**U.S. Army Corps**
**of Engineers**
Seattle District

# Sediment Transport During Reservoir Drawdown Operations: Howard Hanson Dam and the Green River, 2010

**Kent B. Easthouse**
**U.S. Army Corps of Engineers, Seattle District**
**Water Management Section**

**December 2012**

# Table of Contents


1 INTRODUCTION ..... 1
1.1 Purpose and Objective ..... 1
2 Methods and Materials ..... 2
2.1 Site Characterization ..... 2
2.2 Reservoir Drawdown Operations ..... 2
2.3 Water Quality Criteria ..... 2
2.4 Sampling Design and Data Collection Locations ..... 3
2.4.1 Water Quality Standard Conditions Monitoring ..... 3
2.4.2 Suspended Sediments Monitoring ..... 4
2.4.3 Automated Point Sample Suspended Sediment Monitoring ..... 6
2.4.4 Automated *In Situ* Suspended Sediment Monitoring ..... 6
2.5 Quality Assurance Procedures ..... 6
3 Results and Discussion ..... 8
3.1 Water Quality Standard Conditions Monitoring ..... 8
3.1.1 Turbidity Monitoring ..... 8
3.1.2 Water Quality Monitoring ..... 9
3.2 Suspended Sediment Monitoring ..... 9
3.2.1 Cableway and ISCO Pump Samplers ..... 9
3.2.2 LISST-100X Particle Size Analyzer ..... 10
3.2.3 Total Suspended Sediment ..... 11
3.2.4 Particle Size Analysis ..... 12
3.3 Downstream Sediment Analysis ..... 12
4 Conclusions ..... 13
5 References ..... 14
6 Tables ..... 15
7 Figures ..... 20

# Tables

Table 1 Washington Department of Ecology surface water quality standards for Core Summer Salmonid Habitat waters. ....16

Table 2. Monitoring station locations. ....17

Table 3. Methods and detection limits for water quality analyses. ....18

Table 4. Water quality data collected at Stations HAQW, HAHW, and GRAH during the drawdown. ....19

# Figures

Figure 1. Vicinity map of the Howard Hanson Dam reservoir drawdown water monitoring program in King County, Washington. ....21

Figure 2. Howard Hanson Dam water quality monitoring locations. ....22

Figure 3. Inflow, outflow, Auburn and forebay pool elevation measured during the drawdown. ....23

Figure 4. Howard Hanson Dam forebay elevation (top panel) and flows (bottom panel) compared to turbidity values measured during the drawdown. ....24

Figure 5. Comparison of USGS Cableway and ISCO pump sampler suspended sediment, sand and silt/clay concentrations measured during the drawdown. ....25

Figure 6. Cableway/pump sampler complete silt/clay and sand size range concentrations measured during the drawdown. ....26

Figure 7. Comparison of LISST-100X and cableway/pump sampler sand and silt/clay concentrations measured during the drawdown. ....27

Figure 8. Comparison of LISST-100X and cableway/pump sampler 2 µm and 4 µm size fraction concentrations measured during the drawdown ....28

Figure 9. Comparison of LISST-100X and cableway pump sampler 8 µm and 16 µm size fraction concentrations measured during the drawdown. ....29

Figure 10. Comparison of LISST-100X and cableway/pump sampler 31 µm size fraction concentrations measured during the drawdown. ....30

Figure 11. Particle size distribution in the 2µm to 4µm size range as measured by the LISST-100X during the drawdown. ....31

Figure 12. Particle size distribution in the 8µm to 16µm size range as measured by the LISST-100X during the drawdown. ....32

Figure 13. Particle size distribution in the 31µm size range as measured by the LISST-100X during the drawdown. ....33

Figure 14. Comparison of LISST-100X and cableway/pump sampler 63 µm and 125 µm size fraction concentrations measured during the drawdown. .....34

Figure 15. Comparison of LISST-100X and cableway/pump sampler 250 µm size fraction concentrations measured during the drawdown. .....35

Figure 16. Particle size distribution in the 63µm to 125µm size range as measured by the LISST-100X during the drawdown. .....36

Figure 17. Particle size distribution in the 250µm size range as measured by the LISST-100X during the drawdown. .....37

Figure 18. Relationship between suspended sediment concentrations and turbidity values measured during the drawdown. .....38

Figure 19. Frequency analysis for grain size fractions collected by the cableway/pump sampler during the drawdown. .....39

Figure 20. Suspended sediment concentrations measured at Station HAHW and Station AUBW during the drawdown. .....40

Figure 21. Frequency analysis of grain size distributions collected at Station HAHW and Station AUBW during the drawdown .....41

# 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) 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 2010 which outlined a series of goals to progressively reduce the amount of sediment stored behind Howard Hanson Dam (U.S. COE 2009a). 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 2009 through February 2010. The Water Year 2010 Reservoir and Sediment Management Plan (U.S. COE 2009a) described the flow and water quality conditions necessary for implementing an experimental drawdown. There was one period during WY 2010 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 2009) 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 2010 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 2009a). Hydrologic and weather conditions during the water year allowed for one drawdown to be conducted on January 6, 2010. **Figure 3** shows the inflow, outflow, and forebay elevations measured during the drawdown.

## 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. 8064) was issued by WDOE in 2009 for reservoir drawdown operations at Howard Hanson Dam and the Green River (Ecology 2009). The temporary modification allowed for the exceedance of the turbidity standard in the Green River during reservoir drawdowns conducted between November 1, 2009 and February 15, 2010. As a condition of the modification, limits were set on the allowable turbidity values measured downstream during the drawdowns as outlined below. All other water quality standards (**see Table 1**) must be met during a drawdown.

- 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.

## 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. 8064) 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 location of each station is shown in **Table 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 3**.

### 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. 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 5 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 *in-situ* using a Hydrolab MiniSonde 5 water quality probe, a Sutron 9210 XLite 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.

An *in-situ* automated turbidity probe can be difficult to maintain, calibrate and keep clean at high turbidity levels due to fouling on the lens, and can often transmit erroneously high turbidity readings. During the 2007 drawdown study, analysis of all turbidity data collected at Station HAHW (manual grabs, ISCO pump sampler, automated probe) concluded that the automated probe accurately represented the general trend in turbidity but that the turbidity concentrations were too high when compared to the other data sources (USCOE 2009b). For this study, the automated turbidity probe at Station HAHW was not used as the official turbidity station to comply with drawdown water quality standards outlined by Ecology. Instead, hourly manual grab samples collected downstream of the dam at Station HAHW during the drawdown were used to meet the turbidity requirements set forth in the Temporary Short Term Modification of Water Quality Standards (Order No. 8064).

### 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 stations HAHW and 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. 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

Suspended sediment and turbidity samples were collected with a Depth-Integrating Hand Line Type Model US DH-76 sampler from the USGS cableway at station HAHW at hourly intervals during daylight hours (approximately 8AM to 4PM) by two field technicians using the isokinetic, equal-discharge-increment (EDI) method (Edwards and Glysson 1999). In addition, depth integrated sediment and turbidity sampling was conducted from a road bridge crossing at station AUBW about every four hours during daylight using the EDI method. 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 at station HAHW and AUBW according to the following procedures:

- Determine the location of the centroid of flow within each flow increment and mark this location on the cableway and 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 1030 hours to 1730 hours during the day and then collected samples every 2 hours during the night from 1830 hours to 0830 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 2.07 to 350 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 2010: Water Quality Sampling and Analysis (U.S. COE 2009c). 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 and the Green River at Auburn before, during, and after the January 6, 2010 drawdown are presented in **Figure 3**. Turbidity values measured during the drawdown versus forebay elevation and inflow are shown in **Figure 4**.

Multiple sampling methods were used at Station HAHW to measure turbidity during the January 6$^{th}$ drawdown operations including automated samples, ISCO pump samples, and manual grab samples. The data show that the automated turbidity sampler at Station HAHW was consistently higher than hourly manual grab samples collected at the same location, and exceeded the 600 NTU limit set by Ecology on January 6$^{th}$ at 1230 hours (**Figure 4**). Because the manual grab samples were used to comply with Ecology turbidity criteria, the drawdown continued since manual grab sample data did not exceed 500 NTU during the drawdown. However, when the automated turbidity sampler data were compared to point sample turbidity measurements using the ISCO pump sampler, and to the Tacoma Public Utilities (TPU) automated turbidity sampler located about 3.5 miles downstream it became apparent that the manual grab sample values were too low. The drawdown was ceased on January 6$^{th}$ at 2300 hours after it was determined that the 600 NTU limit was likely exceeded at 1230 hours based on turbidity data measured by both the automated sampler and the ISCO pump sampler.

The similar pattern between the HAHW automated sampler, the ISCO pump samples, and the TPU automated sampler suggest that the manual grab samples were not accurately representing turbidity concentrations in the Green River at Station HAHW. It is possible that the manual grab samples were being collected to near to shore or in a back eddy which resulted in inaccurate turbidity concentrations. Consequently, manual grab sample turbidity concentrations were not used in this report to characterize the fate and transport of turbidity and suspended sediments during reservoir drawdown operations.

The automated turbidity sampler at inflow Station HAQW operated only for a short period of time during the study before being fouled by debris resulting in erroneously high turbidity values. During the short operational time, turbidities at Station HAQW changed little during the drawdown event and stayed below about 20 NTU during the entire event, while outflow turbidity values measured at Station HAHW increased dramatically from about 80-100 NTU to over 900 NTU as the pool was drawn down from about 1073 feet to 1071 feet (**Figure 4**). Turbidity values decreased (from about 900 NTU to 640 NTU) when the pool was drawn down from about 1071 feet to 1070 feet, but increased (from about 640 NTU to 730 NTU) when the pool was drawn down further from about 1070 feet to 1069.5 feet. Turbidity values rapidly decreased (from about 730 NTU to 200 NTU) when the reservoir drawdown was halted at 2300 hours on January 6$^{th}$, and the pool was raised to about 1070.5 feet and stabilized through 0700 hours on January 7$^{th}$. Turbidity values continued to drop on January 7$^{th}$ as the pool was raised from elevation 1070.5 feet to greater than 1073 feet. Turbidity values at Station HAHW were similar to pre-drawdown background concentrations at Station HAQW at 1100 hours on January 8$^{th}$.

### 3.1.2 Water Quality Monitoring

Water quality grab 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 are presented in **Table 4**. 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 ISCO pump sample data presented above in Section 3.1.1 and reflect the transport of sediments downstream in the Green River when the forebay pool was lowered below about 1073 feet.

## 3.2 Suspended Sediment Monitoring

### 3.2.1 Cableway and ISCO Pump Samplers

Suspended sediment samples were collected with a Depth-Integrating Hand Line Type Model US DH-76 sampler from the USGS cableway at station HAHW at hourly intervals during daylight hours. In addition, automated point sample suspended sediment monitoring was conducted at station HAHW at hourly intervals during daylight hours and every 2 hours during the night using an ISCO-6712 automatic pump sampler. Comparisons of suspended sediment data collected via the cableway and pump sampler methods during daylight hours are presented in **Figure 5**. These data show a good correlation for total suspended sediment, sand, and silt/clay concentrations between the cableway and pump sampler methods. The strong correlation between the two methods allowed the pump sampler to be used during nighttime hours to represent suspended sediment fractions in the Green River during the drawdown.

Cableway/pump sampler suspended sediment data for silt/clay and sand size ranges are presented in **Figure 6**. These data show an initial rapid rise in silt/clay concentrations from 168 mg/L at a forebay elevation of about 1073 feet to over 2100 mg/L at a forebay elevation of about 1071 feet. Silt/clay concentrations decreased (from over 2100 mg/L to 1425 mg/L) when the pool was drawn down from about 1071 feet to 1070 feet, with concentrations slightly increasing when the pool was drawn down further from about 1070 feet to 1069.5 feet. Concentrations of silt/clay rapidly decreased (from about 1450 mg/L to 330 mg/L) when the reservoir drawdown was halted at 2300 hours on January 6$^{th}$, and the pool was raised from 1069.5 feet to about 1070.5 feet and held at that elevation through 0700 hours on January 7$^{th}$. Silt/clay concentrations decreased to background levels as the reservoir pool rose above 1073 feet on January 7$^{th}$.

The rapid increase in silt/clay concentrations measured between 1073 feet and 1071 feet was not accompanied by a similar increase in sand concentrations (**Figure 6**). Sand concentrations were low throughout the entire drawdown (range from 1 mg/L to 175 mg/L) and displayed the greatest increase when the forebay elevation was drawdown below about 1070.5 feet. Peak sand concentrations were measured at a forebay elevation of 1069.5 feet. Concentrations of sand decreased (from 175 mg/L to 28 mg/L) when the reservoir drawdown was halted at 2300 hours on January 6$^{th}$, and the pool was raised from 1069.5 feet to about 1070.5 feet and held at that elevation through 0700 hours on January 7$^{th}$. Sand concentrations continued to decrease to background levels as the reservoir pool rose above 1073 feet on January 7$^{th}$.

### 3.2.2 LISST-100X Particle Size Analyzer

The LISST-100X is a laser-diffraction sensor designed to measure particle size distribution and volume concentration over a size range of 2.07 to 350 microns. However, cableway/pump sampler data were analyzed over the complete silt/clay and sand range of less than 1 µm to 2000 µm. Therefore, when comparing LISST-100X silt/clay concentrations to cableway/pump sampler silt/clay concentrations, only cableway/pump sampler data within the 2.07 µm to 350 µm range were used for comparisons.

The LISST-100X measurements of the silt/clay fraction compared well with the cableway/pump sampler data, while the sand fraction comparisons were more variable (**Figure 7**). The LISST accurately tracked the cableway/pump sampler silt/clay concentrations including the rapid increase in silt/clay when the forebay pool dropped below about 1073 feet, the steady decrease in silt/clay as forebay elevations were drawn down from about 1071 feet to 1070 feet, and the rapid decrease when the reservoir drawdown was halted at 2300 hours on January 6$^{th}$, and the pool was raised from 1069.5 feet to about 1070.5 feet (**Figure 7**). Moreover, on January 6$^{th}$ between 2000 and 2200 hours when the pool was dropped below 1070 and then quickly raised back above 1070, the LISST-100X accurately tracked the increases and decreases in the silt/clay fraction as the pool fluctuated above and below 1070 feet.

The LISST-100X sand fractions were more variable when compared to the point sampler sand fractions (**Figure 7**). The LISST-100X accurately tracked the slight increase in sand fractions when the forebay pool dropped below 1073 feet. However, in contrast to the cableway/pump sampler data, the LISST-100X measured little change in sand concentrations when the forebay pool was lowered to 1069.5 feet. During the maximum drawdown elevation of 1069.5 feet, the LISST-100X appeared to underestimate the concentration of sand. When the drawdown was halted and the pool raised to 1070.5 feet, the LISST was more accurate at tracking the decrease in sand concentrations.

