratios tended to remain constant during all phases of the drawdown with the majority of sand/silt concentrations in the 8.65 µm to 53.5 µm size range throughout the experiment.

3.2.2 Sand Fractions

Time series analysis of particle sizes corresponding to sand fractions are shown in **Figures 10 and 11** for both the LISST-100X and ISCO-6712 point sampler. For each grain size fraction, the LISST-100X data correlates well with the ISCO-6712 point sampler data. For suspended sediment in the sand size fraction, the finer particles (i.e. 63 µm and 125 µm) had the highest concentrations during the drawdown. Sand concentrations in the 63 µm and 125 µm size ranges increased slightly as the pool was dropped down to about 1070 feet while sand in the 250 µm and 500 µm size ranges maintained very low concentrations. The initial drawdown of the forebay pool below 1070 feet at 0900 hours resulted in a rapid rise in only the 63 µm and 125 µm size fractions with little to no increase in the 250 µm and 500 µm sizes. Spikes in the 250 µm size fraction measured by the LISST-100X may be a result of pulses of coarser grained sand fractions moving down the river as the forebay pool was drawn down. The finest sand fraction (63 µm) concentrations stabilized and began to decrease as the pool elevation was slowly drawn down from about 1069 feet to about 1067 feet. However, the larger sand fractions (125 µm, 250 µm, and 500 µm) increased in concentration as the pool was drawn down from about 1069 to 1067 feet (**Figures10 and 11**). When the pool was drawn down below 1067 feet all sand fraction concentrations increased with the smallest increase in the coarsest (500 µm) fraction.

Particle size distributions and concentrations over the sand size range measured by the LISST-100X are presented in **Figures 12 and 13**. The LISST-100X data show that the majority of sand particles fell within the 63.1 µm to 237 µm size range during the drawdown. However, unlike the silt/clay fractions, the sand fraction ranges responded differently as the forebay pool was drawn down below 1070 feet. The finer sand fractions (63.1 µm to 122 µm) showed relatively gradual increases and decreases in concentration as the forebay pool was drawn down from 1070 feet to 1067 feet and a sharp increase below 1067 feet. The coarser sand fractions (144 µm to 237 µmm) also experienced relatively gradual increases and decreases as pool levels were lowered from 1070 feet to 1067 feet and a sharp increase below 1067 feet. However, this size range also exhibited spikes in sand concentrations as the pool fell from 1070 feet to 1067 feet and below 1067 feet. The coarsest sand fractions (280 µm to 460 µm) showed little increase when the pool was drawn down from 1070 feet to 1067 feet. Sand fractions in the 280 µm and 331 µm size range exhibited spikes in concentrations as the pool was lowered to 1067 feet, while the coarsest sand fractions (390 µm and 460 µm) showed no spikes. All sand fractions except 460 µm increased when the forebay pool was lowered below 1067 feet. Only spikes in concentrations were measured for the 460 µm size class.

3.2.3 Total Suspended Sediment

Total suspended sediment concentrations during the drawdown were calculated from the ISCO-6712 point samples collected at Station HAHW. Turbidity values were measured from these samples to estimate the relationship between turbidity and total suspended sediments during

drawdown operations at Howard Hanson Dam (**Figure 14**). The relationship between total suspended sediment concentrations and turbidity values measured during the drawdown was good (r^2=0.9165), with an excellent relationship between the clay/silt fractions and turbidity (r^2=0.985) and a modest relationship between the sand fractions and turbidity (r^2=0.6771). Because the majority of the Green River sediment loads are transported during a few large storms each year, determining a relationship between suspended sediment and turbidity at Station HAHW is of value. Turbidity measurements are easier to obtain than suspended sediment data and the historical record for turbidity is substantially greater than for suspended sediment.

Estimating silt/clay suspended sediment fractions based on turbidity would appear to be possible based on the data collected during the drawdown event. However, estimates of suspended sand concentrations would be much more variable and considerable less accurate due to the modest relationship measured.

3.2.4 Particle Size Analysis

Frequency analysis for the grain size fractions collected by the ISCO-6712 point sampler during the drawdown are presented in **Figure 15**. In general, samples collected early or late in the drawdown when forebay pool elevations were near or above 1069 feet had the highest percentage of particles in the silt/clay size range. Samples with the highest percentage of particles in the sand size range tended to be collected during the middle of the drawdown when pool elevations were between 1068 and 1066 feet. Silt/clay in the 8 µm to 31 µm size range and sand in the 63 µm to 250 µm particle size range dominated all sample grain size fractions during the drawdown.

3.2.5 Downstream Sediment Analysis

Suspended sediment monitoring was conducted about 32 miles downstream of Howard Hanson Dam near the city of Auburn (Station AUBW). This station provided valuable information on the fate and transport of suspended sediments downstream in the Green River during a drawdown event. Suspended sediment concentrations measured at AUBW were considerably lower than at HAHW (**Figure 16**). Additionally, suspended sediments at AUBW were dominated by the silt/clay fraction (70 to 90 percent), with very little sand measured. These data were in contrast to station HAHW where the silt/clay fraction and sand fraction accounted for about 50 percent each. The difference in particle size distribution between AUBW and HAHW are clearly shown in the frequency analysis graphs (**Figure 17**).

4 CONCLUSIONS

Results from the 2007 drawdown experiment at Howard Hanson Dam indicate that substantial increases in sediment concentrations in the Green River are associated with drawing down the reservoir below the 1070 foot elevation. In-situ and automatic pump samplers deployed about 0.7 miles downstream of the dam at Station HAHW measured abrupt increases in suspended sediment when the pool was dropped below 1070 feet. These suspended sediment increases were largely dominated by the silt/clay fraction with lesser amounts of fine sand fractions. When the pool was lowered below the 1067 foot elevation a second increase in suspended sediments was measured. This second increase was dominated by sand fractions in the 63 µm to 250 µm size range. When the pool was increased back above the 1067 foot elevation and the 1070 foot elevation, suspended sediment concentrations in the Green River quickly decreased to near background levels.

Spikes in sand concentrations measured during the drawdown suggest that pulses of sand moved down the river during periods when the forebay pool was lowered and little sand moved down river when the forebay pool was held at a constant elevation. The data suggest that the lower the forebay pool, the greater the concentration of coarser sand to move down the river. The limited LISST-100X data showed that during the drawdown, two critical forebay elevations existed. The first elevation was at 1070 feet. When the forebay was drawn below this elevation, silt/clay (2.72 µm to 53.5 µm) and finer grained sands (63.1 µm to 237 µm) began to be transported down the river. When the forebay was drawn below 1067 feet, coarser grained sands (280 µm to 460 µm) began to be transported down the river.

Monitoring 32 miles downstream of the dam at Station AUBW showed little to no change in suspended sediment concentrations or particle sizes as a result of the reservoir drawdown. Downstream suspended sediments were dominated by silt/clay particle size fractions. A regression of turbidity values measured immediately downstream of the dam at Station HAHW to suspended sediment concentrations indicated that a good relationship between the two parameters existed during the drawdown experiment. In particular, the silt/clay fraction was highly related to the turbidity values while the sand fraction was only moderately related to the turbidity values.

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6 TABLES

Table 1 Washington Department of Ecology surface water quality standards for Core Summer Salmonid Habitat waters.

Parameter	Standard
Turbidity	Shall not exceed 5 NTU over background turbidity when background turbidity is 50 NTU or less, or have more than a 10 percent increase in turbidity when the background turbidity is more than 50 NTU.
Dissolved oxygen	Lowest 1-Day minimum of 9.5 mg/L.
Temperature	Highest seven day average of the daily maximum temperatures (7-DADMax) shall not exceed 16 °C due to human activities. When natural conditions exceed 16 °C, no temperature increases will be allowed witch will raise the receiving water temperature 7-DADMax by greater than 0.3 °C.
pH	Shall be within the range of 6.5 to 8.5 with a human-caused variation within a range of less than 0.2 units.

Source: WAC 173-201A
mL milliliters
mg/L milligrams per liter
NTU Nephelometric turbidity units

Table 2. Methods and detection limits for water quality analyses.

Parameter	Method	Method Number [a]	Detection Limit/Unit
Field Parameters			
Temperature	Thermistor	SM 2550B	0.1°C
pH	Electrometric	SM 4500-H and B	–
Conductivity	Platinum Electrode	SM 2510B	1 µS/cm
Turbidity	Nephelometric	SM 2130B	0.1 NTU
Dissolved Oxygen	Membrane Electrode	SM 4500-OG	0.1 mg/L
Laboratory Parameters			
Total Suspended Solids	Gravimetric at 103C	EPA 160.2	1.0 mg/L
Settleable Solids	Gravimetric	EPA 160.5	1.0 mg/L
Particle Size Fractions	Particle Counter	SM 2560	1 µm

[a] SM method numbers are from APHA et al. (1992), EPA method numbers are from U.S. EPA (1983, 1984)
NTU Nephelometric turbidity units
mg/L Milligrams per liter
µS/cm Microsiemens per centimeter

Table 3. Monitoring station locations.

Site Identifier	Station Name	Latitude	Longitude
HAHW	Green River at Howard Hanson Dam	47° 16' 50"	121° 47' 19"
HAQW	Green River above Reservoir Pool	47° 14' 31"	121° 43' 44"
GRAH	Green River at Tacoma Headworks near Palmer	47° 18' 19"	121° 50' 58'
AUBW	Green River near Auburn	47° 18' 45"	122° 12' 10'

Table 4. Automated and manual turbidity readings collected at Station HAQW and Station HAHW during the drawdown.

Date and Time	Forebay Elevation (feet)	Tailwater Station HAHW Grab Sample Turbidity (NTU)	Tailwater Station HAHW Automatic Sampler Turbidity (NTU)	Tailwater Station HAHW Isco Pump Sampler Turbidity (NTU)	Inflow Station HAQW Automatic Sampler Turbidity (NTU)	Inflow (cfs)	Outflow (cfs)
12/2/07 1:00	1074.0		4.9		3.9	443	429
12/2/07 2:00	1074.0		5.1		3.9	440	426
12/2/07 3:00	1074.0		5.1		3.9	440	426
12/2/07 4:00	1074.0		4.9		3.9	440	426
12/2/07 5:00	1074.0		4.9		4.4	426	426
12/2/07 6:00	1074.0		4.9		3.8	443	429
12/2/07 7:00	1074.0		5.1		3.8	426	426
12/2/07 8:00	1074.1		4.8		4.0	440	426
12/2/07 9:00	1074.1		4.9		4.0	440	426
12/2/07 10:00	1074.1		4.8		3.9	426	426
12/2/07 11:00	1074.1		4.6		3.9	429	429
12/2/07 12:00	1074.1		4.9		3.9	412	426
12/2/07 13:00	1074.1		4.5		3.9	440	426
12/2/07 14:00	1074.0		5.5		3.9	398	426
12/2/07 15:00	1074.1		5.2		3.9	496	426
12/2/07 16:00	1074.1		5.2		3.9	426	426
12/2/07 17:00	1074.1		5.4		3.9	507	535
12/2/07 18:00	1073.9		5.5		4.0	497	763
12/2/07 19:00	1073.6		6.2		3.9	415	763
12/2/07 20:00	1073.4		6.8		3.9	441	758
12/2/07 21:00	1073.2		6.1		4.0	417	758
12/2/07 22:00	1072.9		5.8		3.8	429	754
12/2/07 23:00	1072.7		6.1		3.8	445	754
12/2/07 23:59	1072.5		5.4		3.9	487	754
12/3/07 1:00	1072.3		5.3		3.9	512	750
12/3/07 2:00	1072.2		5.7		4.0	579	750
12/3/07 3:00	1072.1		7.4		4.1	705	849
12/3/07 4:00	1071.9		10.8		4.3	757	940
12/3/07 5:00	1071.8		17.9		4.7	865	1021
12/3/07 6:00	1071.8		32.2		4.8	1074	1100
12/3/07 7:00	1071.8		59.3		5.7	1400	1413
12/3/07 8:00	1071.6	49.3	81.7		6.4	1431	1612
12/3/07 9:00	1071.6		116.1		5.6	1580	1606
12/3/07 10:00	1071.7		150.4		7.6	1876	1721
12/3/07 11:00	1071.6		164.7		8.9	1914	2108
12/3/07 12:00	1071.5		173.8		9.1	2024	2101
12/3/07 13:00	1071.6		162.1		13.5	2178	2101
12/3/07 14:00	1071.7				12.8	2402	2286
12/3/07 15:00	1071.6		180.0		17.8	2384	2526
12/3/07 16:00	1071.3		154.0		17.3	2231	2526
12/3/07 17:00	1071.2		174.6		16.0	2377	2517
12/3/07 18:00	1071.2		192.3		12.9	2458	2508
12/3/07 19:00	1071.2		178.0		24.4	2508	2508
12/3/07 20:00	1071.1		175.6		15.8	2593	2669

Table 4. Automated and manual turbidity readings collected at Station HAQW and Station HAHW during the drawdown. (Continued)

Date and Time	Forebay Elevation (feet)	Tailwater Station HAHW Grab Sample Turbidity (NTU)	Tailwater Station HAHW Automatic Sampler Turbidity (NTU)	Tailwater Station HAHW Isco Pump Sampler Turbidity (NTU)	Inflow Station HAQW Automatic Sampler Turbidity (NTU)	Inflow (cfs)	Outflow (cfs)
12/3/07 21:00	1071.0		182.5		19.3	2635	2761
12/3/07 22:00	1070.9		225.4		20.2	2595	2771
12/3/07 23:00	1070.9		237.9		17.5	2783	2771
12/3/07 23:59	1070.9		244.2		22.7	2798	2836
12/4/07 0:00	1070.86		244.0		23	2912	2836
12/4/07 1:00	1070.86		245.0		21	2973	2912
12/4/07 2:00	1070.86		240.0		18	2964	2998
12/4/07 3:00	1070.82		256.0		22	3046	2989
12/4/07 4:00	1070.83		247.0		19	3159	3096
12/4/07 5:00	1070.78		252.0		20	3116	3096
12/4/07 6:00	1070.79		227.0		18	3099	3216
12/4/07 7:00	1070.7		260.0		21	3095	3297
12/4/07 8:00	1070.24	179.0	302.8		23.6	3095	3527
12/4/07 8:30	1070	295.0	456.0				
12/4/07 9:00	1069.7	360.0	576.0		27.3	2928	3580
12/4/07 10:00	1069.51	390.0	579.0	400	27.6	3323	3548
12/4/07 11:00			589.0	435	25.4		
12/4/07 11:15		395.0	613.0			3309	3558
12/4/07 11:45	1069.31	355.0	618.0			3569	3569
12/4/07 12:00			602.0	404	30.5		
12/4/07 12:45	1069.55	441.0	636.0			3900	3580
12/4/07 13:00			550.0	339	35.0		
12/4/07 13:10	1069.72	390.0	572.0			3900	3580
12/4/07 14:00			467.0	319	30.2		
12/4/07 14:30	1069.2	322.0	527.0	305		3700	3853
12/4/07 15:00		436.0	591.0	448	23.6		
12/4/07 15:30	1068.53	448.0	710.0			3700	3775
12/4/07 16:00			611.0	346	35.9		
12/4/07 16:15	1069.17	304.0	529.0			3700	3558
12/4/07 17:00			426.0		29.4		
12/4/07 17:20	1069.34	274.0	426.0			3750	3775
12/4/07 18:00			361.2		31.8		
12/4/07 18:25	1069.22	225.0	361.8			3750	3931
12/4/07 19:00				251	30.0		
12/4/07 19:20	1068.93	235.0	373.5			3700	4022
12/4/07 20:00	1068.71	247.0			28.7	3700	3976