#### 3.2.2.1 Silt/Clay Fractions

Time series analysis of particle sizes corresponding to silt/clay fractions are shown in **Figures 8 through 10** for both the LISST-100X and cableway/pump sampler. For each silt/clay size fraction, the LISST data correlates well with the cableway/pump sampler data. In the silt/clay size fraction, particle sizes in the 4 µm to 16 µm range had the highest concentrations, with lower concentrations for the smallest (2 µm) and largest (31 µm) particle sizes. Silt/clay fractions in the 2 µm to 31 µm size ranges showed similar responses to the drawdown of the forebay pool, with a rapid increase as the pool was dropped down from about 1073 feet to 1071 feet, a decrease as the pool was dropped from 1071 feet to about 1070 feet, and a slight increase when the pool was lowered from about 1070 feet to 1069.5 feet. All silt/clay particles decreased when the forebay pool elevation was raised from 1069.5 feet to 1070.5 feet and continued to decrease when the pool was stabilized at 1070.5 feet.

Particle size distributions and concentrations over the silt/clay size range measured by the LISST-100X are presented in **Figures 11 through 13**. The LISST-100X data show that the majority of silt/clay particles fell within the 4.01 µm to 29.2 µm size range. All silt/clay fractions (2.07 µm to 56.7 µm) followed a similar pattern during the drawdown experiment with

a decrease as the pool was slowly drawn down from 1071 to 1070 feet, a slight increase when the pool was lowered below 1070 feet, and a decrease when the pool was raised above 1070 feet. Particle size distribution ratios were consistent during all phases of the drawdown with the majority of silt/clay concentrations in the 4.01 µm to 29.2 µm size range throughout the experiment.

#### 3.2.2.2 Sand Fractions

Time series analysis of particle sizes corresponding to sand fractions are shown in **Figures 14 and 15** for both the LISST-100X and cableway/pump sampler. For the 63 µm grain size, the LISST did not correlate well with the cableway/pump sampler, with better correlations for the 125 µm and 250 µm grain size fractions. Sand size fractions were dominated by finer particles (i.e. 63 µm) with very little sand measured in the 125 µm and 250 µm size range. Sand concentrations in the 63 µm size range increased slightly as the pool was dropped down from about 1073 feet to 1071 feet. When the pool was lowered below 1070 feet, the LISST measured little change in the 63 µm size particles while the cableway/pump sampler measured a modest increase. Sand in the 250 µm and 500 µm size ranges maintained very low concentrations throughout the entire drawdown.

Particle size distributions and concentrations over the sand size range measured by the LISST-100X are presented in **Figures 16 and 17**. The LISST data show that the majority of sand particles fell within the 66.9 µm to 110 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. The finer sand fractions (63.1 µm to 130 µm) showed a modest increase in concentration as the forebay pool was drawn down from 1073 feet to 1071 feet. These finer sand fractions were relatively stable as the pool was lowered from 1071 feet to 1070 feet with a slight increase as the pool was brought down to 1069.5 feet. Fine sand fractions decreased when the pool was raised from 1069.5 feet to 1070.5 feet. The coarser sand fractions (153 µm to 350 µm) showed little to no increase at any forebay elevation during the drawdown.

### 3.2.3 Total Suspended Sediment

Total suspended sediment concentrations during the drawdown were calculated from cableway/pump samples collected at Station HAHW. Turbidity values were measured from these samples to estimate the relationship between turbidity and suspended sediments during drawdown operations at Howard Hanson Dam (**Figure 18**). The relationship between total suspended sediment concentrations and turbidity values measured during the drawdown was good ($r^2$=0.9571), with an excellent relationship between the clay/silt fractions and turbidity ($r^2$=0.9707) but a poor relationship between the sand fractions and turbidity ($r^2$=0.2759).

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. Although the 2010 drawdown relationships between turbidity and suspended sediments were good, they were substantially different than the relationships measured during the 2007 drawdown (U.S. COE 2009b). The difference in the turbidity vs. suspended sediments

relationships between the 2007 and 2010 drawdown suggest that a universal relationship between these two parameters during drawdown operations is likely not possible. Therefore, it is recommended that suspended sediments and particle size analysis continue to be measured for future drawdown operations.

### 3.2.4 Particle Size Analysis

Frequency analysis for the grain size fractions collected by the cableway/pump sampler during the drawdown is presented in **Figure 19**. In general, samples collected when forebay pool elevations were highest had the greatest percentage of finer particles. As the forebay was drawn down from 1072.86 feet to 1069.56 feet the size class of the particles increased.

## 3.3 Downstream Sediment Analysis

Limited suspended sediment monitoring was conducted about 32 miles downstream of Howard Hanson Dam near the city of Auburn (Station AUBW). Five suspended sediment samples were collected before, during, and after the drawdown. This station provided valuable information on the fate and transport of suspended sediments downstream in the Green River during the drawdown event. Silt/clay concentrations measured at AUBW were considerably lower than at HAHW while sand concentrations were more similar (**Figure 20**). Time series plots show that silt/clay concentrations increased at AUBW from about 100 mg/L before the drawdown to over 800 mg/L about 16 to 24 hours after the peak silt/clay concentrations were measured at HAHW. A similar increase in sand fractions was not measured at AUBW with sand concentrations remaining relatively stable during the drawdown period. These data indicate that the increase in silt/clay concentrations generated by the drawdown was detected 32 miles downstream at AUBW. The shift in particle size with time is clearly shown in the frequency analysis for grain sizes measured at AUBW (**Figure 21**). Pre-drawdown background suspended sediment concentrations at AUBW were about 30 percent sand and 70 percent silt/clay, while samples collected from 24 to 30 hours after the drawdown began were comprised of about 10 percent sand and 90 percent silt/clay.

# 4 CONCLUSIONS

Results from the 2010 drawdown experiment at Howard Hanson Dam indicate that substantial increases in sediment concentrations in the Green River were associated with drawing down the reservoir below the 1073 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 lowered from 1073 feet to 1071 feet. These suspended sediment increases were dominated by the silt/clay fraction with very little amounts of fine sand fractions. When the pool was lowered from 1070 feet to 1069.5 feet a second increase in suspended sediments was measured. This second increase was dominated by silt/clay fractions with a small increase in sand fractions in the 63 µm size range. When the pool was increased back above the 1073 foot elevation, suspended sediment concentrations in the Green River quickly decreased to near background levels.

Particle size analysis indicate that the sediments transported down the river during the 2010 drawdown were dominated by silt/clay in the 4.01 µm to 29.2 µm size range. Minor amounts of fine grained sands (66.9 µm to 130 µm) were transported down river. The majority of silt/clay particles were transported downstream during the initial drawdown of the forebay pool from 1073 to 1071 feet. As the forebay was drawn down from 1071 to 1070 feet, the concentration of silt/clay particles mobilized during the drawdown declined. The minor increase in sand concentrations measured during the drawdown suggests that limited amounts of sand moved down the river during periods when the forebay pool was greater than 1070 feet. An increase in sand transport downriver was measured when the forebay was lowered from 1070 feet to 1069.5 feet. The limited data suggest that the lower the forebay pool, the greater the concentration of sand transported down river.

Monitoring 32 miles downstream of the dam at Station AUBW showed an increase in suspended sediment concentrations and a change in particle sizes as a result of the reservoir drawdown. Increases in the silt/clay particle sizes were measured as a result of the drawdown while little to no change in sand particle sizes were measured. 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 weakly related to the turbidity values. However, the difference in the turbidity vs. suspended sediments relationships between the 2007 and 2010 drawdown events suggest that a universal relationship between these two parameters during drawdown operations is not possible.

# 5 REFERENCES

APHA, AWWA, WEF. 1992. Standard methods for the examination of water and wastewater. 18th edition. Edited by A.E. Greenberg, American Public Health Association; A.D. Eaton, American Water Works Association; and L.S. Clesceri, Water Environment Federation.

Ecology. 2009. Administrative Order Number 8064 for the Temporary Short-term Modification of Water Quality Standards, Howard Hanson Dam. Northwest Regional Office, Bellevue, Washington.

Edwards, T.K. and G.D. Glysson. 1999. Field methods for measurements of fluvial sediments. United States Geological Survey Techniques of Water Resources Investigations, Book 3, Chapter C2.

Pottsmith, C. 2007. Personal communication (Phone conversation with Kent Easthouse, US Army Corps of Engineers, Seattle District). Sequoia Scientific, Redmond, WA.

U.S. COE. 2001. Howard A. Hanson Dam water control manual. U.S. Army Corps of Engineers, Seattle District, April 2001.

U.S. COE. 2009a. Howard Hanson Dam Reservoir Operations and Sediment Management Plan Water Year 2010. Seattle District.

U.S. COE. 2009b. Howard Hanson Dam water quality monitoring data review and quality assurance end of year report for water year 2008. Seattle District

U.S. COE. 2009c. Howard Hanson Dam Reservoir Operations and Sediment Management Plan for Water Year 2010: Water Quality Sampling and Analysis. Seattle District.

U.S. EPA. 1983. Methods for chemical analysis of water and wastes. EPA-600/4-79-020. U.S. Environmental Protection Agency, Environmental Monitoring and Support Laboratory, Cincinnati, Ohio.

U.S. EPA. 1984. Guidelines Establishing Test Procedures for the Analysis of Pollutants under the Clean Water Act; Final Rule and Interim Final Rule. U.S. Environmental Protection Agency. CFR Part 136. Friday, October 26, 1984.

USGS. 1999. National field manual for the collection of water quality data: Chapter A4 Collection of water samples. Edited by Wilde, F.D., Radtke, D.B., Gibs, Jacob, and Iwatsubo, R.T. United States Geological Survey Techniques of Water Resources Investigations, Book 9, Chapter A4.

# 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. 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 3. 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 4. Water quality data collected at Stations HAQW, HAHW, and GRAH during the drawdown.**

| Location | Date | Time | Temp (°C) | Dissolved Oxygen (mg/L) | pH | Conductivity (µS/cm) | Turbidity (NTU) | Total Suspended Sediment (mg/L) |
|---|---|---|---|---|---|---|---|---|
| HAHW-2-1 | 1/6/2010 | 1000 | 4.02 | 13.16 | 6.48 | 33 | 169 | 294 |
| HAHW-2-2 | 1/6/2010 | 1600 | 4 | 13.37 | 6.42 | 37.3 | 684 | 1492 |
| HAHW-2-3 | 1/7/2010 | 930 | 2.46 | 12.75 | 6.38 | 38.2 | 126 | 301 |
| HAHW-2-4 | 1/7/2010 | 1430 | 2.68 | 13.71 | 6.41 | 33.6 | 39.1 | 100 |
| HAQW-2-1 | 1/6/2010 | 1045 | 3.6 | 12.71 | 6.54 | 30.1 | 2.83 | 6 |
| HAQW-2-2 | 1/6/2010 | 1530 | 3.41 | 12.45 | 6.61 | 30.3 | 2.11 | 5 |
| HAQW-2-3 | 1/7/2010 | 1230 | 2.45 | 12.65 | 6.66 | 31.6 | 1.65 | 2 |
| GRAH-2-1 | 1/6/2010 | 1130 | 4.23 | 13.21 | 6.52 | 33 | 121 | 194 |
| GRAH-2-2 | 1/6/2010 | 1720 | 4.01 | 13.12 | 6.46 | 34.1 | 471 | 944 |
| GRAH-2-3 | 1/7/2010 | 1030 | 2.36 | 13.64 | 6.46 | 33.6 | 136 | 341 |
| GRAH-2-4 | 1/7/2010 | 1500 | 2.72 | 13.68 | 6.45 | 32.3 | 43.5 | 113 |

# 7 FIGURES

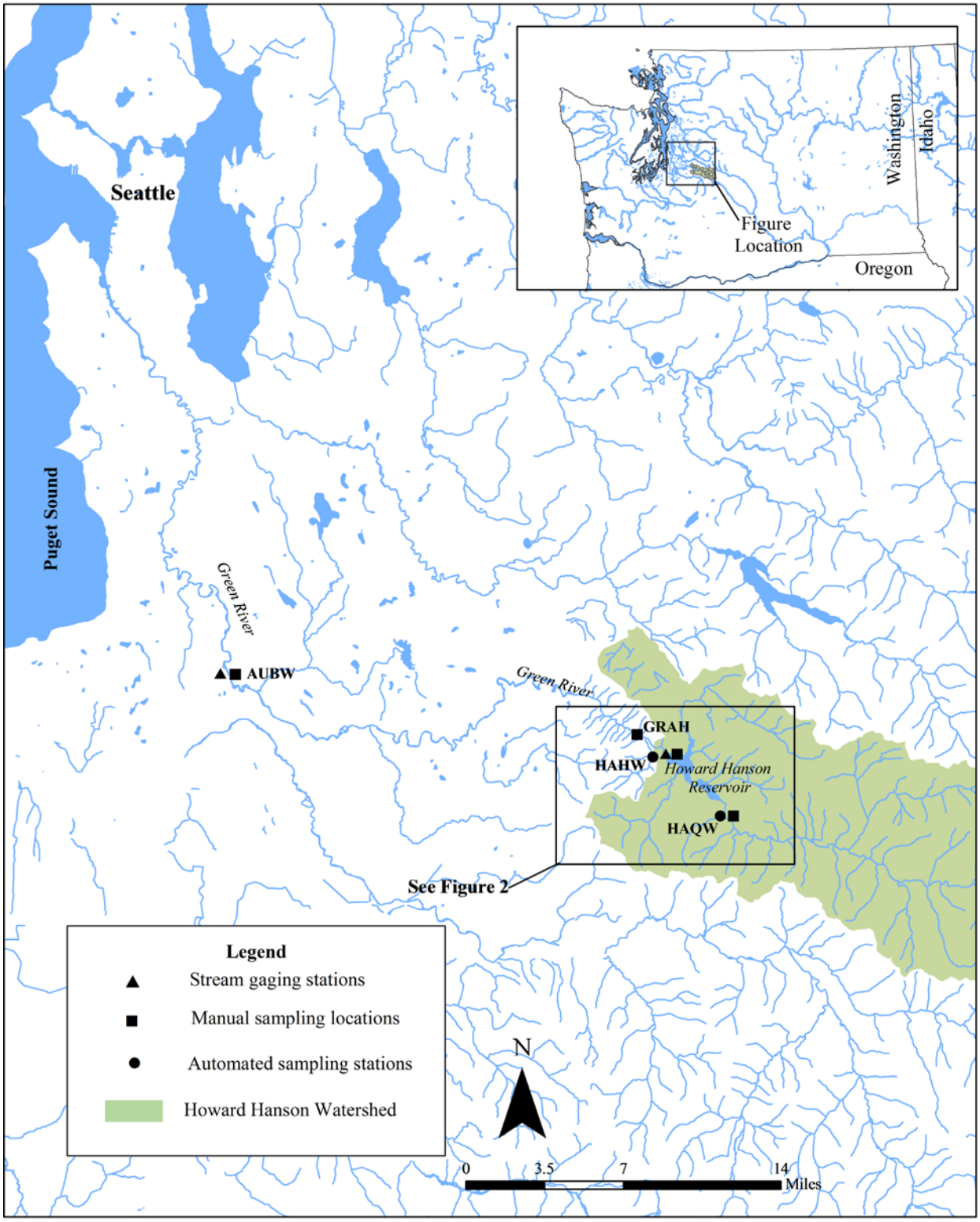



**Figure 1. Vicinity map of the Howard Hanson Dam reservoir drawdown water monitoring program in King County, Washington.**