Table 4. Automated and manual turbidity readings collected at Station HAQW and Station HAHW during the drawdown. (Continued)

Date and Time	Forebay Elevation (feet)	Tailwater Station HAHW Grab Sample Turbidity (NTU)	Tailwater Station HAHW Automatic Sampler Turbidity (NTU)	Tailwater Station HAHW Isco Pump Sampler Turbidity (NTU)	Inflow Station HAQW Automatic Sampler Turbidity (NTU)	Inflow (cfs)	Outflow (cfs)
12/4/07 21:00	1068.38	240.0	421.0		25.4	3650	3964
12/4/07 22:00	1068.39	256.0	435.0	285	23.4	3600	3808
12/4/07 23:00	1068.2	252.0	555.0		23.6	3600	3797
12/5/07 0:00	1068	263.0	435.0		23.5	3550	3786
12/5/07 1:00	1067.8	316.0	502.0	320	21.7	3500	3764
12/5/07 2:00	1067.4	301.0	534.0		20.6	3480	3720
12/5/07 3:00	1067.1	339.0	602.0		20.6	3460	3590
12/5/07 4:00	1066.9	283.0	661.0	438	18.6	3440	3537
12/5/07 5:00	1066.74	556.0	778.0		17.7	3420	3516
12/5/07 5:30	1066.94	425.0	789.0			3400	3338
12/5/07 6:00	1067.01	362.0	737.0		16.9	3350	3338
12/5/07 7:00	1066.83	404.0	728.0	476	17.7	3200	3250
12/5/07 8:00	1067.01	422.0	662.0		15.9	3200	3186
12/5/07 9:00	1067.02		517.0		15.0	3180	3176
12/5/07 10:00	1066.59	366.0	534.0	386	13.6	3150	3230
12/5/07 11:00	1066.41	507.0	691.0	508	14.1		3156
12/5/07 12:00	1066.37	514.0	783.0	583		3000	3010
12/5/07 12:50	1066.55	524.0					2930
12/5/07 13:00	1066.68	489.0	698.0	524	13.8	3000	2921
12/5/07 14:00	1066.97	463.0	674.0	499	12.7	2900	2845
12/5/07 15:00	1067.22	344.0	551.0	362	12.8	2850	2770
12/5/07 16:00	1067.46	326.0	452.0		12.2	2800	2742
12/5/07 17:00	1067.47	274.0	387.0	272	12.3	2750	2770
12/5/07 18:00	1067.26	226.0	377.4		12.4	2725	2771
12/5/07 19:00	1067.47	241.0	386.9		12.1	2700	2624
12/5/2007 20:00	1067.91		312.6	220	12.2	2700	2474
12/5/2007 21:00	1068.18	163.0	368.1		11.8	2700	2500
12/5/2007 22:00	1068.3	144.0	264.8		18.0	2600	2517
12/5/2007 23:00	1068.31	146.0	277.3	139	11.9	2530	2517
12/6/2007 0:00	1068.21	131.0	196.4		11.4	2450	2517
12/6/2007 1:00	1068.68	104.0	177.9		11.5	2450	2253
12/6/2007 2:00	1069.29	122.0	138.4	106	11.2	2400	2109
12/6/2007 3:00	1069.9	56.3	104.5		11.6	2400	2017
12/6/2007 4:00	1070.58	54.4	144.9		11.5	2400	1890
12/6/2007 5:00	1071.28	51.6	63.1	48	10.9	2380	1783
12/6/2007 6:00	1071.92	41.0	51.1		10.4	2380	1652
12/6/2007 7:00	1072.62	53.0	46.3		10.3	2380	1507

Table 4. Automated and manual turbidity readings collected at Station HAQW and Station HAHW during the drawdown. (Continued)

Date and Time	Forebay Elevation (feet)	Tailwater Station HAHW Grab Sample Turbidity (NTU)	Tailwater Station HAHW Automatic Sampler Turbidity (NTU)	Tailwater Station HAHW Isco Pump Sampler Turbidity (NTU)	Inflow Station HAQW Automatic Sampler Turbidity (NTU)	Inflow (cfs)	Outflow (cfs)
12/6/2007 8:00	1073.25	40.2	92.0	23	10	2360	1514
12/6/2007 9:00	1074.29	39.2	52.8		10	2266	1521
12/6/2007 10:00	1074.54		48.4		9	2237	1533
12/6/2007 11:00	1075.04		19.8		9	2201	1444
12/6/2007 12:00	1075.5		19.7		9	2151	1451
12/6/2007 13:00	1075.91		16.8		9	2083	1463
12/6/2007 14:00	1076.3		21.6		9	2081	1469
12/6/2007 15:00	1076.65				9	2040	1476
12/6/2007 16:00	1076.98		18.7		9	1985	1482
12/6/2007 17:00	1077.28		9.3		9	1968	1489
12/6/2007 18:00	1077.55		10.2		10	1951	1495
12/6/2007 19:00	1077.8		12.8		9	1910	1501
12/6/2007 20:00	1077.92		13.7		9	1863	1501
12/6/2007 21:00	1078.14		14.9		9.7	1862	1508
12/6/2007 22:00	1078.35		10.0		9.9	1851	1508
12/6/2007 23:00	1078.53		34.1		9.3	1808	1514
12/7/2007 0:00	1078.69		177.4		9.0	1775	1514
12/7/2007 1:00	1078.84		19.8		9.1	1766	1521
12/7/2007 2:00	1078.97		66.9		9.1	1733	1521
12/7/2007 3:00	1079.08		10.2		9.4	1711	1527
12/7/2007 4:00	1079.18		6.2		9.4	1697	1527
12/7/2007 5:00	1079.26		5.5		9.4	1662	1527
12/7/2007 6:00	1079.33		4.9		9.6	1645	1527
12/7/2007 7:00	1079.40		58.7		9.5	1652	1533
12/7/2007 8:00	1079.26		327.5		9.1	1632	1869
12/7/2007 9:00	1078.89		43.4		9.3	1600	2220
12/7/2007 10:00	1078.23		12.7		9.4	1564	2642
12/7/2007 11:00	1077.76		28.8		9.5	1458	2211
12/7/2007 12:00	1077.53		8.7		9.3	1486	1848
12/7/2007 13:00	1077.49		5.5		8.3	1470	1533
12/7/2007 14:00	1077.52		5.3		8.3	1492	1444
12/7/2007 15:00	1077.58		28.5		8.3	1458	1364
12/7/2007 16:00	1077.72		7.8		8.4	1507	1286
12/7/2007 17:00	1077.88		14.6		7.2	1452	1200
12/7/2007 18:00	1078.09		8.1		7.3	1463	1128
12/7/2007 19:00	1078.30		6.9		7.1	1471	1128
12/7/2007 20:00	1078.50		7.0		6.7	1460	1133
12/7/2007 21:00	1078.67		5.7		6.8	1411	1133
12/7/2007 22:00	1078.84		6.1		6.8	1416	1139
12/7/2007 23:00	1078.99		4.6		7.0	1384	1139
12/8/2007 0:00	1079.14		4.3		6.9	1392	1139

Table 5. Water quality data collected at Stations HAQW, HAHW, and GRAH during the December 2007 drawdown.

Station	Date	Time	pH	Dissolved Oxygen (mg/L)	Conductivity (µS/cm)	Turbidity (NTU)	Total Suspended Sediment (mg/L)	Temperature (°C)
Upstream (HAQW)								
	4-Dec	1230	7.54	12.65	31.4	20	54	4.3
	4-Dec	1600	7.57	12.87	31.1	19	49	4.5
	5-Dec	920	8.02	13.2	31.7	7	13	4.5
	5-Dec	1600	7.84	13.1	32.1	4	8	4.9
	6-Dec	1430	7.96	13.03	33.8	3	2	4.9
Tailwater (HAHW)								
	4-Dec	1030	7.55	12.82	30.7	388	1238	4.8
	4-Dec	1630	7.71	12.95	30.7	308	1019	5.2
	5-Dec	1000	7.97	13.88	33.1	365	1000	4.9
	5-Dec	1630	7.95	13.36	33.4	274	972	5.2
	6-Dec	1400	8.11	13.4	38.5	38	82	4.6
Downstream of Headworks (GRAH)								
	4-Dec	1045	7.56	12.81	30.9	325	833	4.8
	4-Dec	1645	7.55	12.81	29.9	318	750	5.3
	5-Dec	1100	7.81	13.76	31.1	322	987	5.1
	5-Dec	1645	7.6	12.94	32.3	254	679	5.4
	6-Dec	1530	7.72	12.69	35.2	12	54	4.7

7 FIGURES

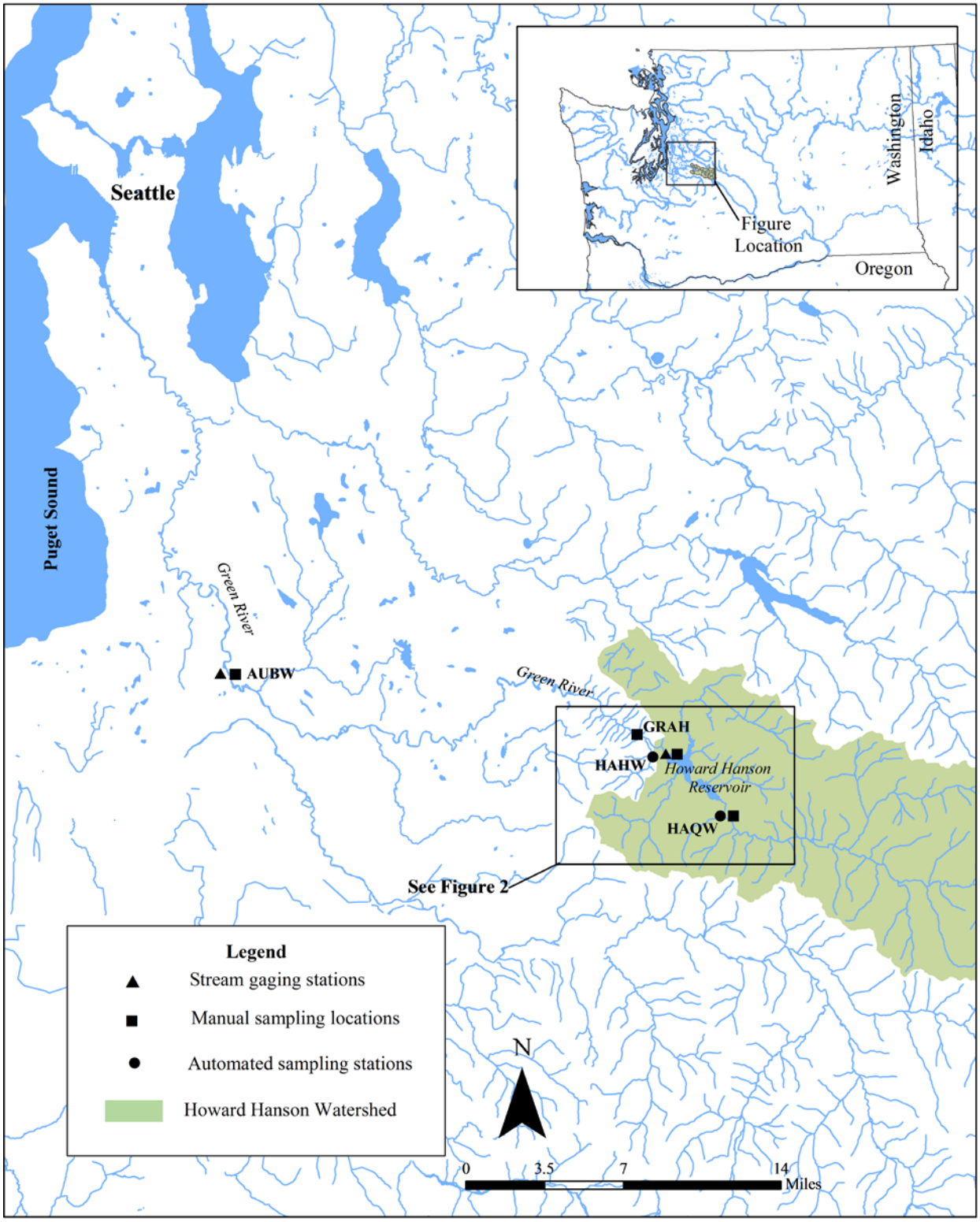


Figure 1. Vicinity map of the Howard Hanson Dam reservoir drawdown water monitoring program in King County, Washington.

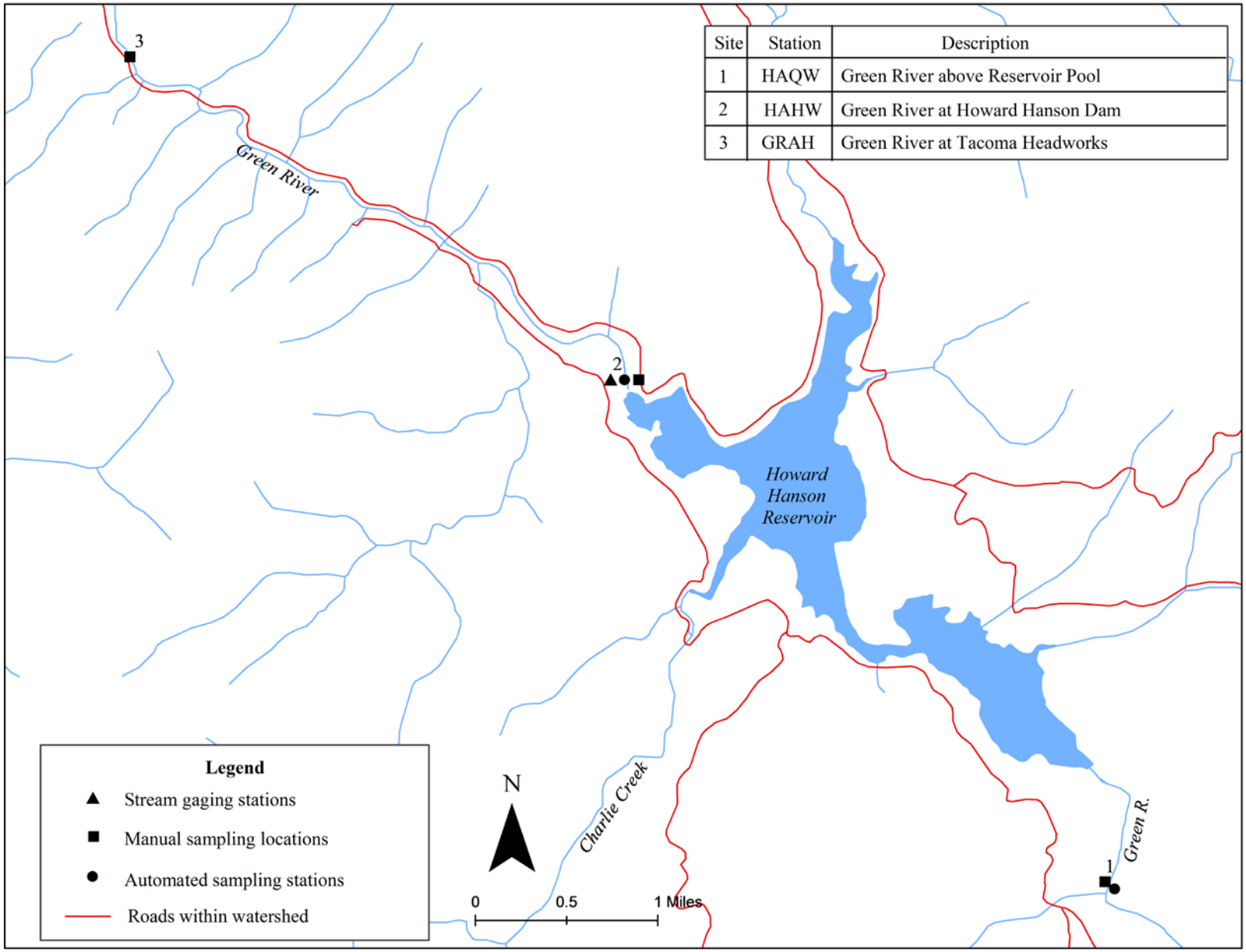


Figure 2. Howard Hanson Dam water quality monitoring locations.

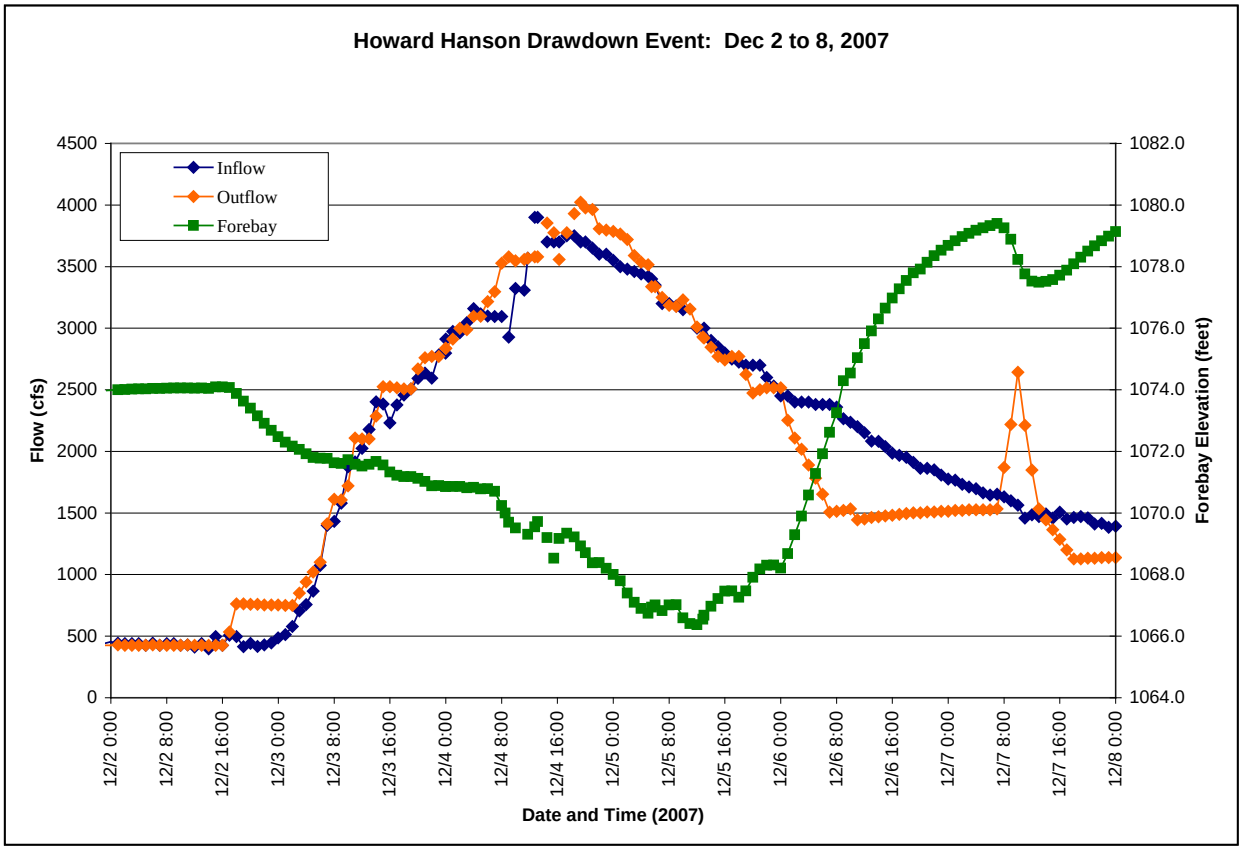
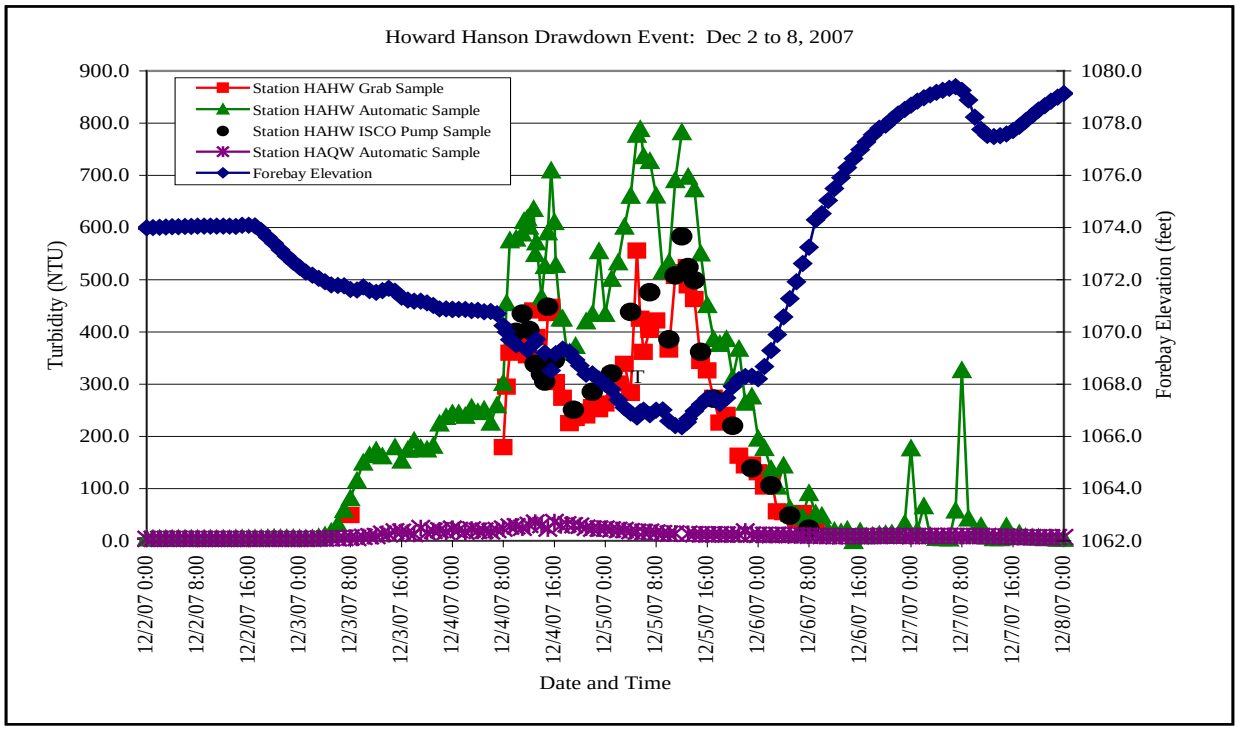


Figure 3. Inflow, outflow, and forebay pool elevation measured during the drawdown.



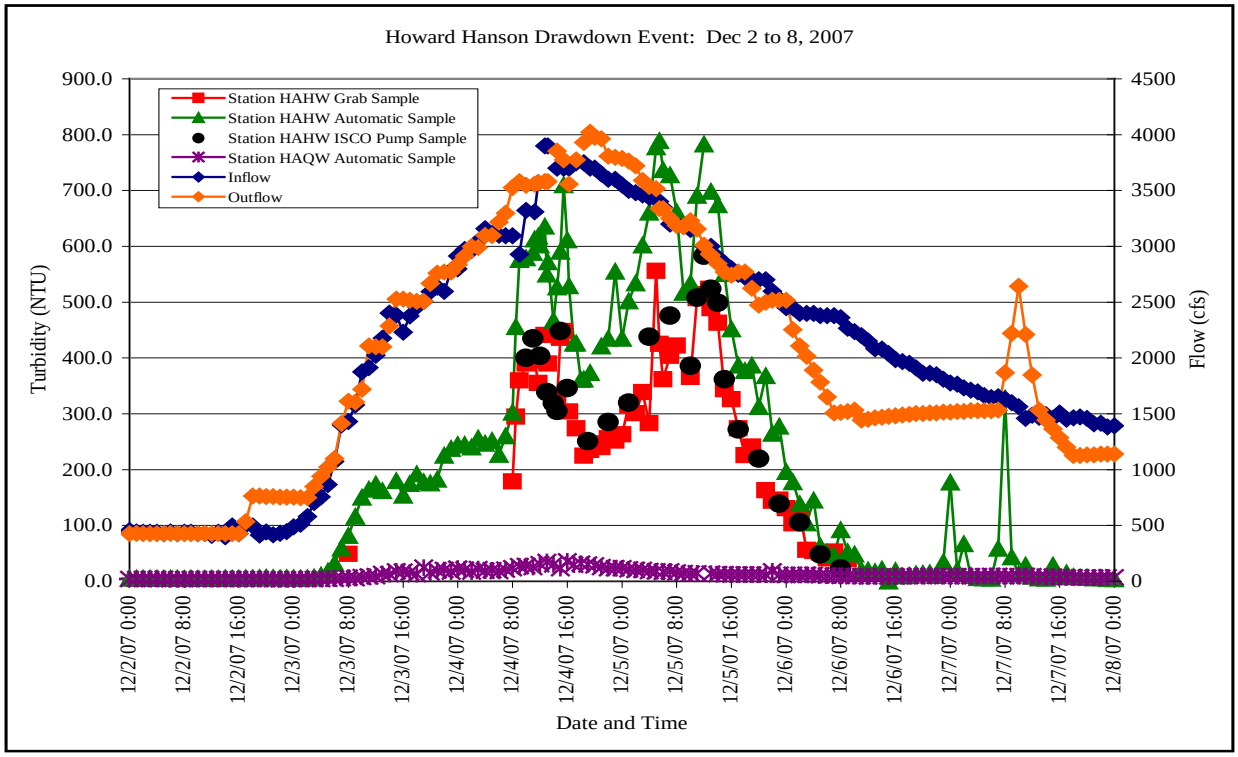


Figure 4. Howard Hanson Dam forebay elevation and flows compared to turbidity values measured during the drawdown.