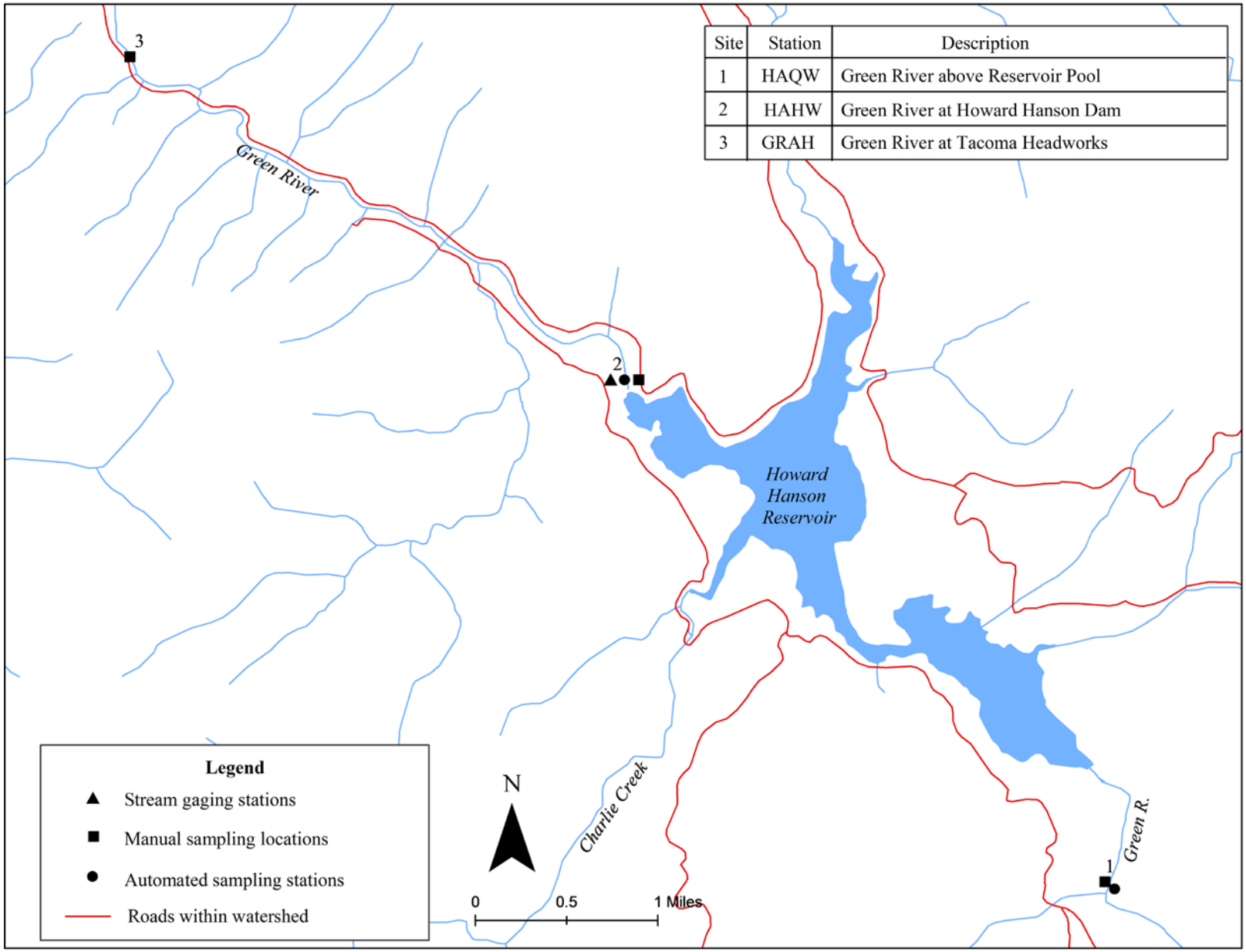



**Figure 2. Howard Hanson Dam water quality monitoring locations.**

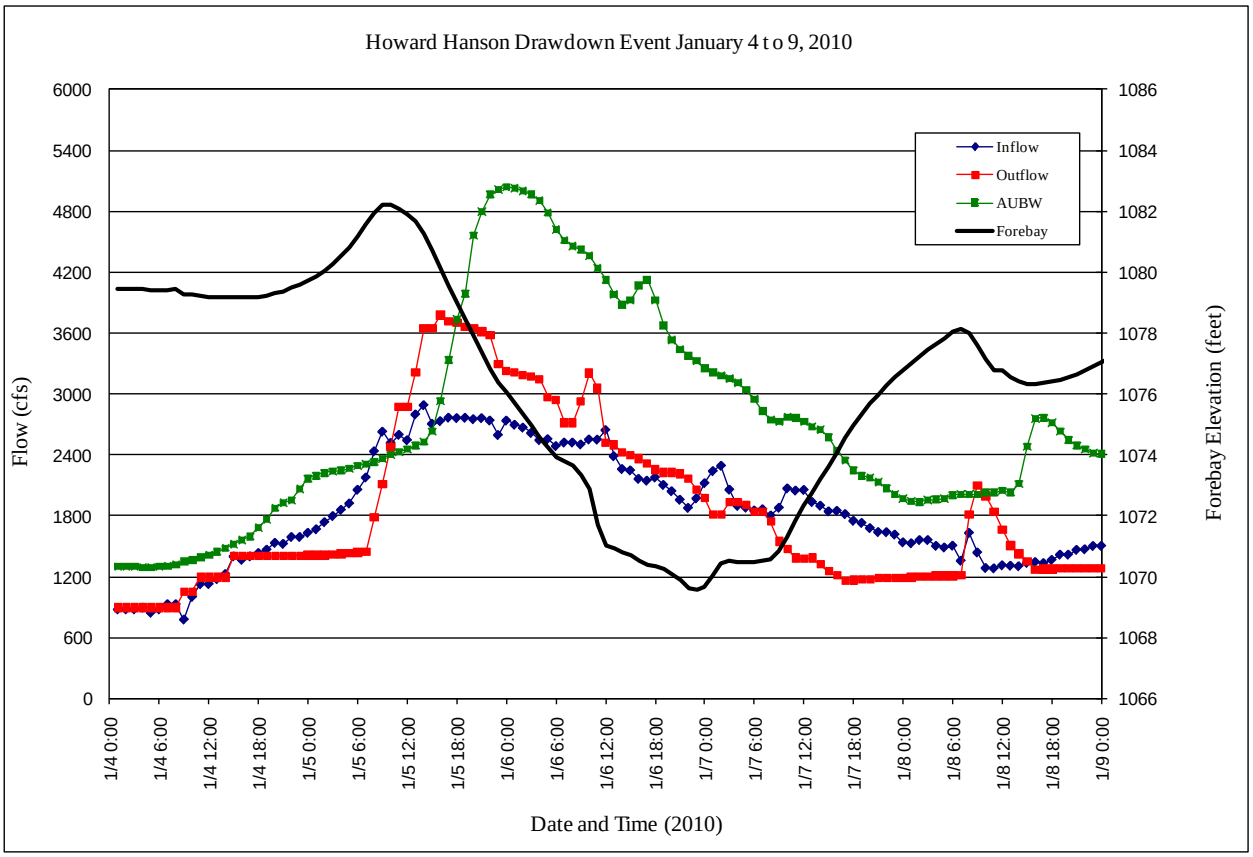



**Figure 3. Inflow, outflow, Auburn and forebay pool elevation measured during the drawdown.**

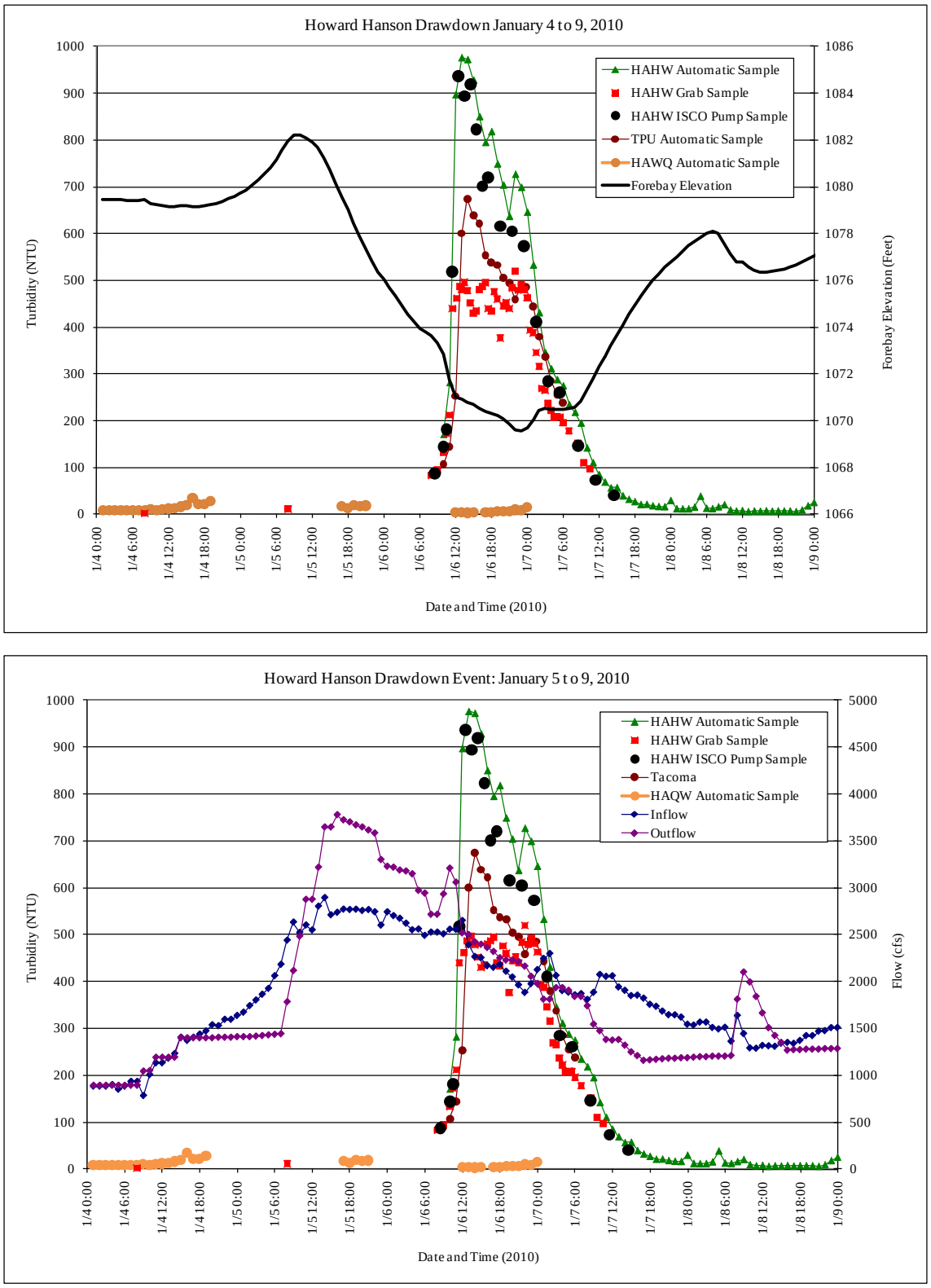



**Figure 4. Howard Hanson Dam forebay elevation (top panel) and flows (bottom panel) compared to turbidity values measured during the drawdown.**

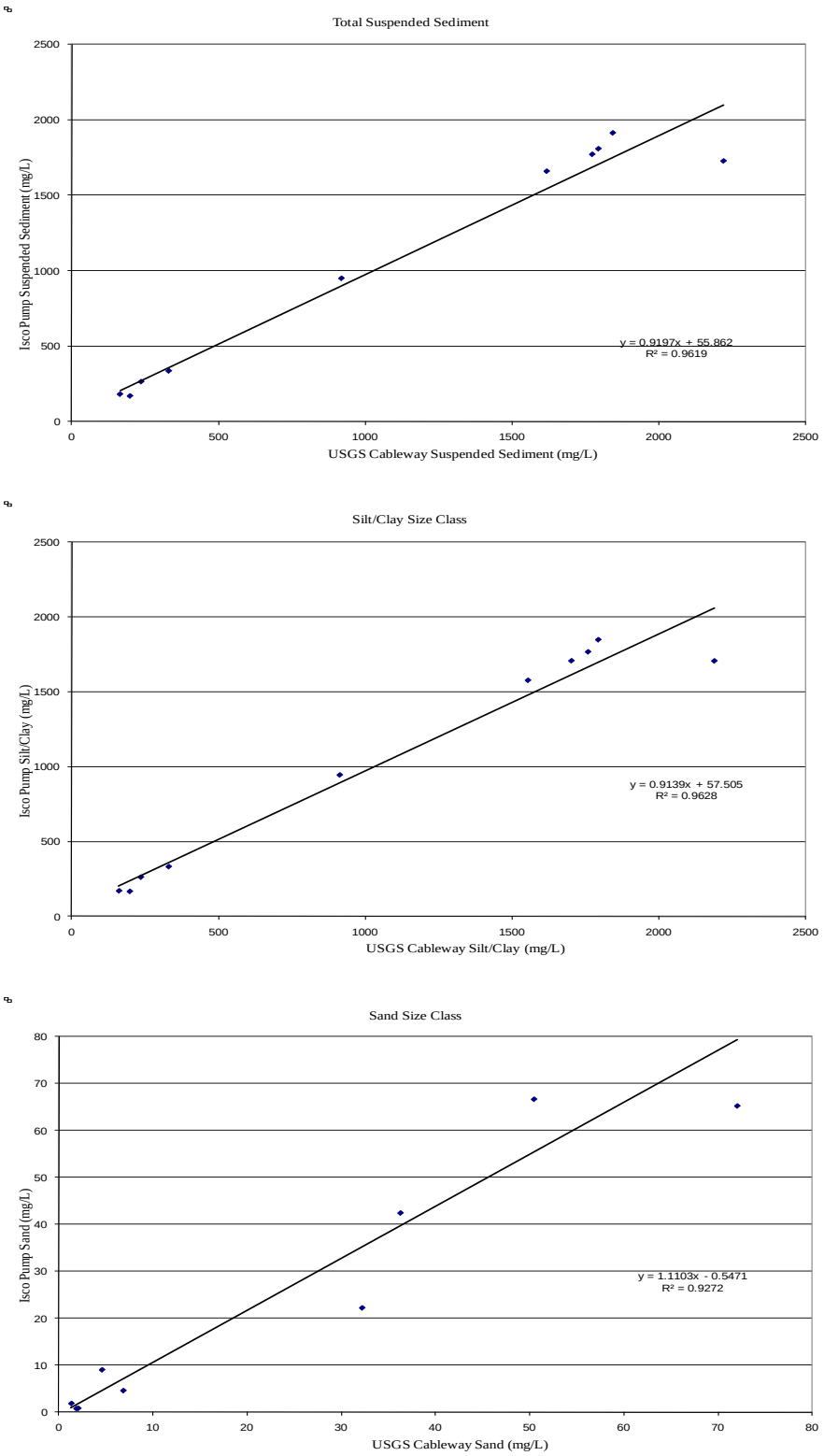



**Figure 5. Comparison of USGS Cableway and ISCO pump sampler suspended sediment, sand and silt/clay concentrations measured during the drawdown.**