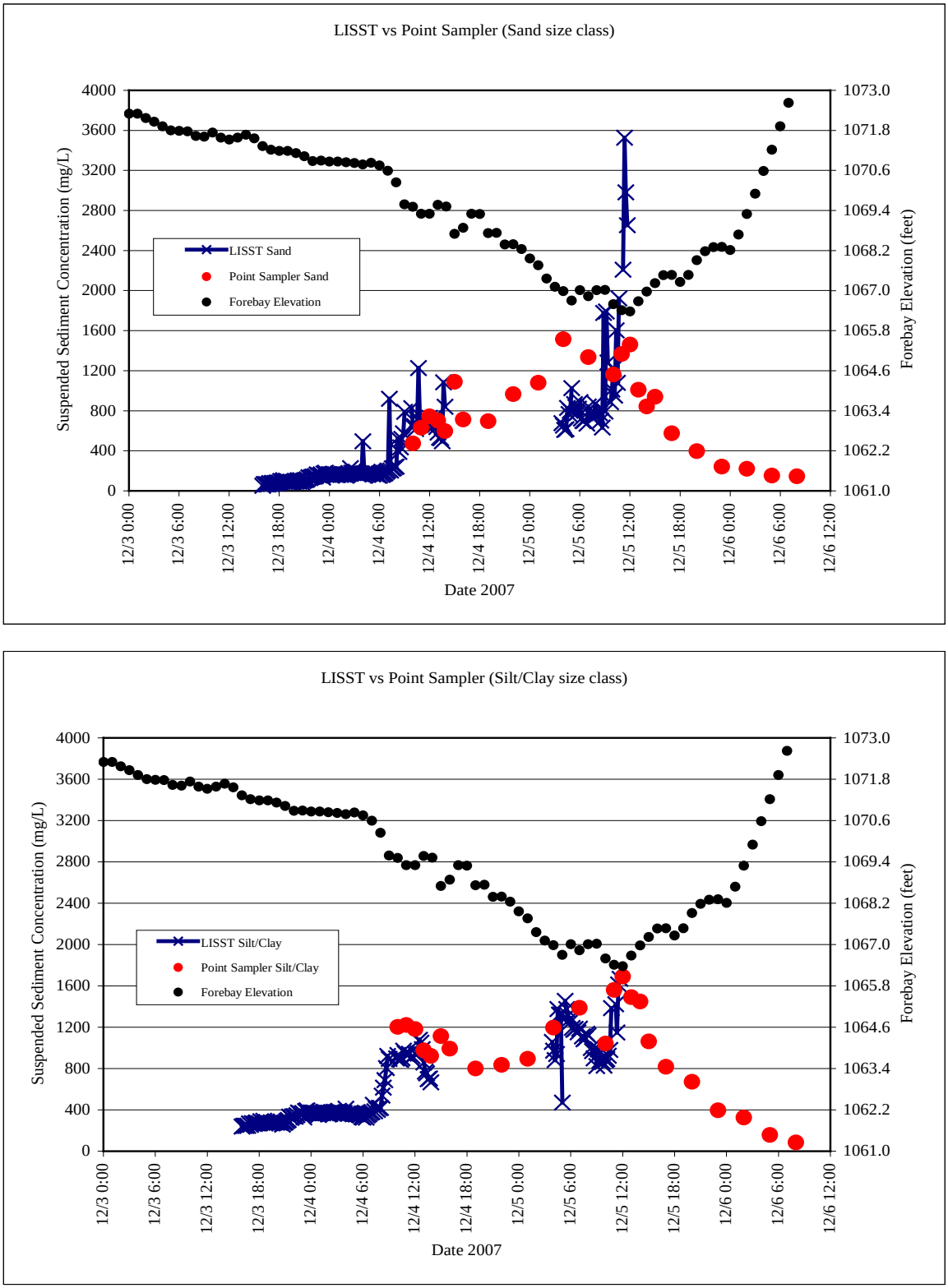


Figure 5. Comparison of LISST and point sampler sand and silt/clay concentrations measured during the drawdown.

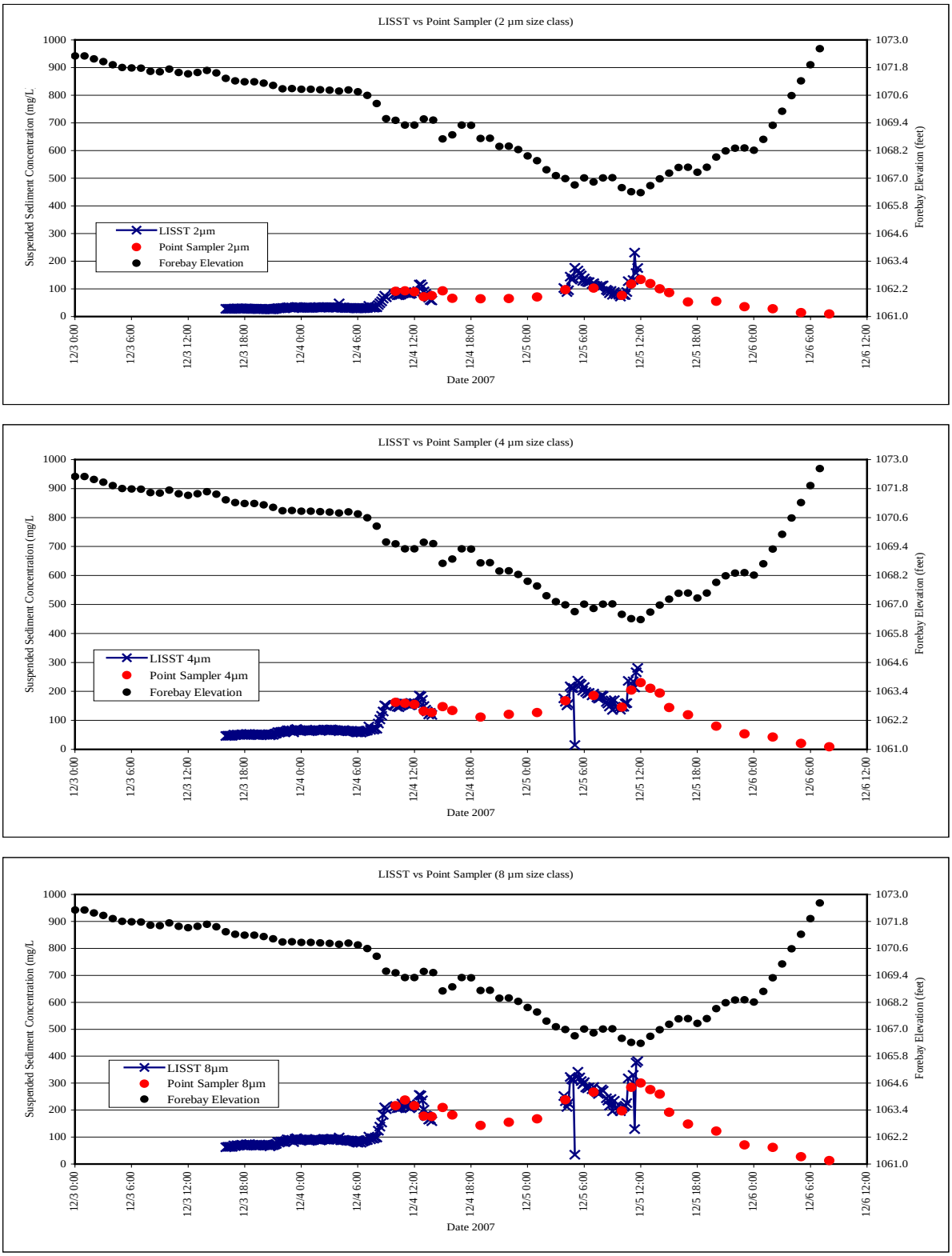
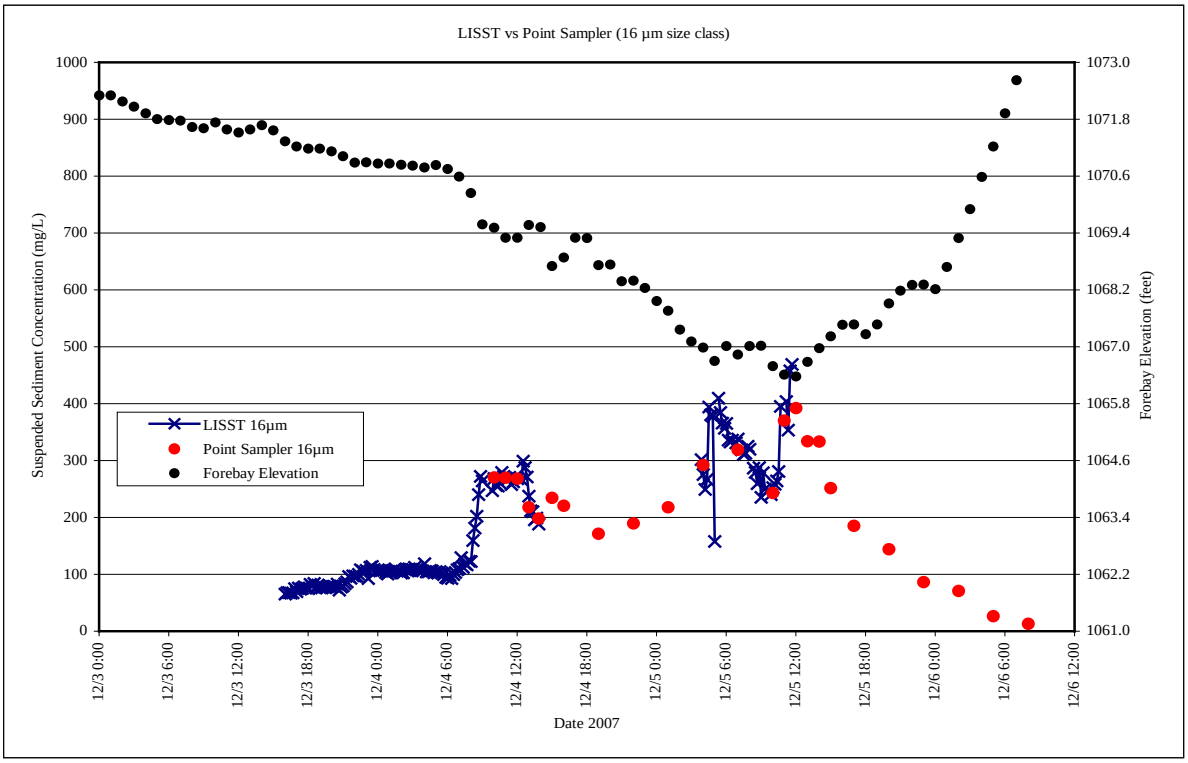


Figure 6. Comparison of LISST and point sampler silt/clay fraction concentrations measured during the drawdown.



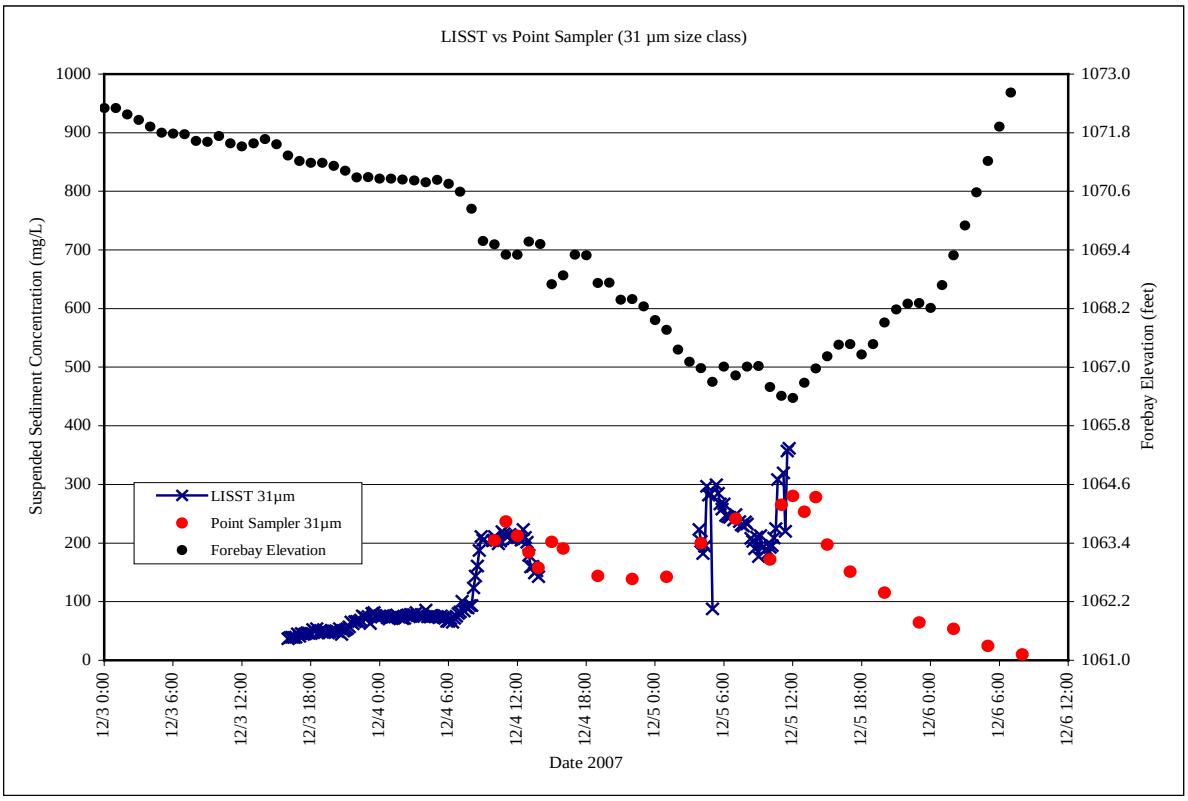
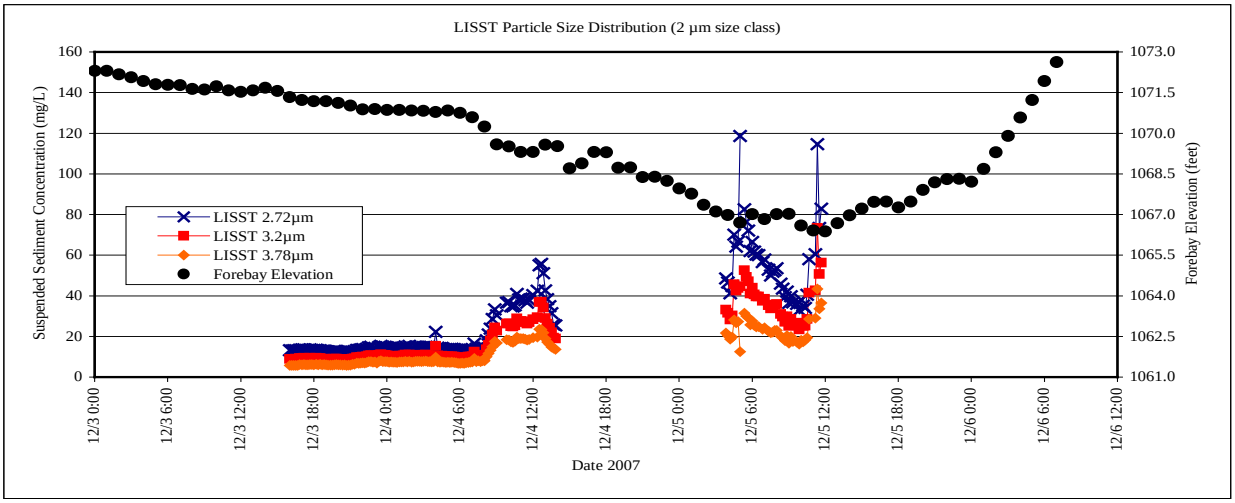
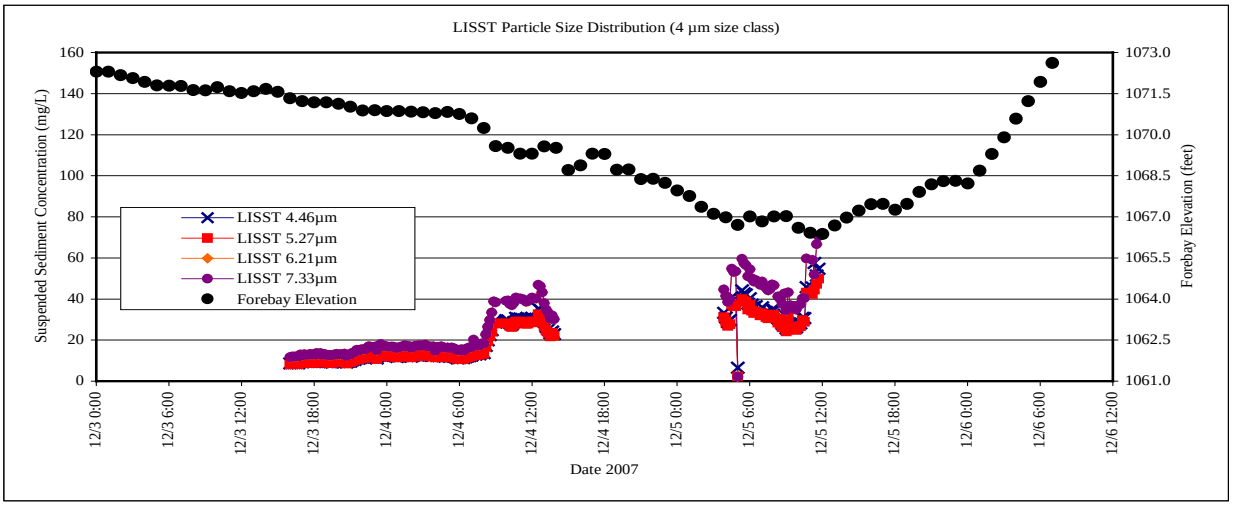


Figure 7. Comparison of LISST and point sampler silt/clay fraction concentrations measured during the drawdown.





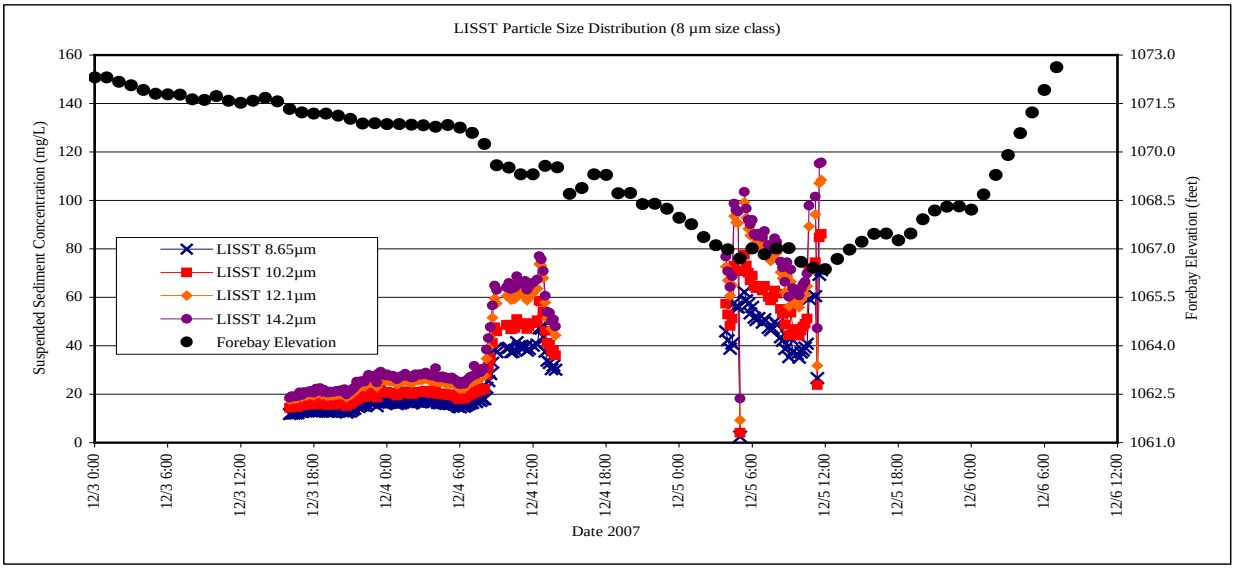
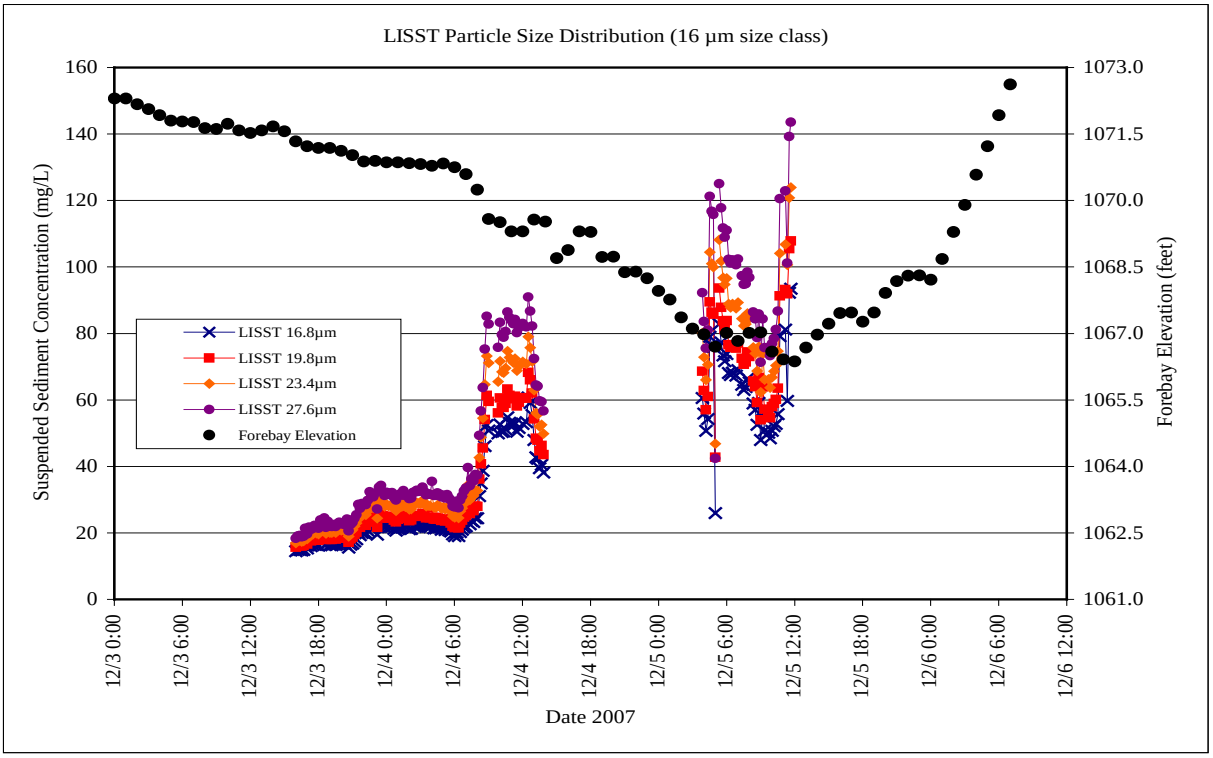


Figure 8. Particle size distribution in the 2µm to 8µm size range as measured by the LISST-100X during the drawdown.



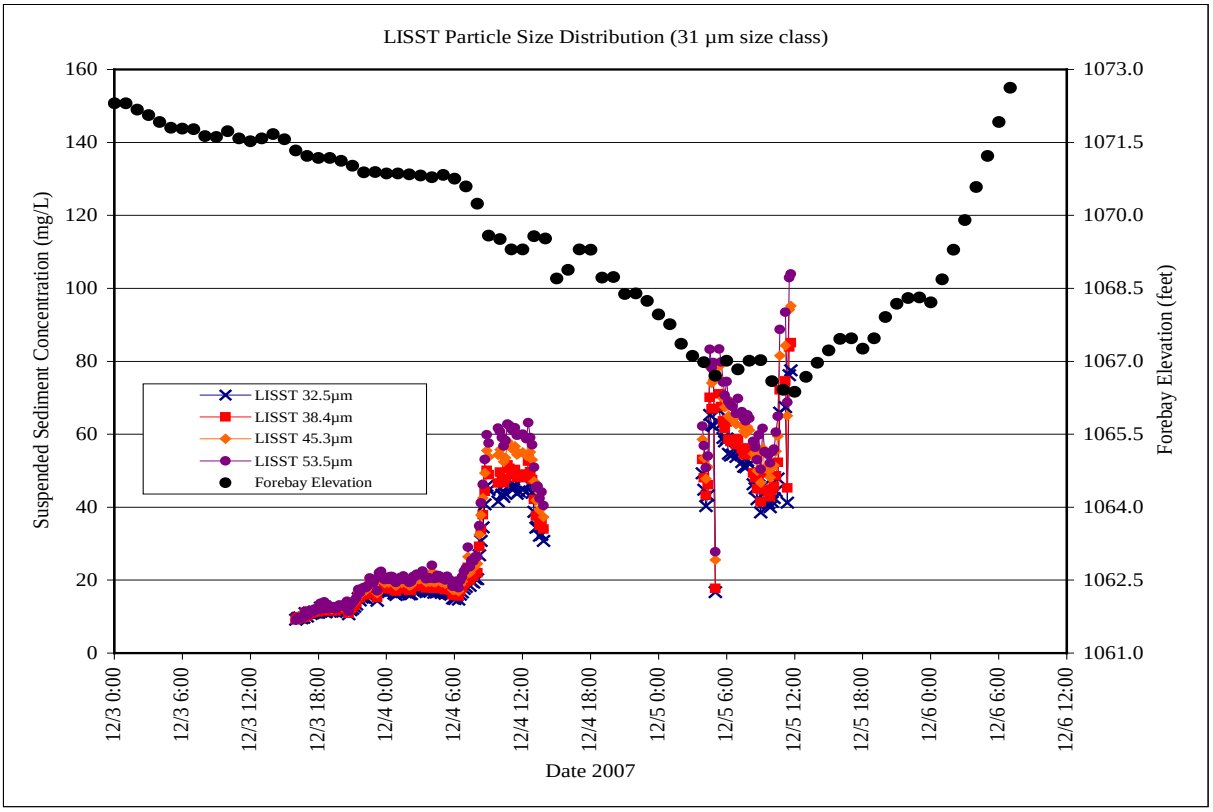
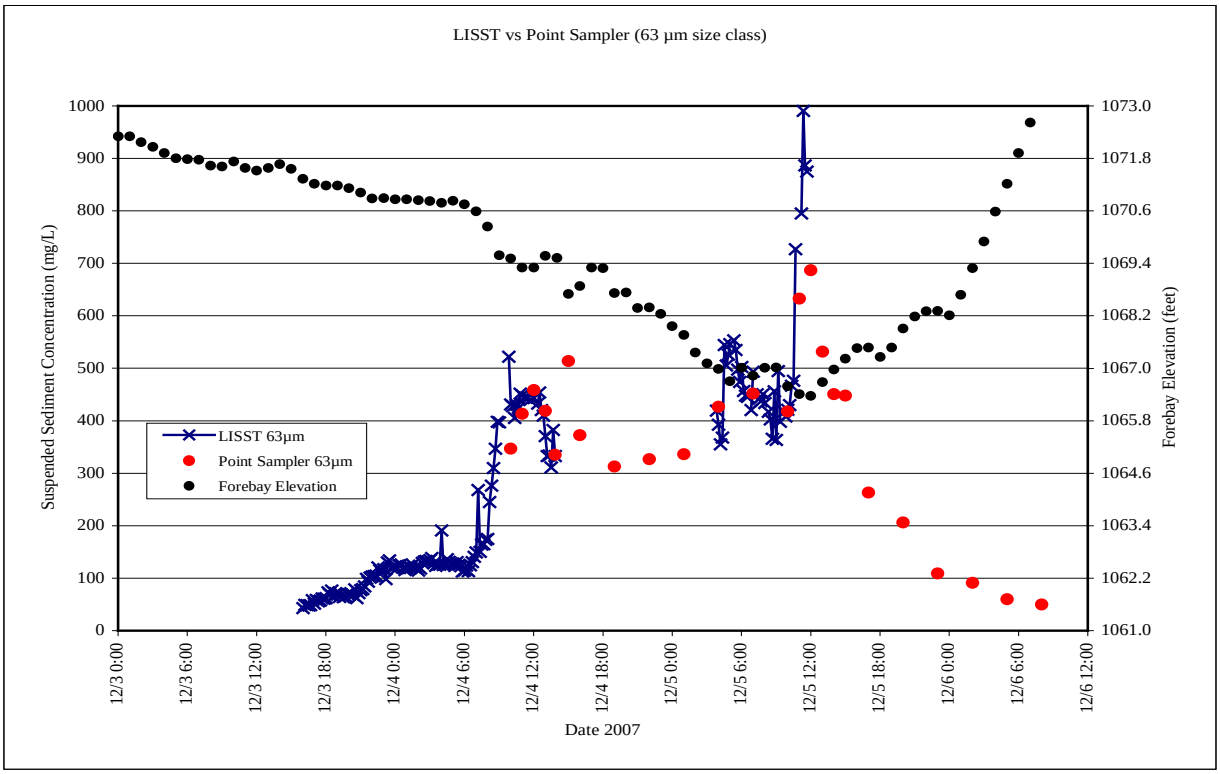


Figure 9. Particle size distribution in the 16µm to 31µm size range as measured by the LISST-100X during the drawdown.