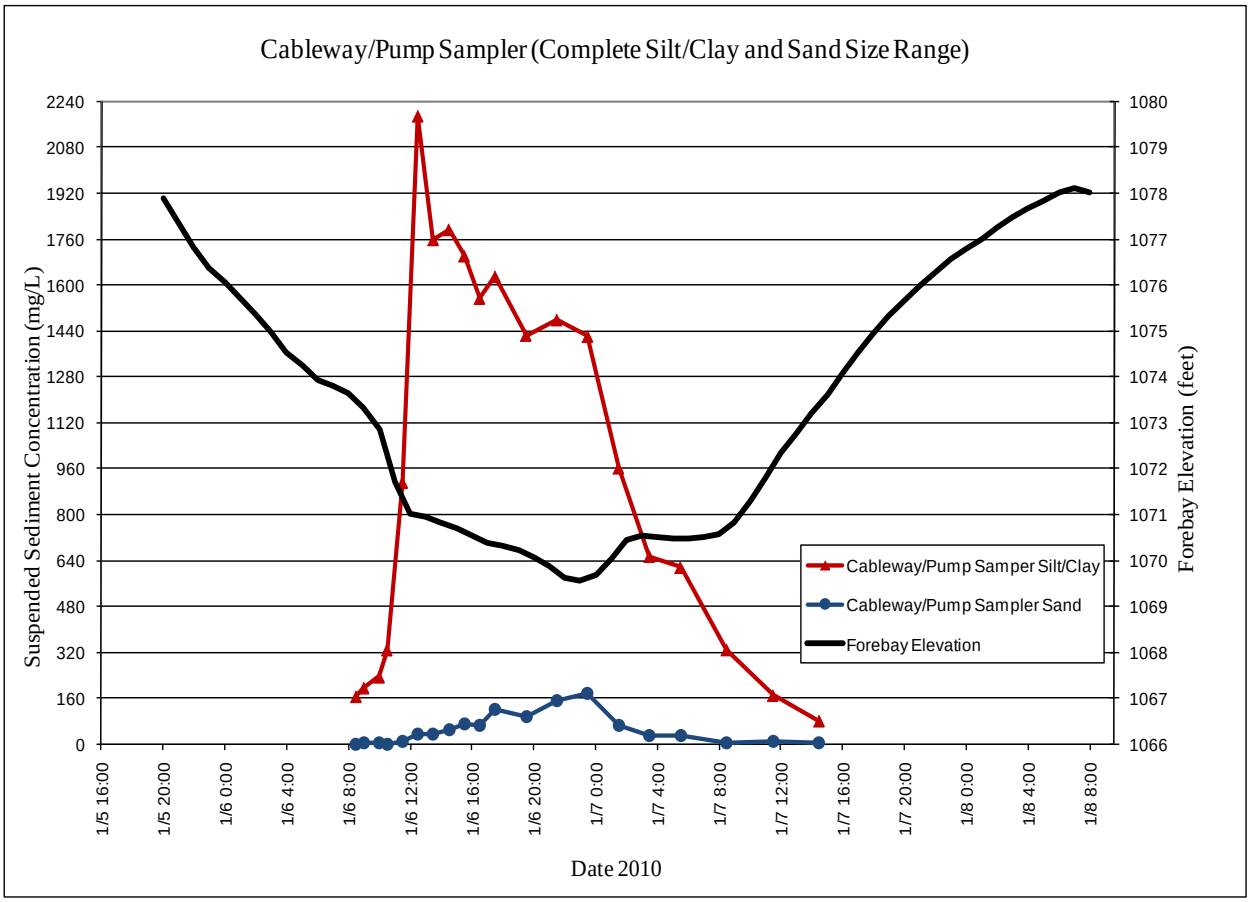
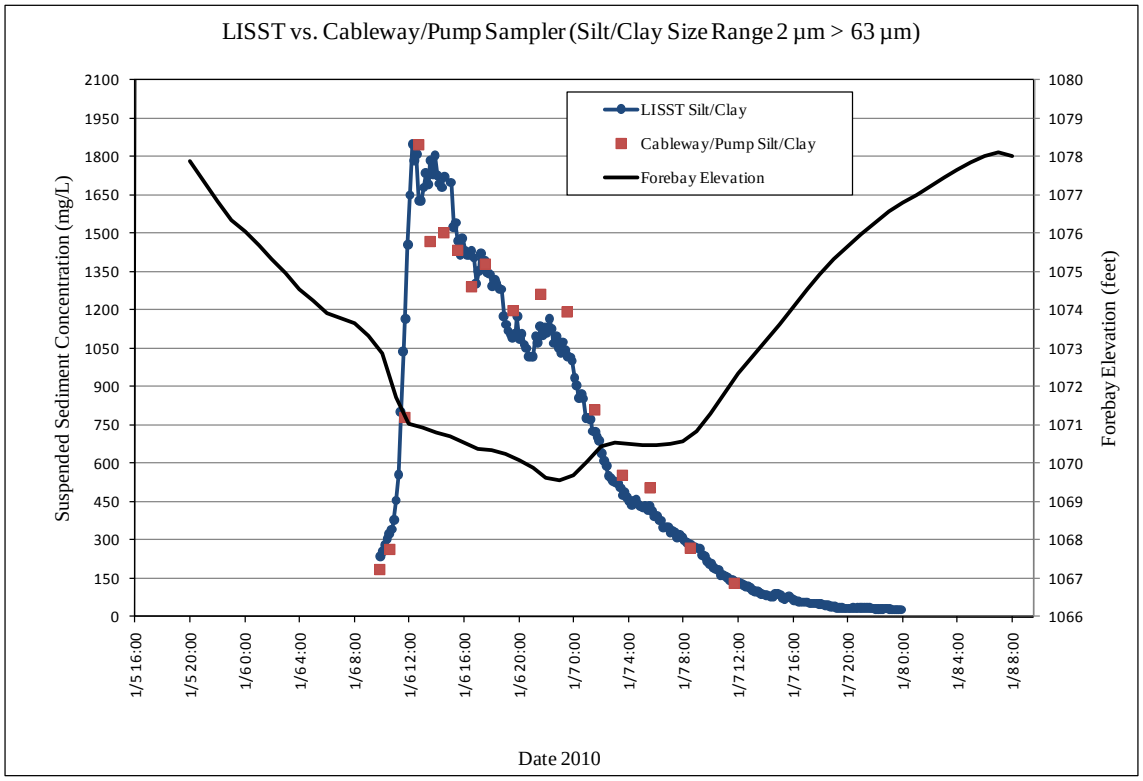



**Figure 6. Cableway/pump sampler complete silt/clay and sand size range concentrations measured during the drawdown.**



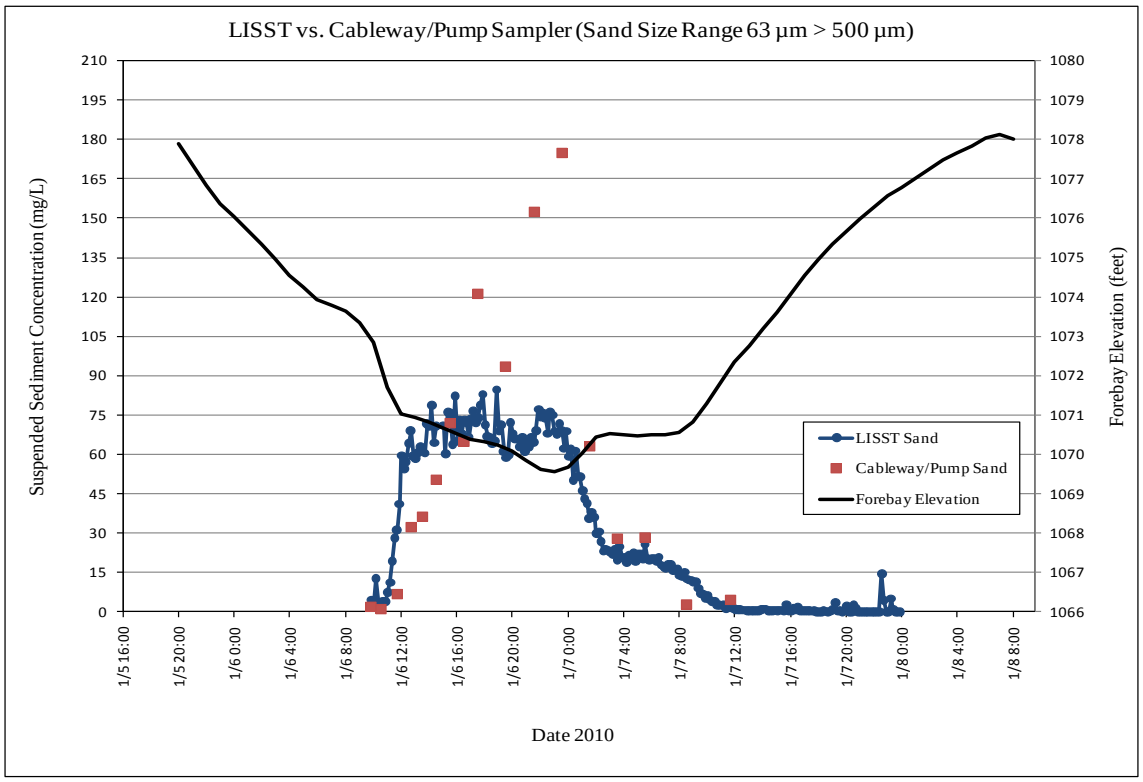
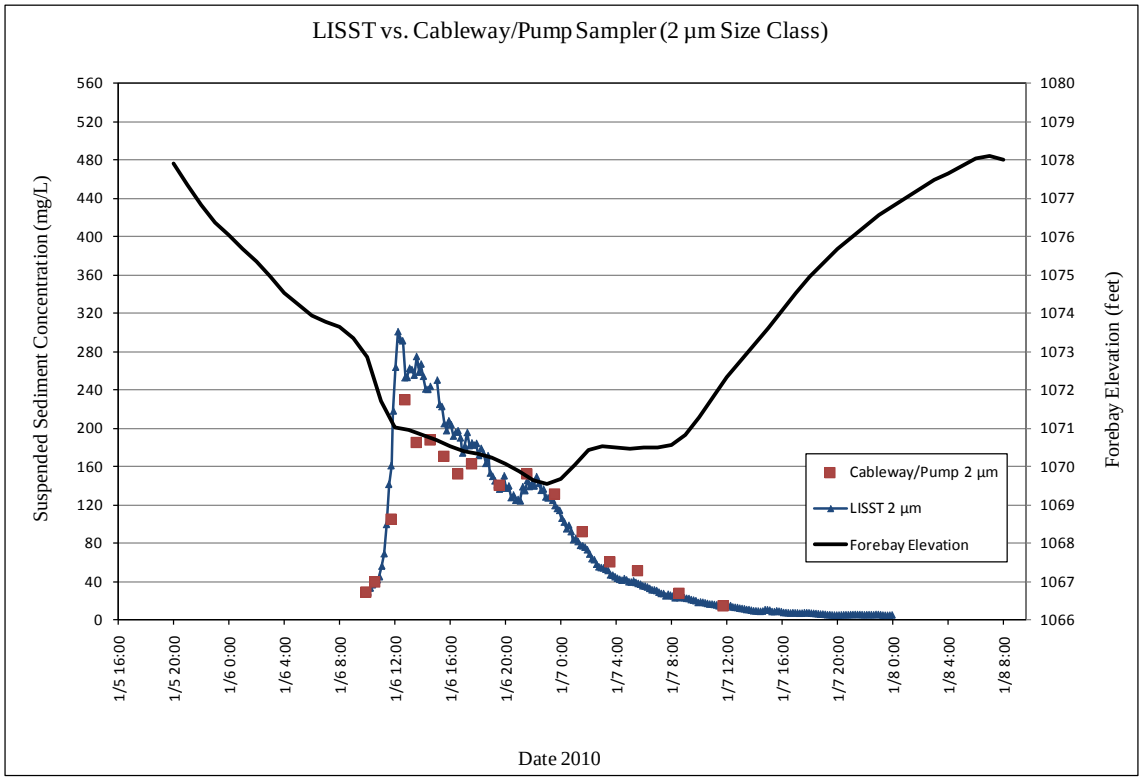




**Figure 7. Comparison of LISST-100X and cableway/pump sampler sand and silt/clay concentrations measured during the drawdown.**



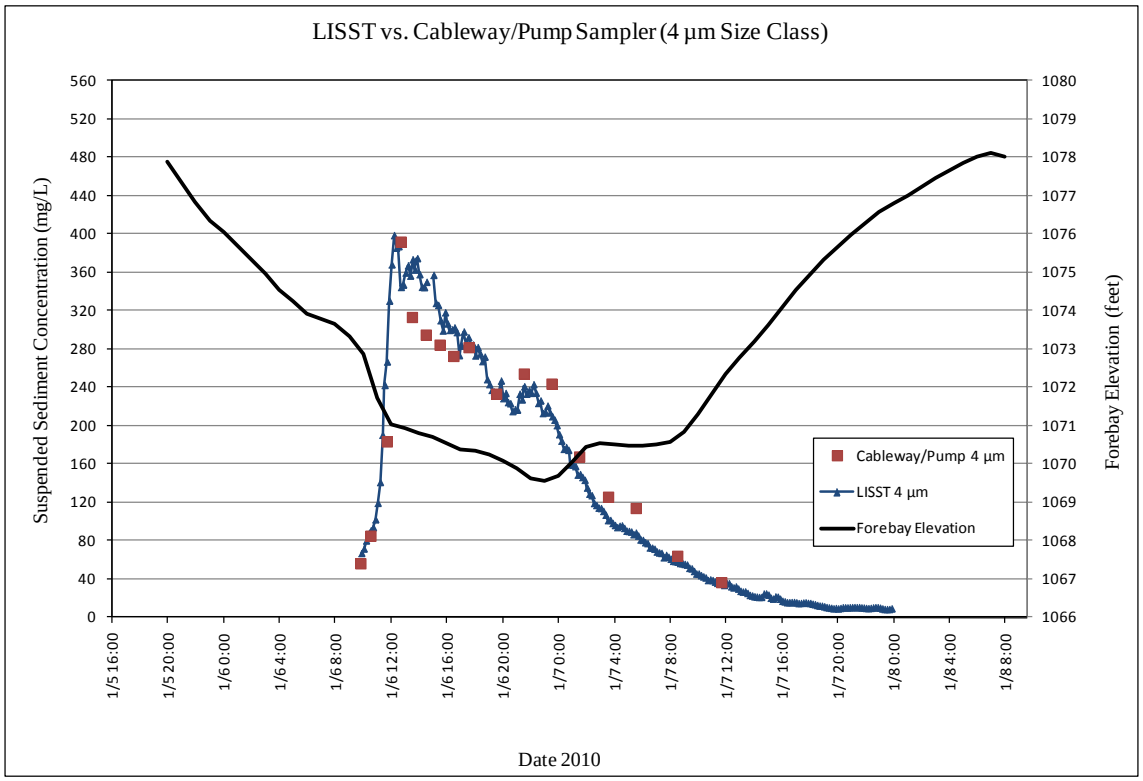




**Figure 8. Comparison of LISST-100X and cableway/pump sampler 2 µm and 4 µm size fraction concentrations measured during the drawdown**

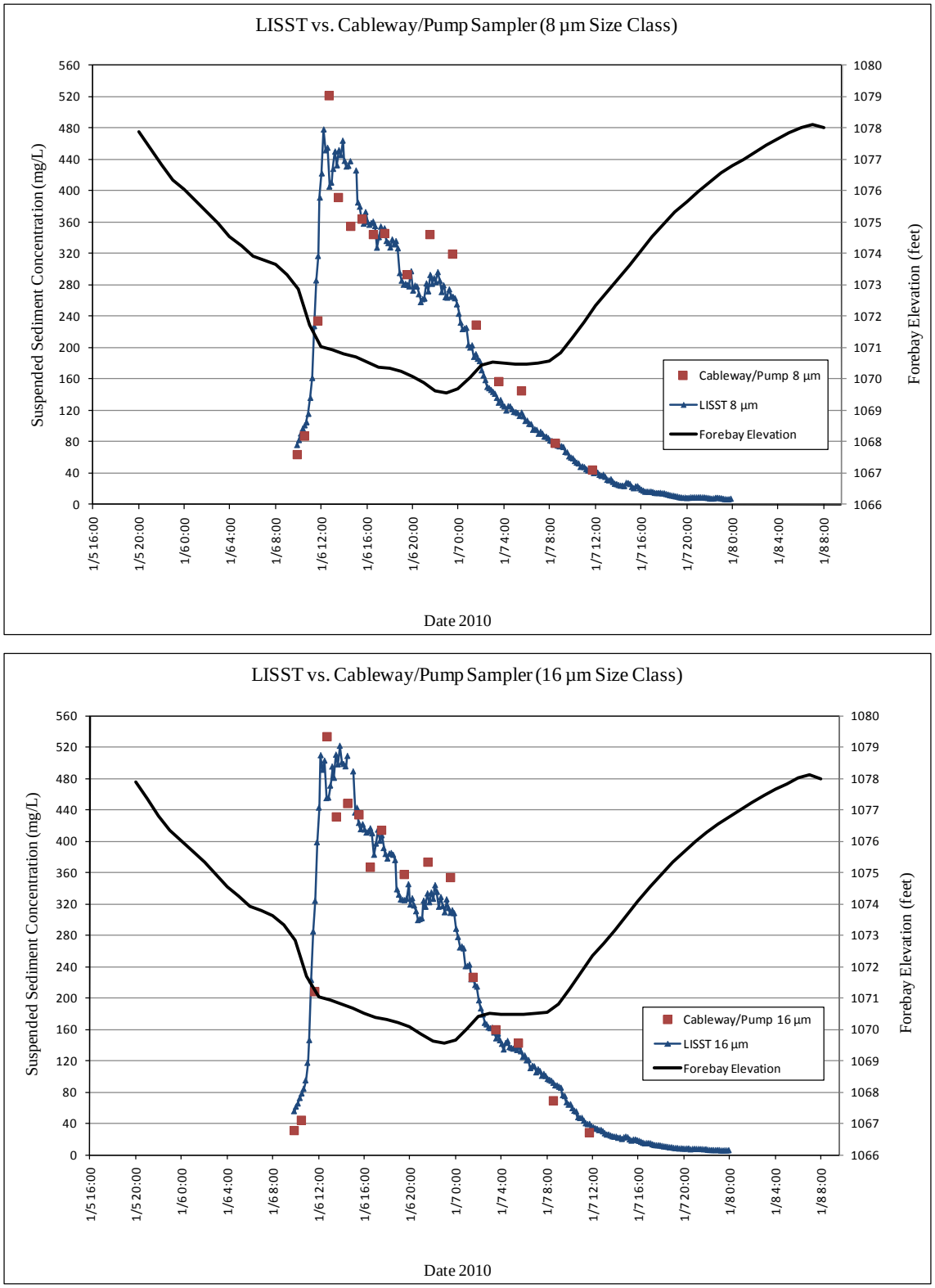



**Figure 9. Comparison of LISST-100X and cableway pump sampler 8 µm and 16 µm size fraction concentrations measured during the drawdown.**

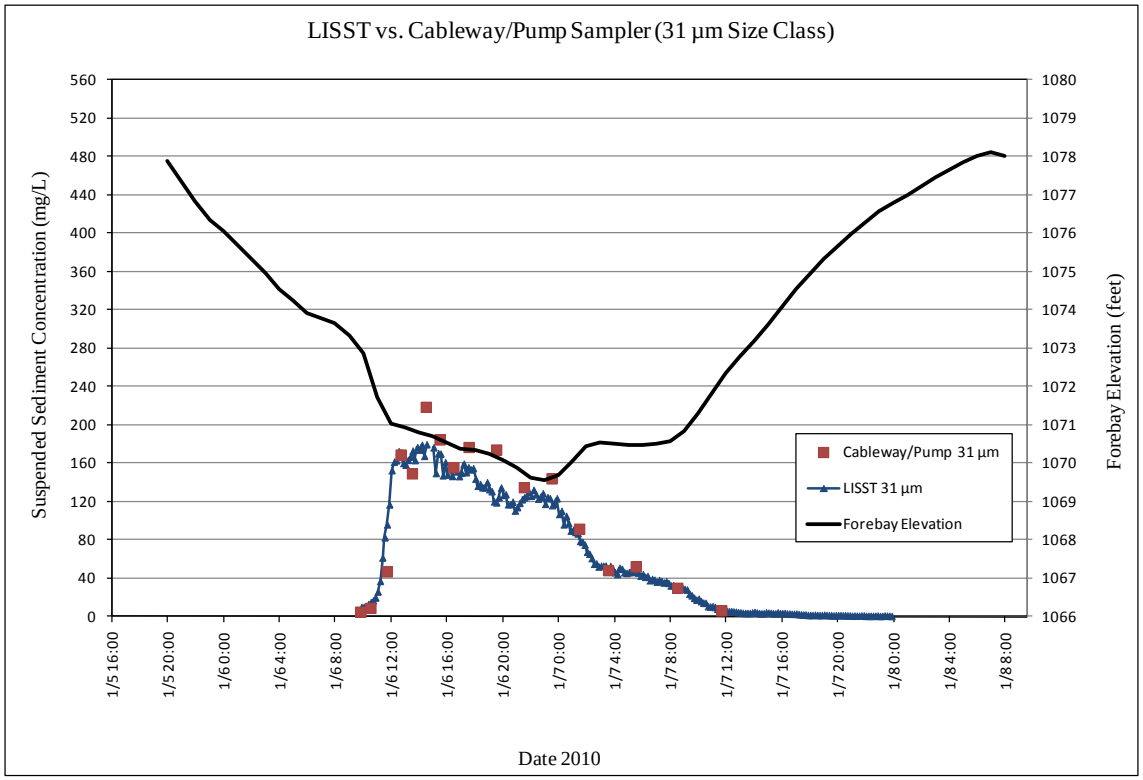
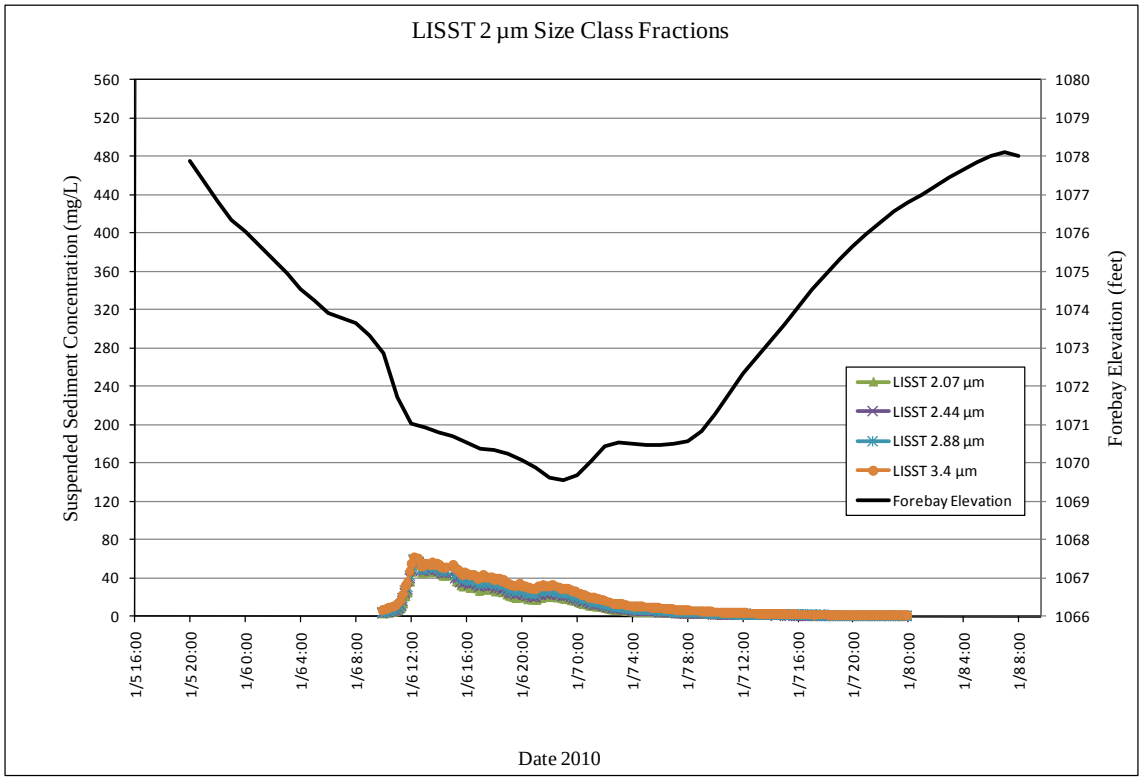



**Figure 10. Comparison of LISST-100X and cableway/pump sampler 31 µm size fraction concentrations measured during the drawdown.**



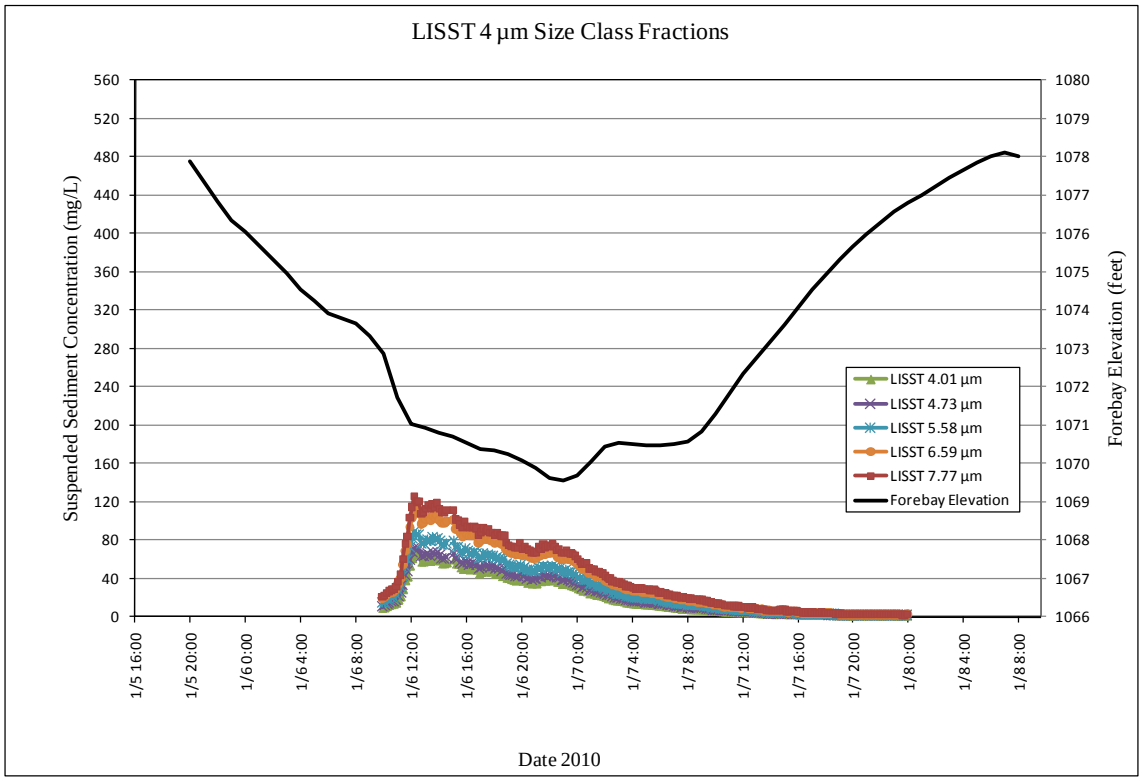
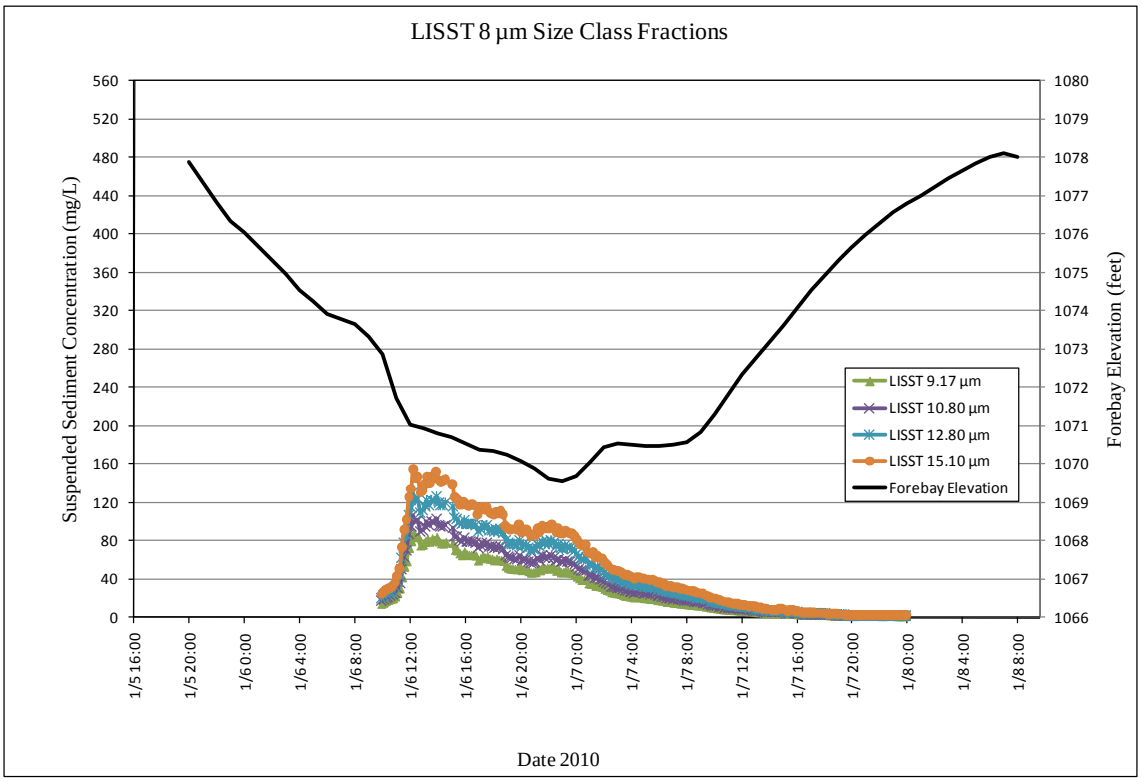