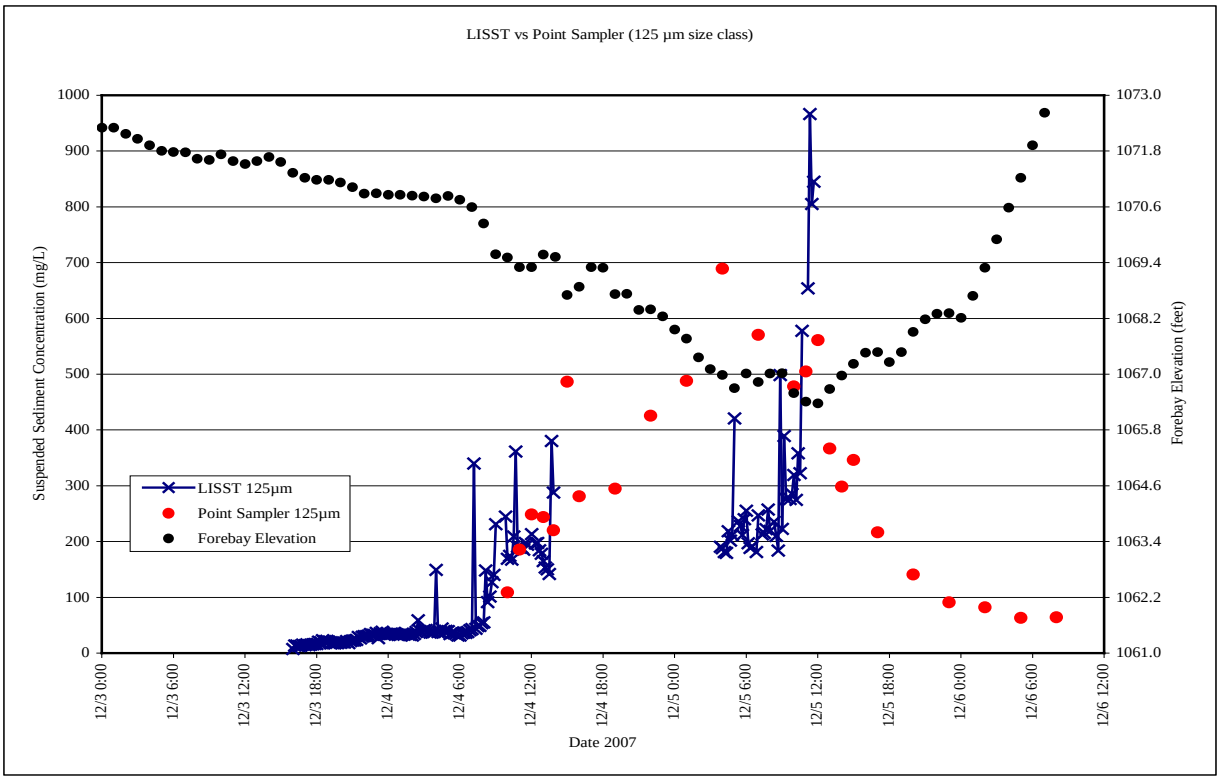
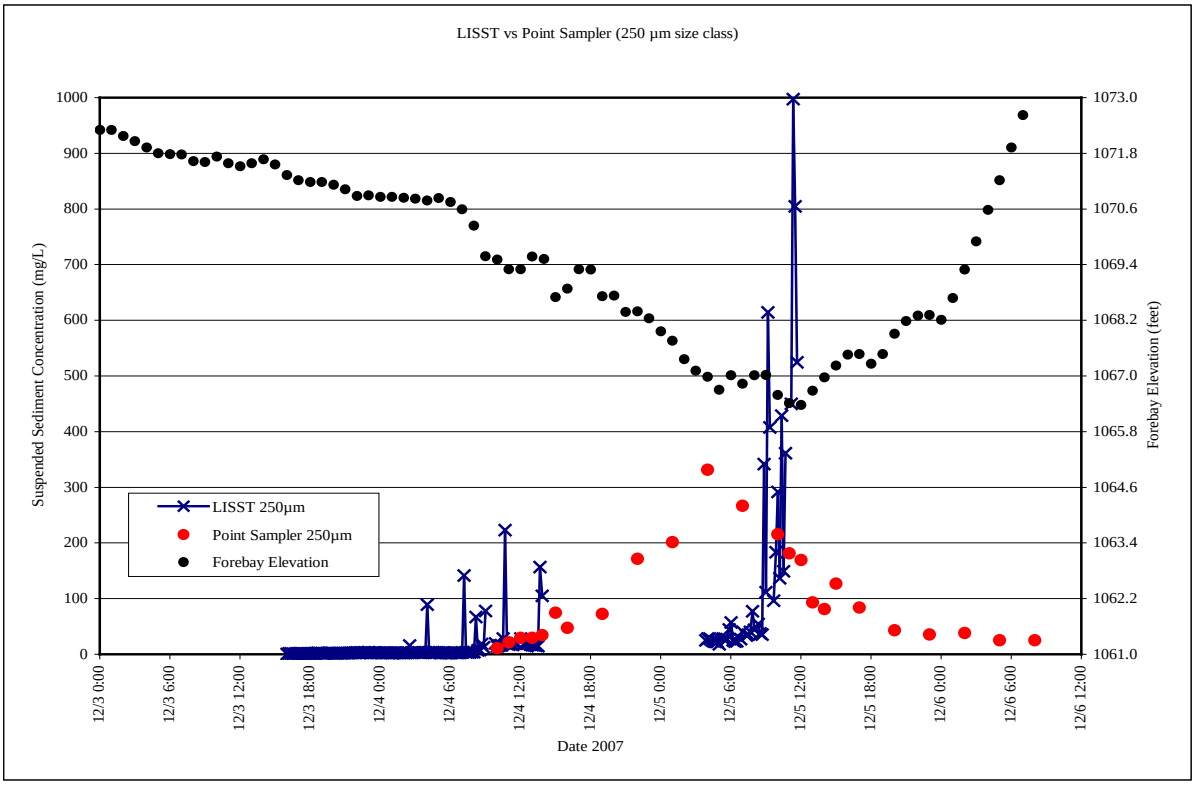


Figure 10. Comparison of LISST and point sampler sand fraction concentrations measured during the drawdown.



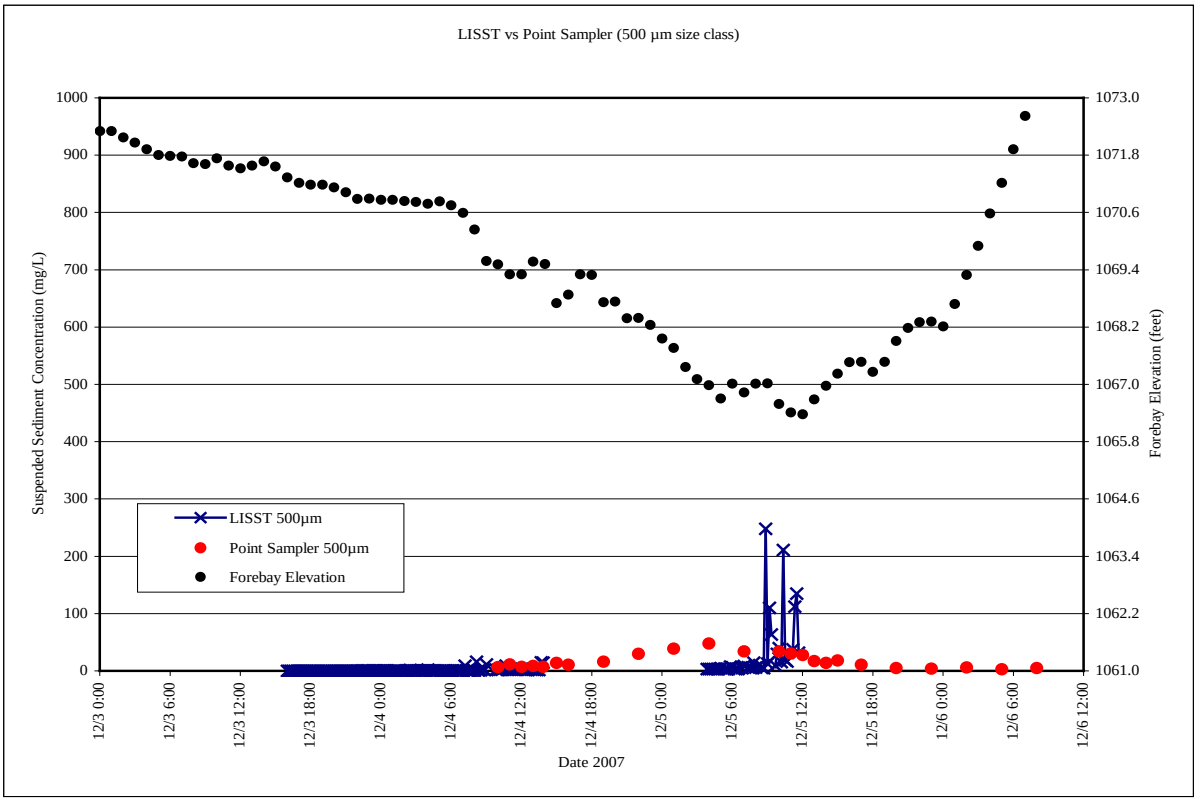
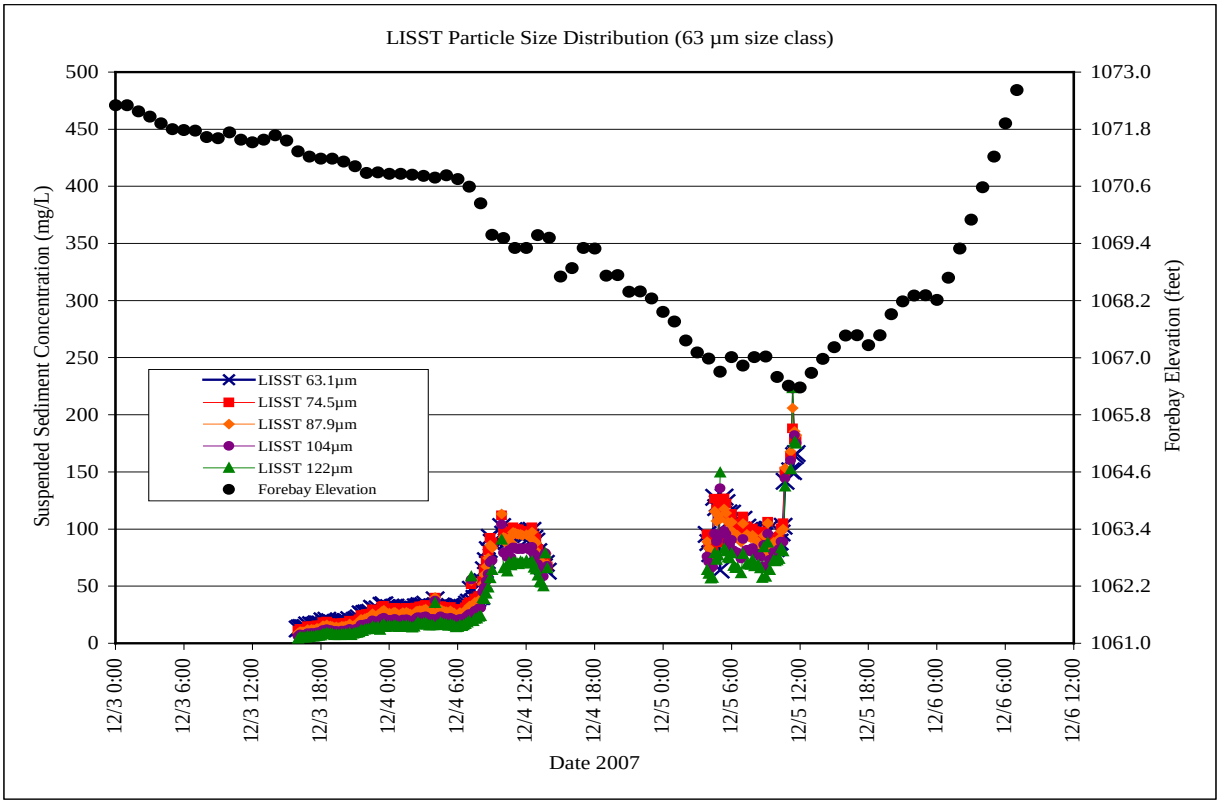


Figure 11. Comparison of LISST and point sampler sand fraction concentrations measured during the drawdown.



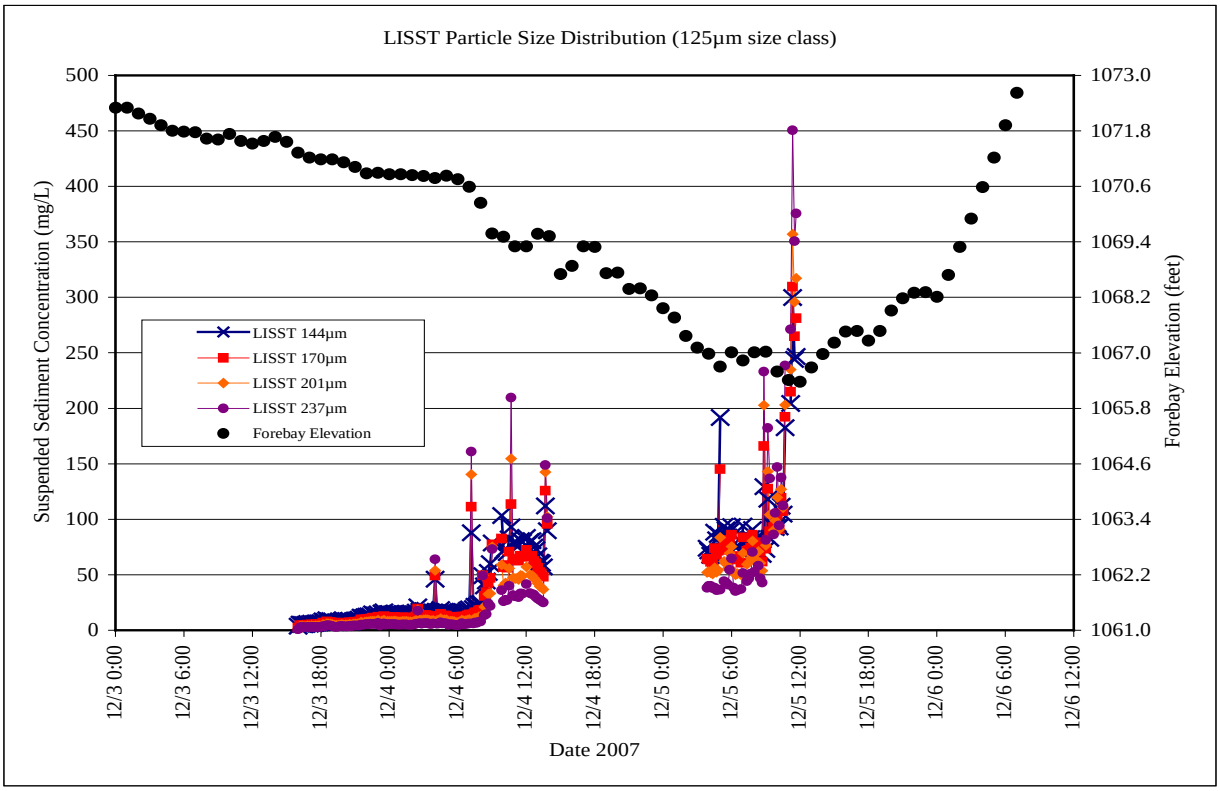
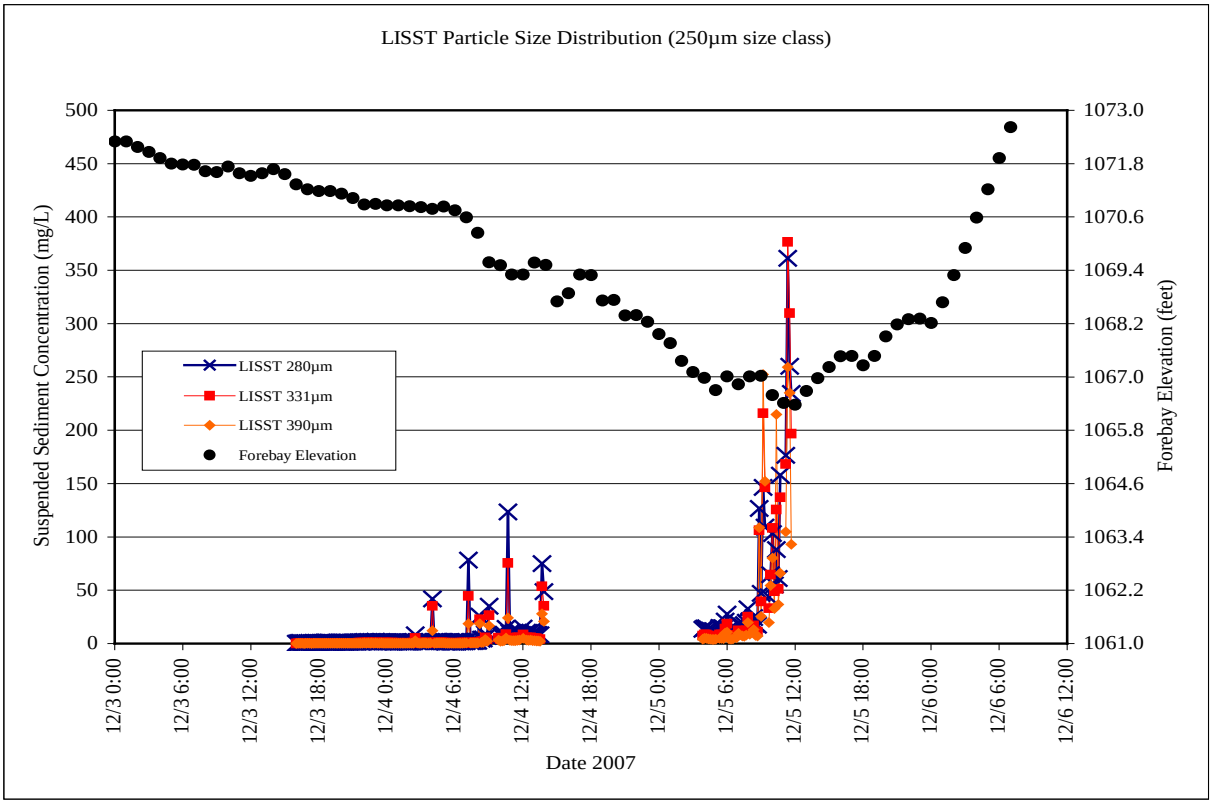