**Figure 11. Particle size distribution in the 2µm to 4µm size range as measured by the LISST-100X during the drawdown.**



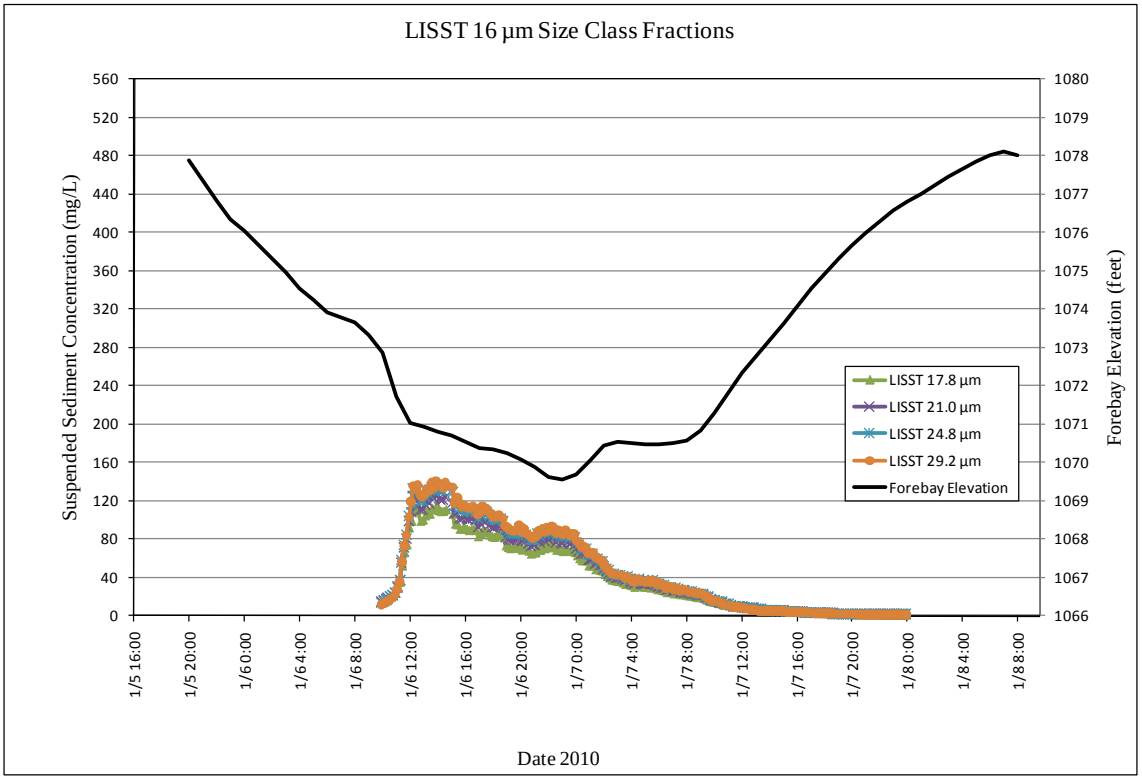




**Figure 12. Particle size distribution in the 8µm to 16µm size range as measured by the LISST-100X during the drawdown.**

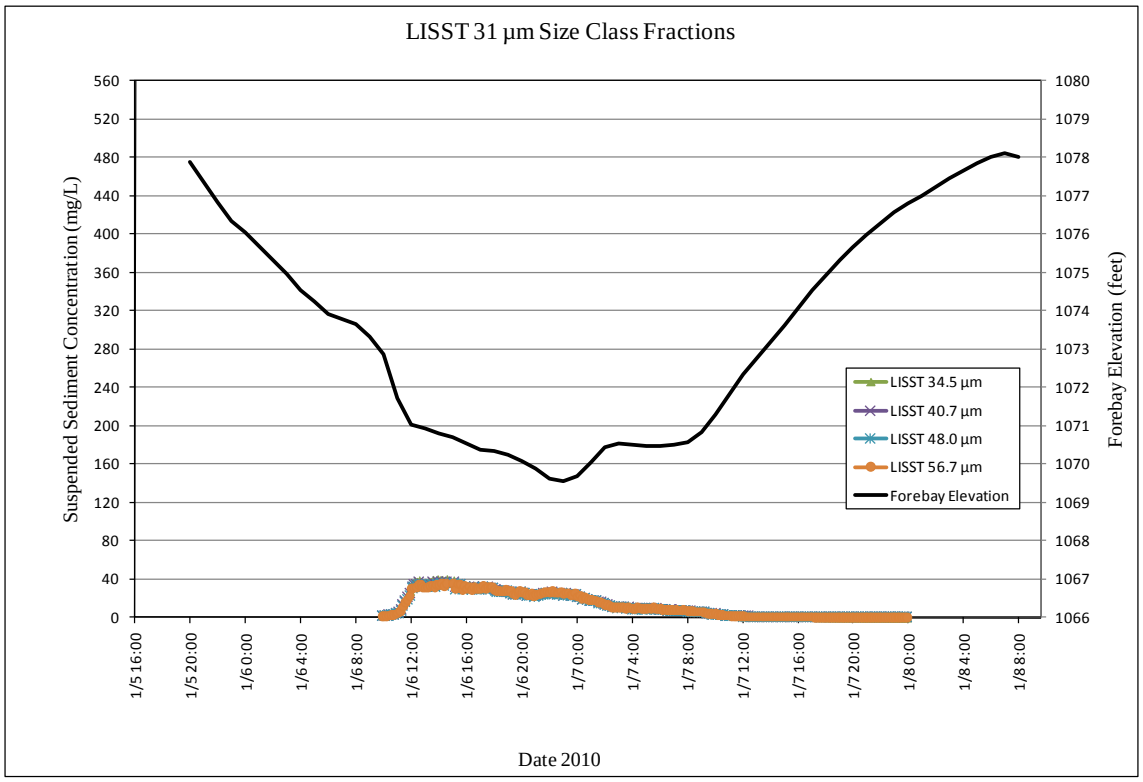
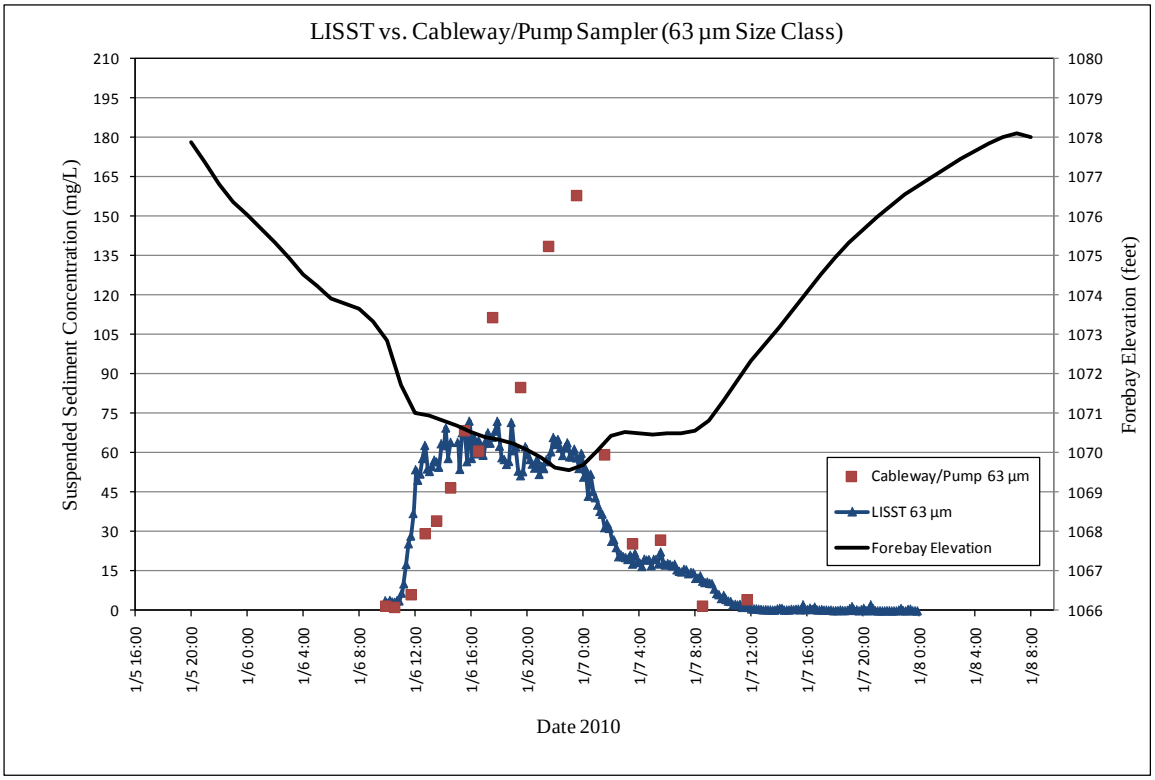



**Figure 13. Particle size distribution in the 31µm size range as measured by the LISST-100X during the drawdown.**



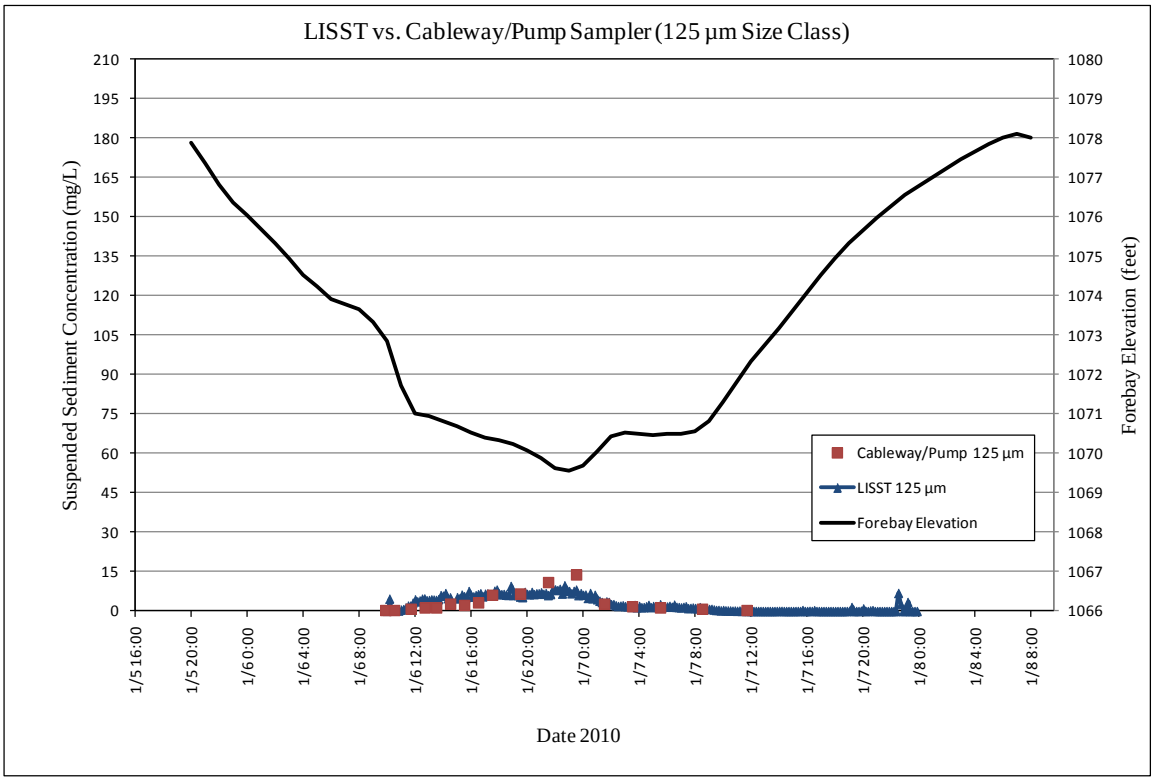




**Figure 14. Comparison of LISST-100X and cableway/pump sampler 63 µm and 125 µm size fraction concentrations measured during the drawdown.**

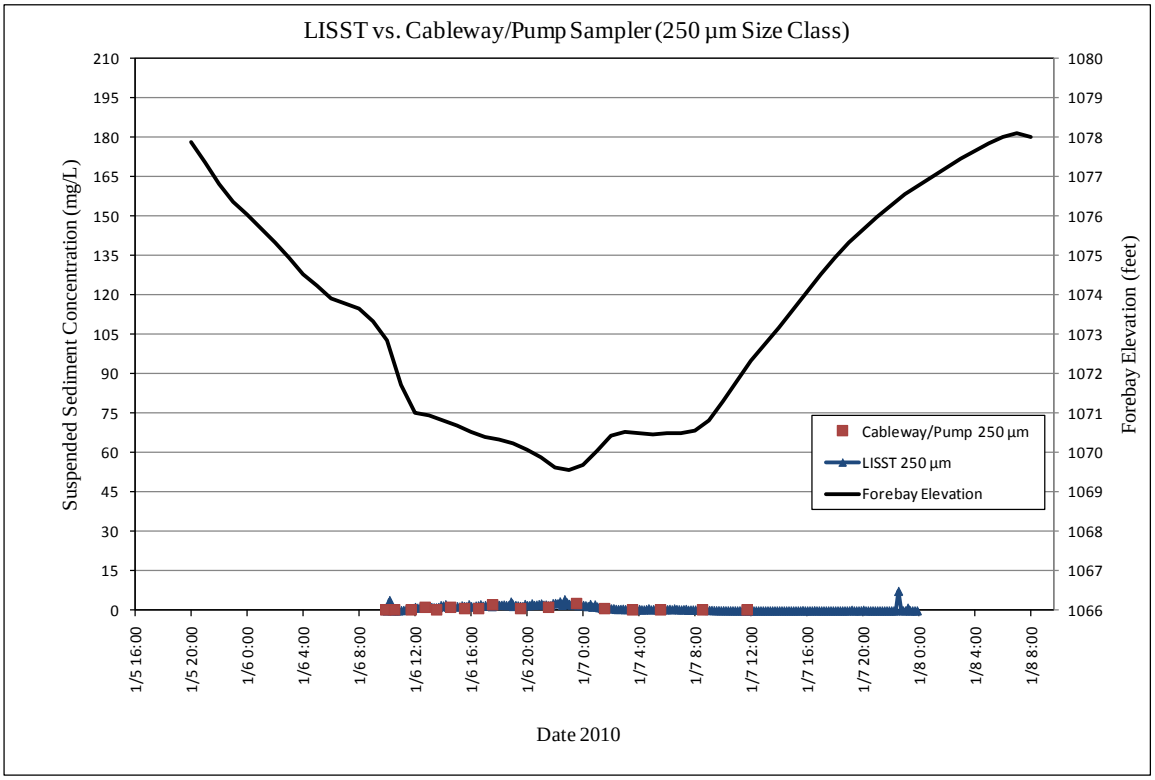
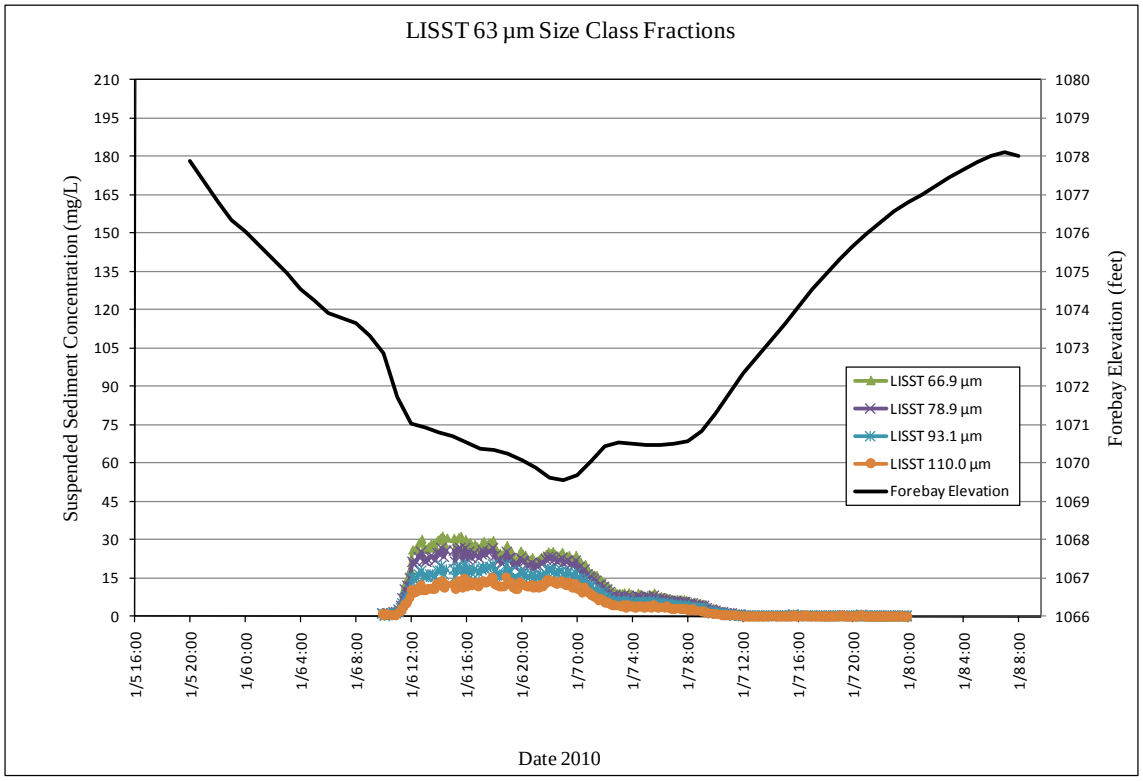



**Figure 15. Comparison of LISST-100X and cableway/pump sampler 250 µm size fraction concentrations measured during the drawdown.**



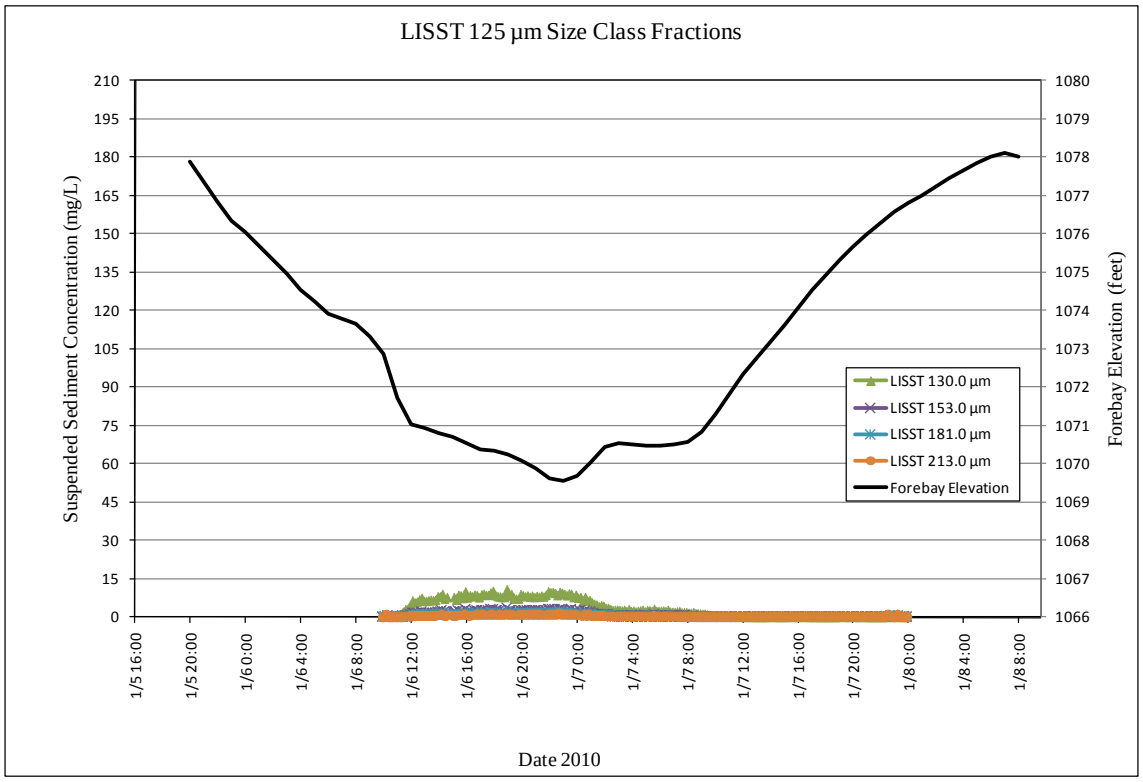




**Figure 16. Particle size distribution in the 63µm to 125µm size range as measured by the LISST-100X during the drawdown.**

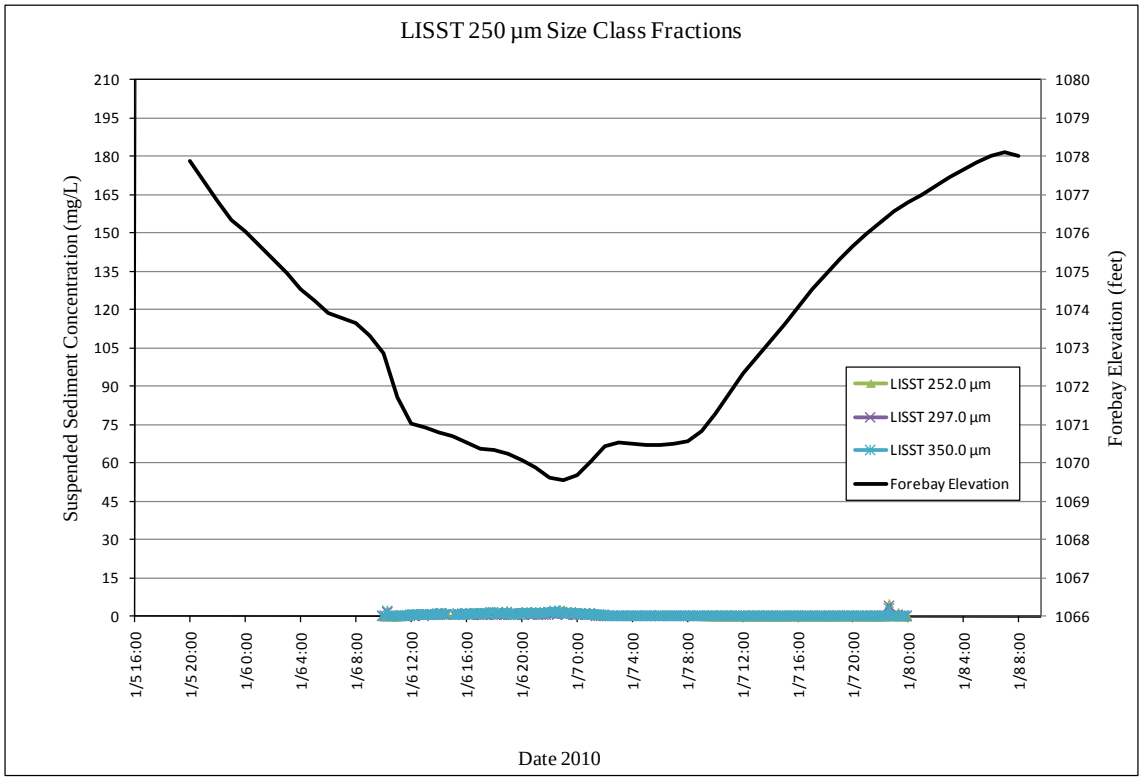
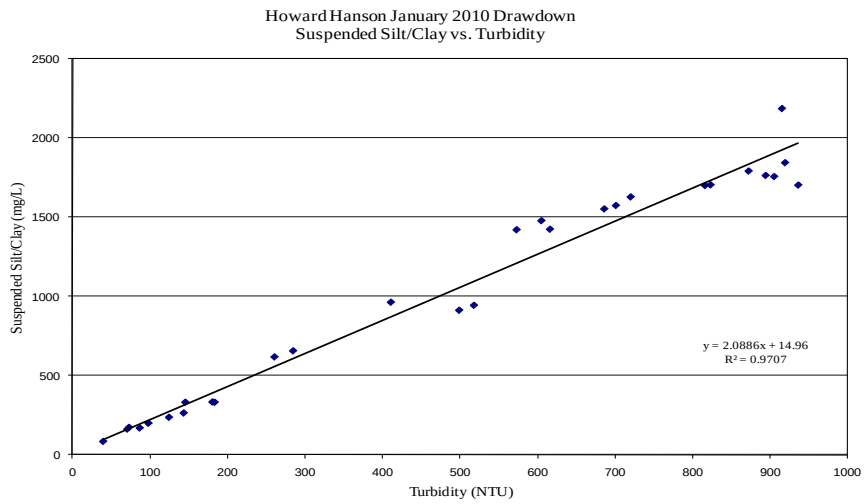
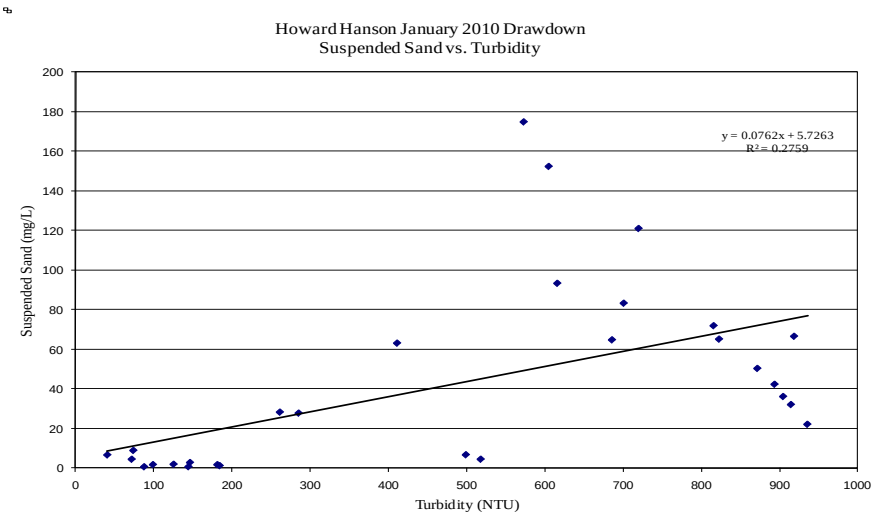