Figure 12. Particle size distribution in the 63µm to 125µm size range as measured by the LISST-100X during the drawdown.



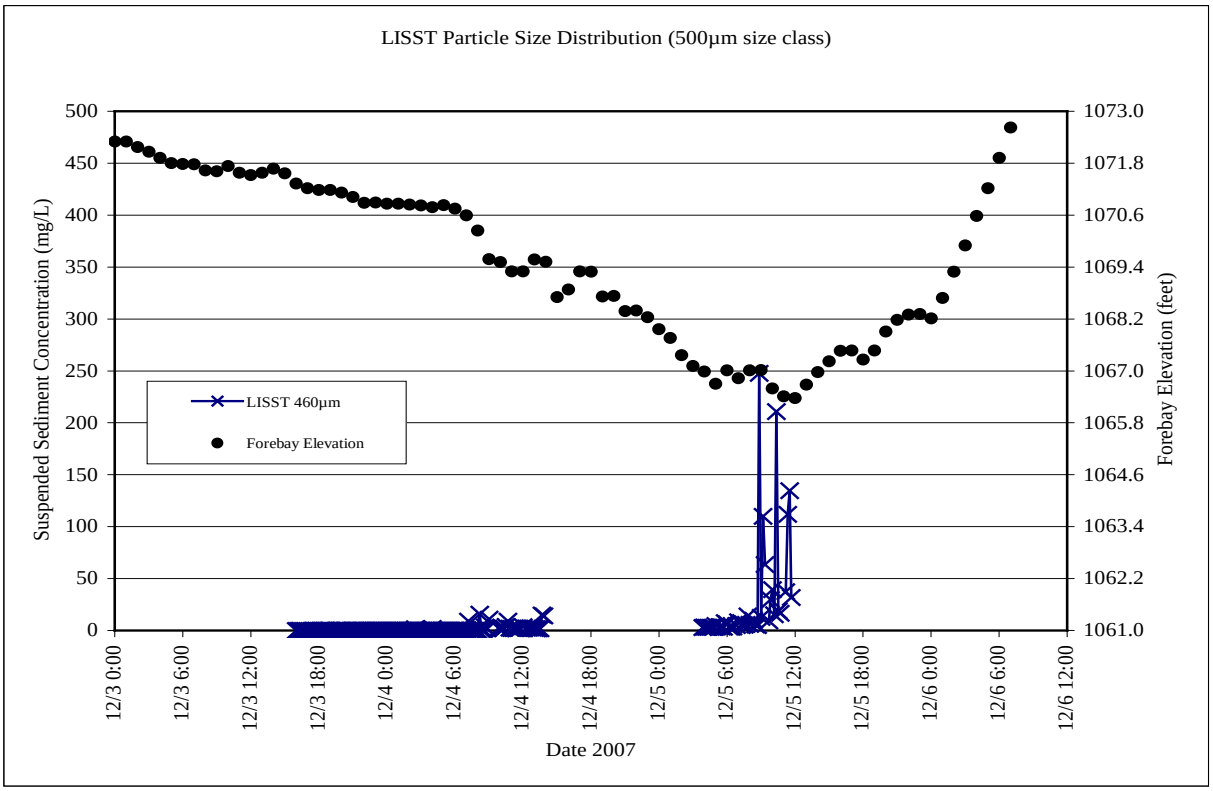
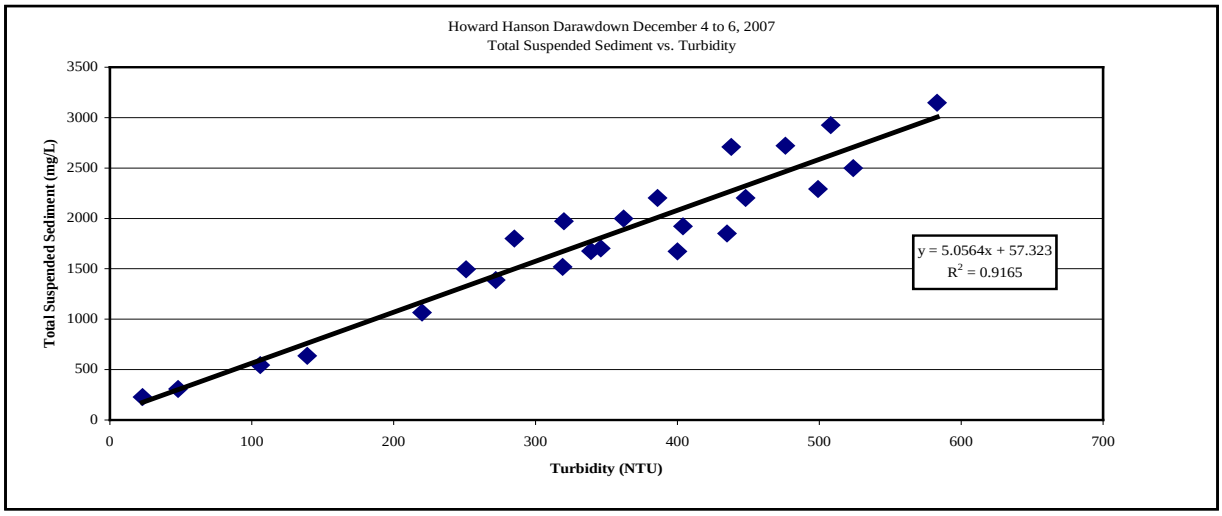
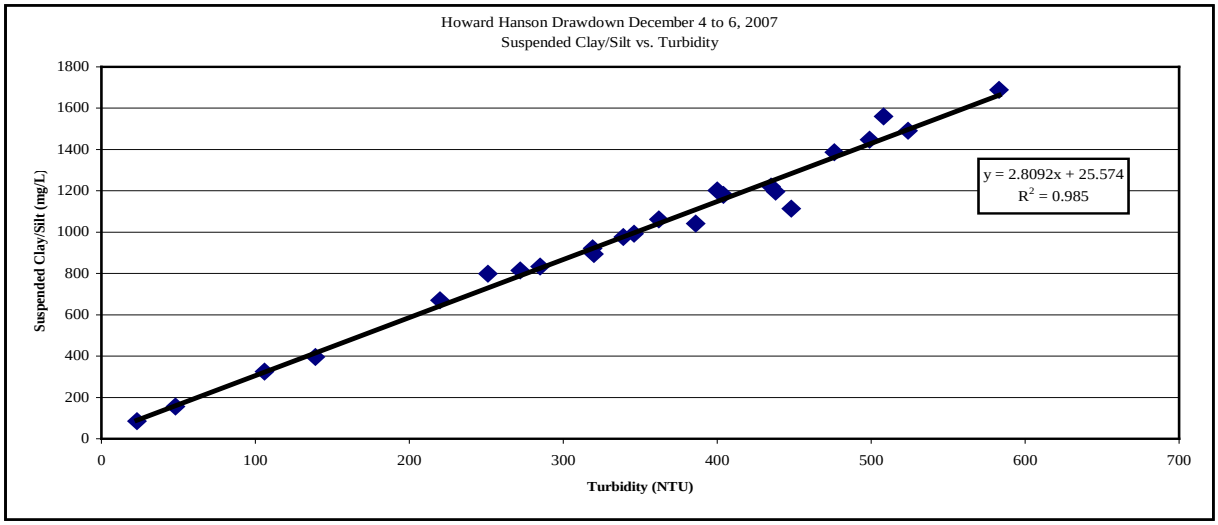


Figure 11. Particle size distribution in the 250µm to 500µm size range as measured by the LISST-100X during the drawdown.





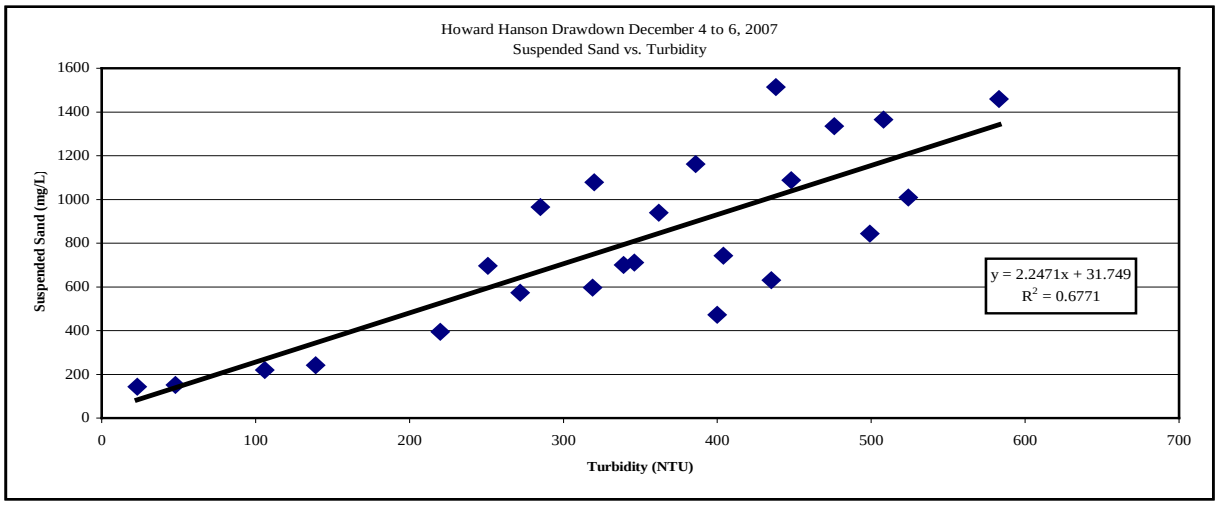


Figure 14. Relationship between suspended sediment concentrations and turbidity values measured during the drawdown.

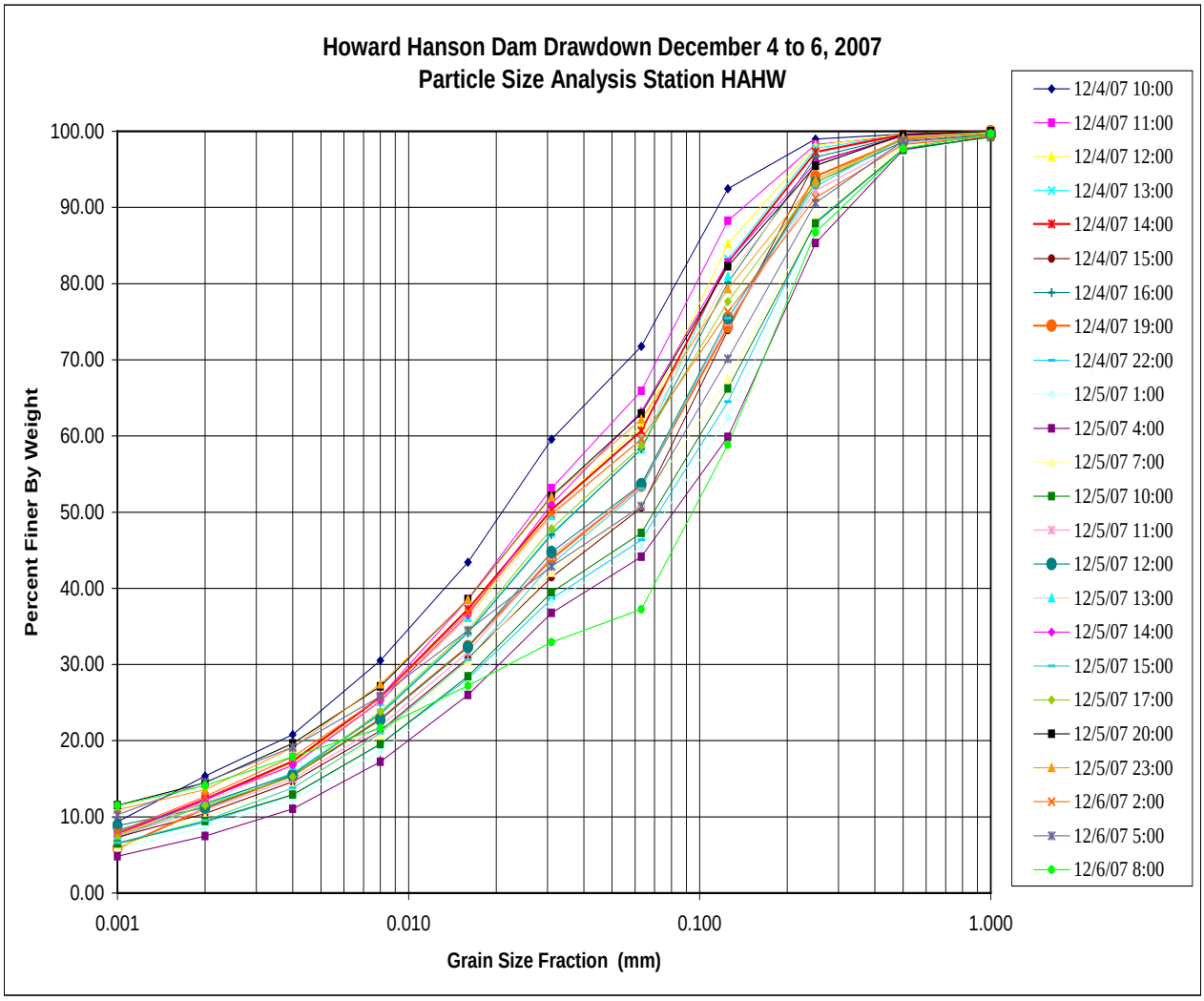
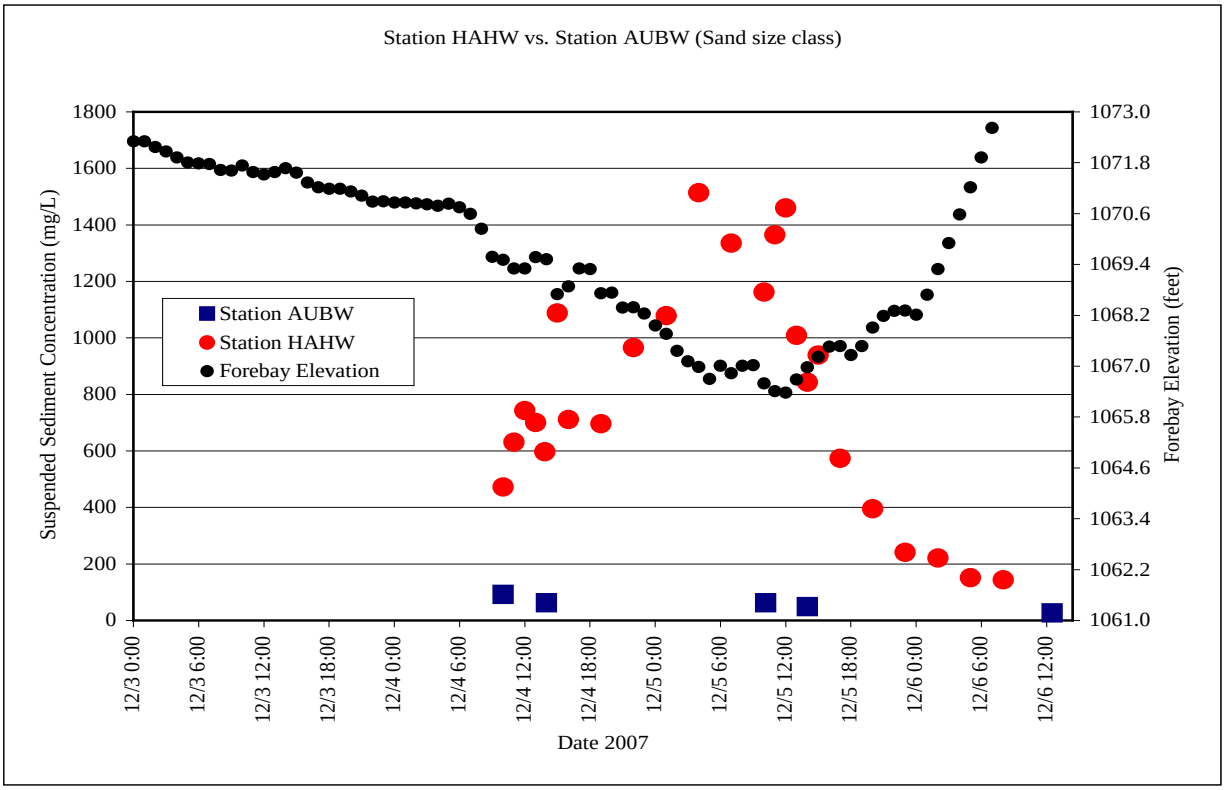


Figure 15. Frequency analysis for grain size fractions collected by the point sampler during the drawdown.



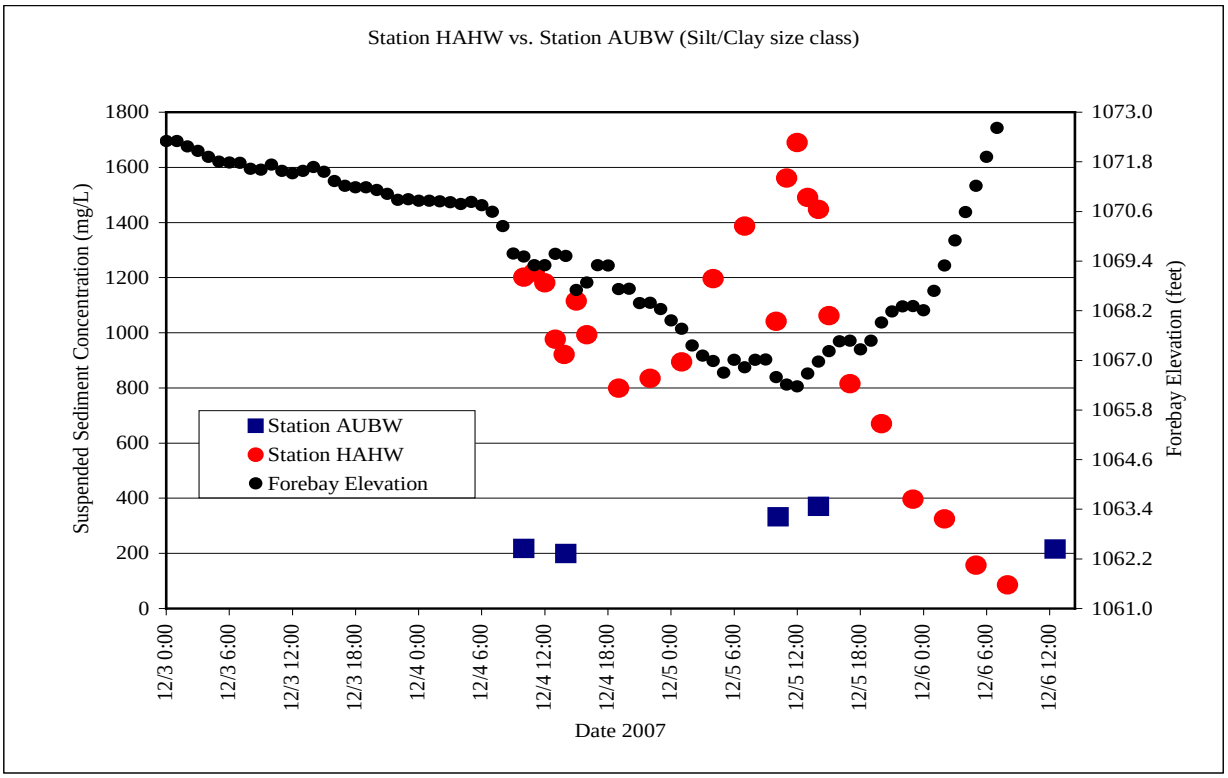
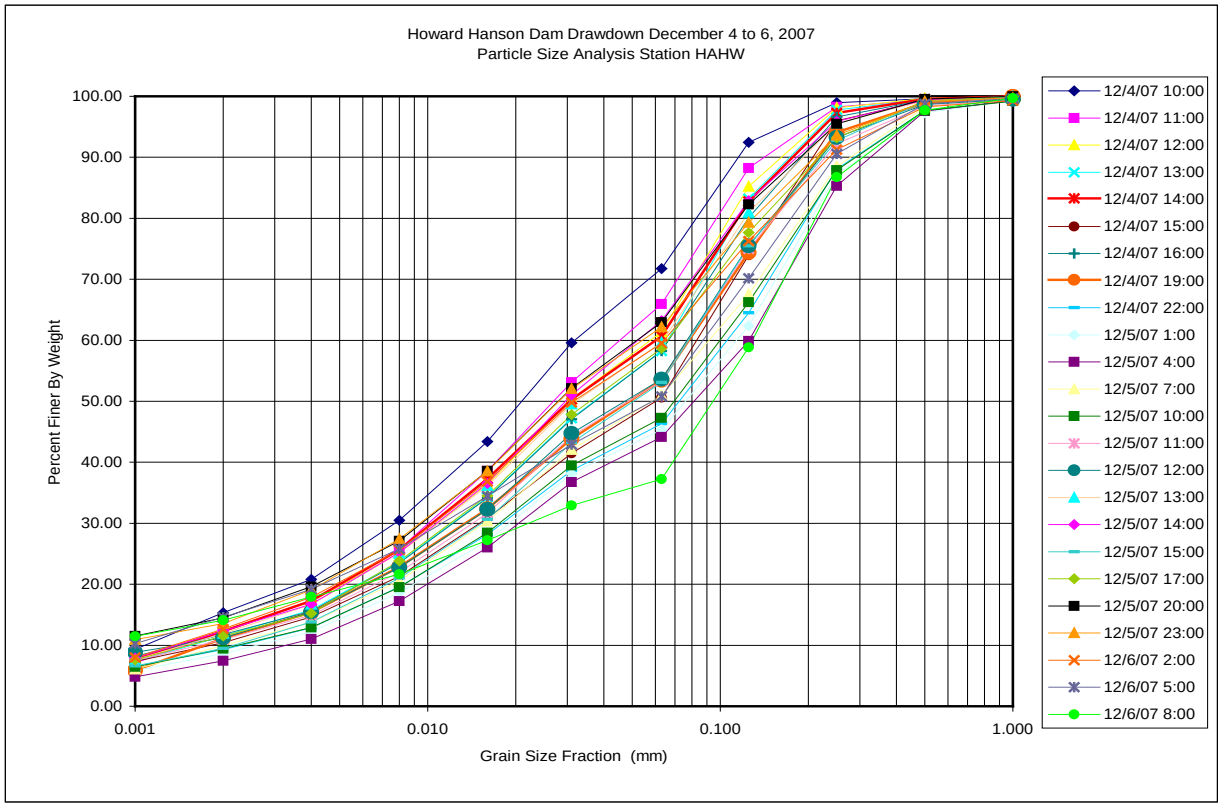


Figure 16. Suspended sediment concentrations measured at Station HAHW and Station AUBW during the drawdown.



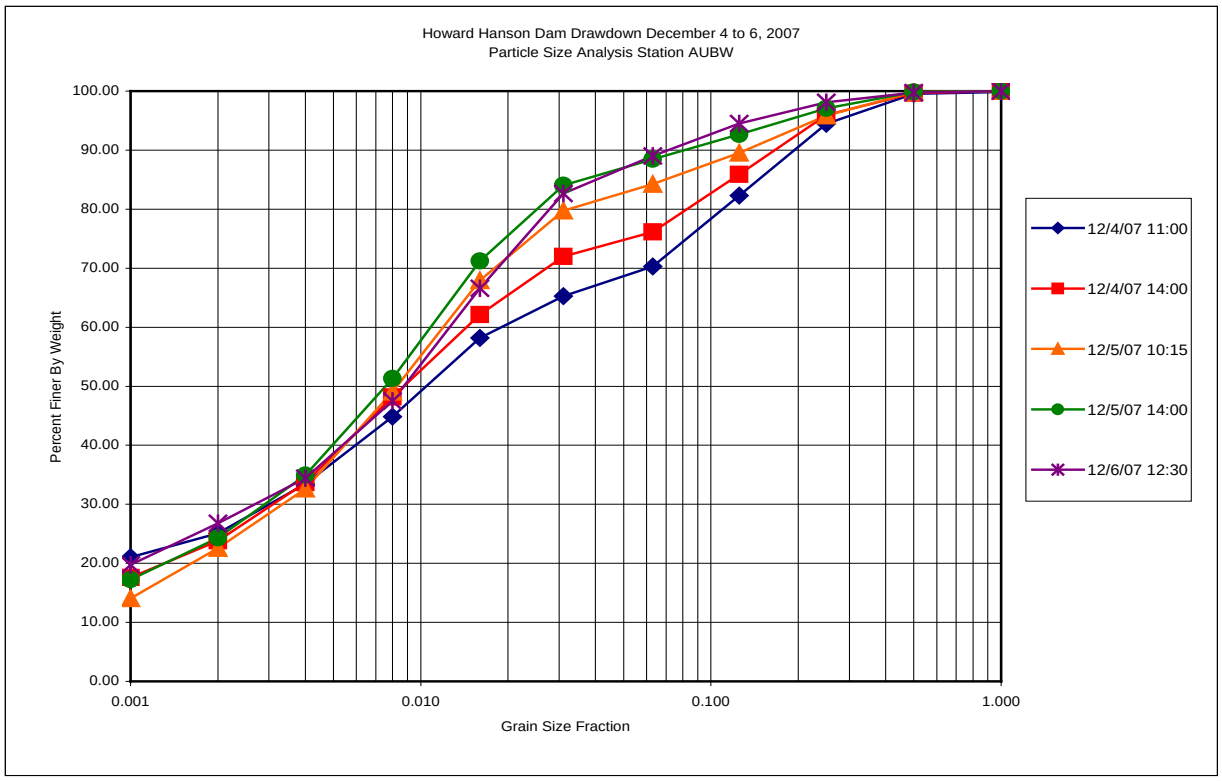


Figure 17. Frequency analysis of grain size distributions collected at Station HAHW and Station AUBW during the drawdown