**Figure 17. Particle size distribution in the 250µm size range as measured by the LISST-100X during the drawdown.**



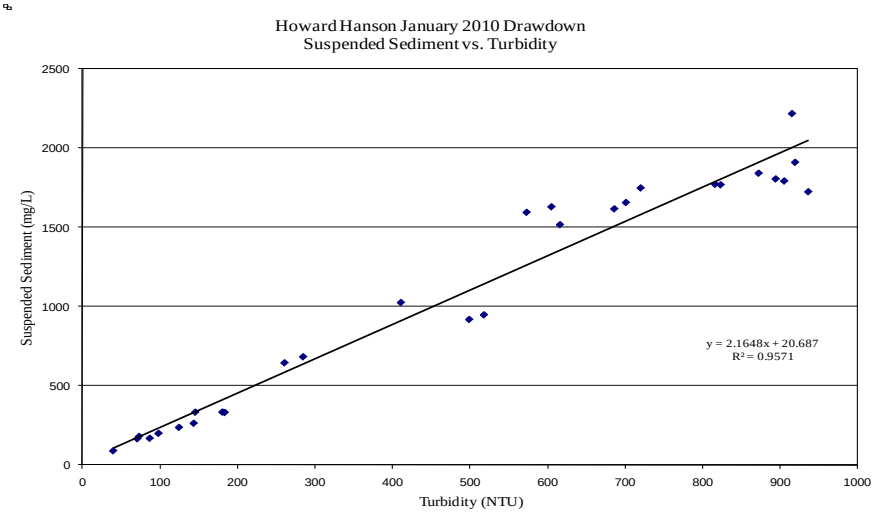




**Figure 18. Relationship between suspended sediment concentrations and turbidity values measured during the drawdown.**

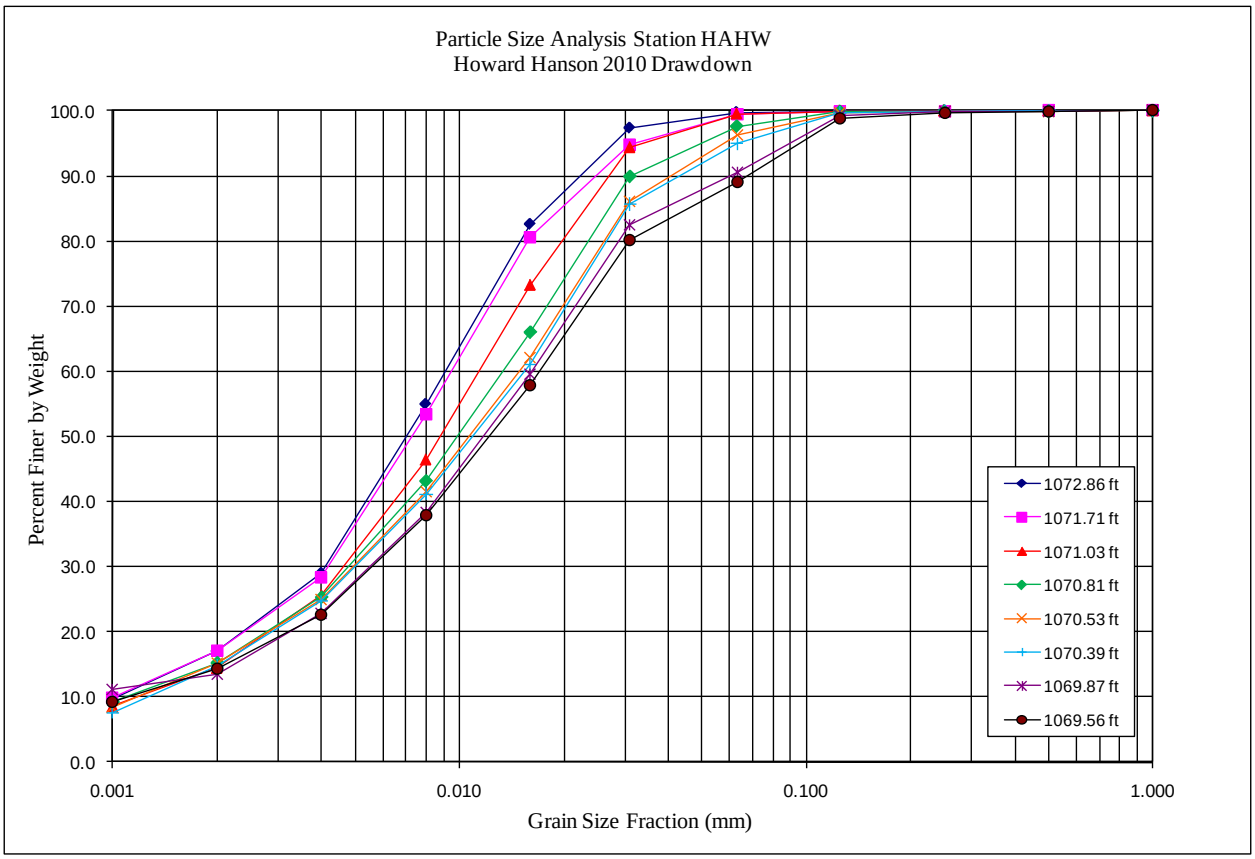
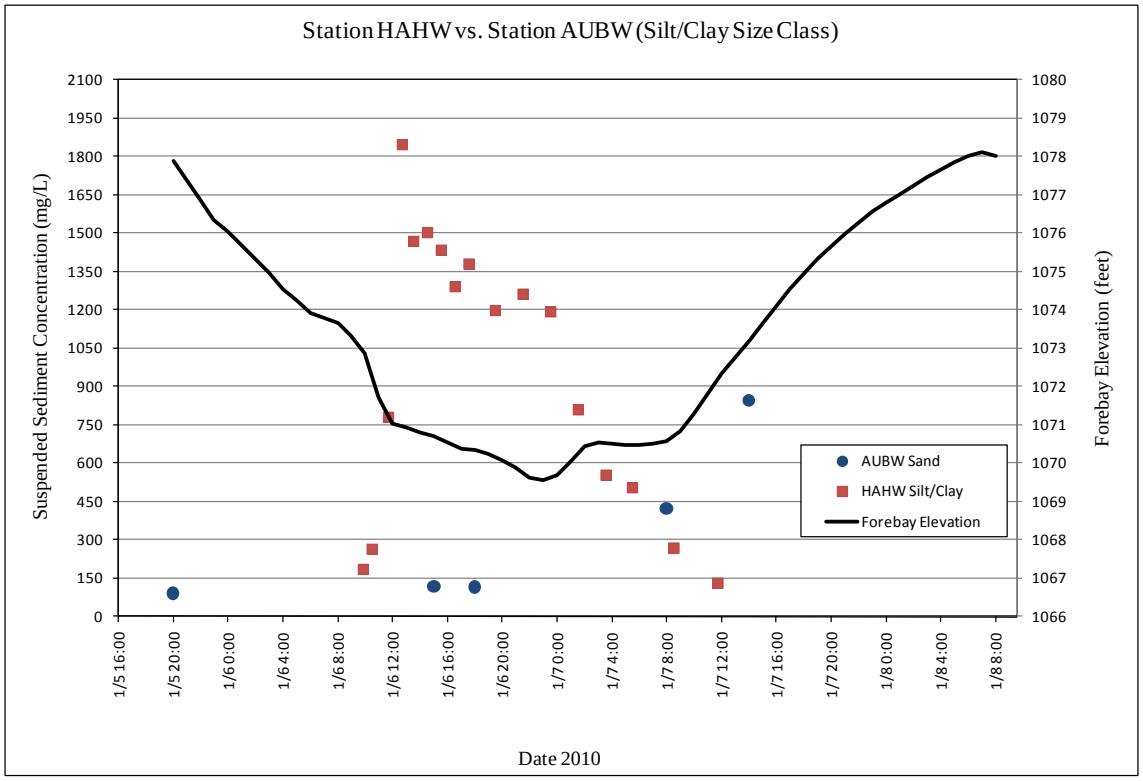



**Figure 19. Frequency analysis for grain size fractions collected by the cableway/pump sampler during the drawdown.**



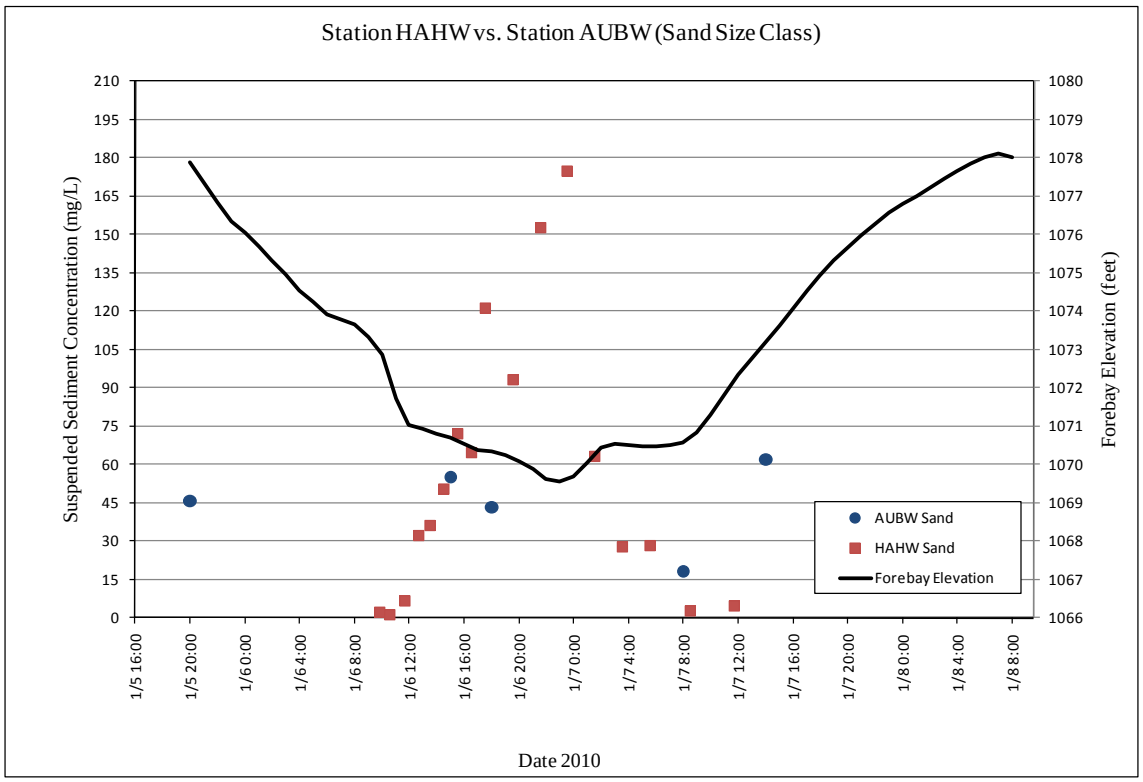
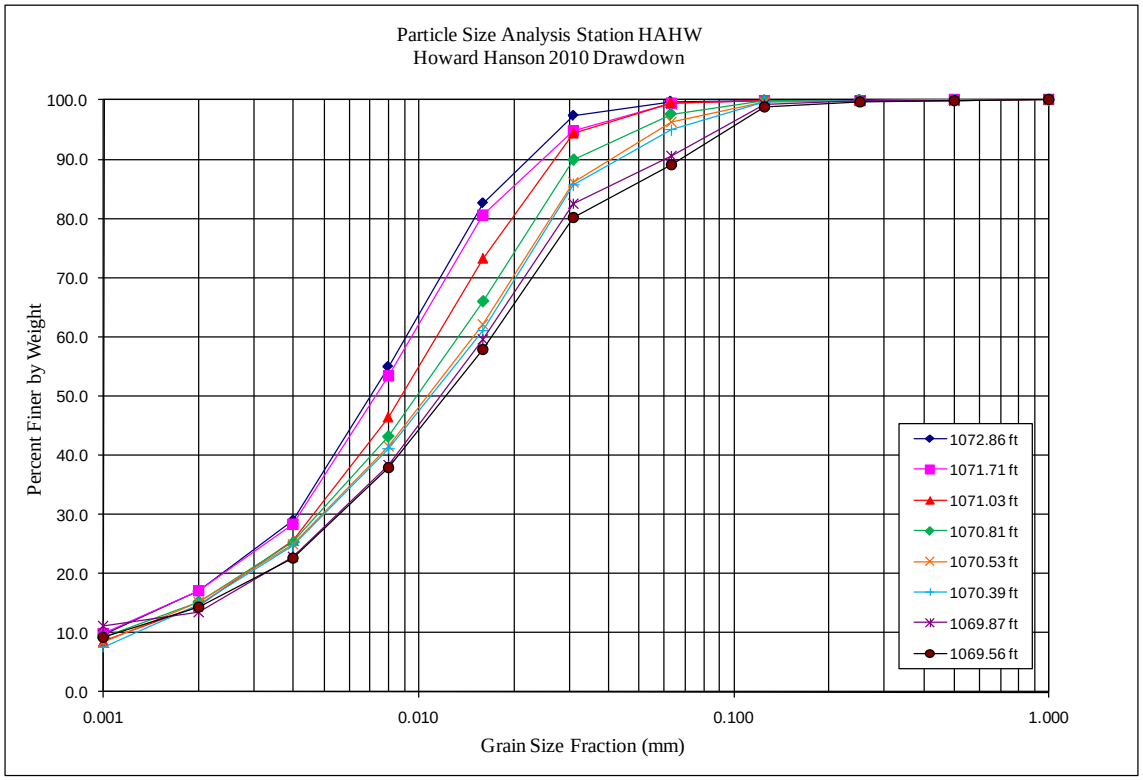




**Figure 20. Suspended sediment concentrations measured at Station HAHW and Station AUBW during the drawdown.**



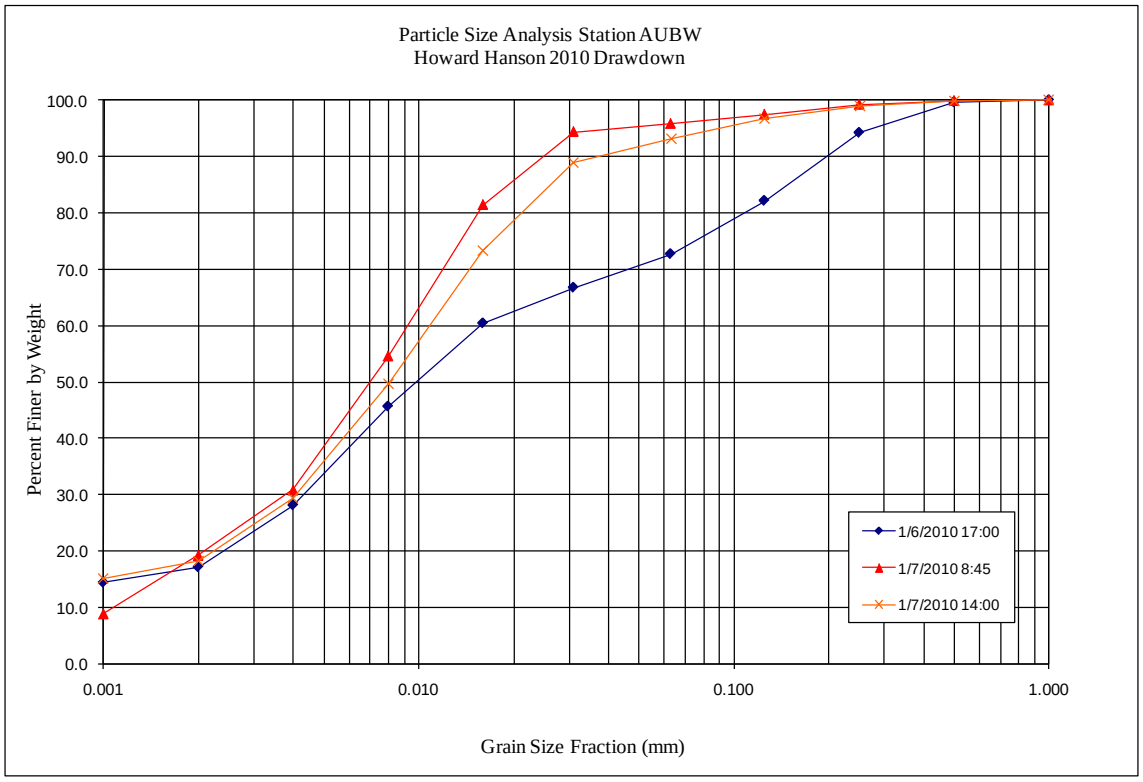




**Figure 21. Frequency analysis of grain size distributions collected at Station HAHW and Station AUBW during the drawdown**