Relicensing Study 3.1.3

Northfield Mountain Pumped Storage Project

Sediment Management Plan -

FINAL REPORT

Northfield Mountain Pumped Storage Project (No. 2485) and Turners Falls Hydroelectric Project (No. 1889)

Prepared for:

FirstLight Power Resources

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OCTOBER 2016

EXECUTIVE SUMMARY

FirstLight Hydro Generating Company (FirstLight) is the current licensee of the Northfield Mountain Pumped Storage Project (Northfield Mountain Project, FERC No. 2485) and the Turners Falls Hydroelectric Project (Turners Falls Project, FERC No. 1889). FirstLight has initiated with the Federal Energy Regulatory Commission (FERC, the Commission) the process of relicensing the Northfield Mountain and Turners Falls Projects using the FERC's Integrated Licensing Process (ILP). The current licenses for Northfield Mountain and Turners Falls Projects were issued on May 14, 1968 and May 5, 1980, respectively, with both set to expire on April 30, 2018.

Prior to initiation of the FERC relicensing process, the U.S. Environmental Protection Agency (USEPA) issued an Administrative Order dated August 4, 2010, which requested a report identifying measures to prevent discharges of sediments associated with draining the Northfield Mountain Upper Reservoir. Subsequently, by letter dated January 20, 2011, FERC staff requested a plan to avoid or minimize the entrainment of sediment into the Project works during Upper Reservoir maintenance drawdowns. On July 15, 2011, FirstLight filed the *Northfield Mountain Pumped Storage Sediment Management Plan* (the Plan) in response to the USEPA and FERC requests.

The Plan was developed in consultation with the USEPA and Massachusetts Department of Environmental Protection (MADEP). The Plan contained proposed methods to assess sediment dynamics in the Project's Upper Reservoir and the Connecticut River (Turners Falls Impoundment) from 2011 through 2014. Furthermore, FirstLight committed to propose management measures to minimize entrainment of sediment into the Project works and Connecticut River at the conclusion of the data collection and assessment efforts.

During the study plan development phase of the Project relicensing, the USEPA requested that FirstLight integrate the *Sediment Management Plan* into the FERC relicensing process. FirstLight agreed and designated the Plan as relicensing Study No. 3.1.3 *Northfield Mountain Project Sediment Management Plan* (Study No. 3.1.3). FirstLight also committed to extending data collection efforts pursuant to the Plan an additional year, through 2015. FERC approved the Plan as Study No. 3.1.3 in September 2013. As required by the FERC approved Revised Study Plan (RSP), FirstLight is obligated to file: 1) annual reports with FERC, USEPA, and MADEP summarizing the previous year's monitoring activities by December 1 of the year in which the monitoring occurred,[1] 2) an Updated Study Report to be filed with FERC based on the information it has collected to date,[2] and 3) a report to be filed with USEPA, MADEP and FERC, which would include any additional field data collected after September 2015.[3]

Study No. 3.1.3 contained various field studies, data collection, and modeling efforts which occurred from 2011-2016. The results of these efforts were used to inform management measures to minimize entrainment of sediment into the Project works and discharge to the Connecticut River during drawdown or dewatering activities. The enclosed report has been expanded from the report filed on December 1, 2015 with two principal additions: (1) tasks that were still outstanding as of December 1, 2015 have been completed and are discussed in later sections, and (2) FirstLight's proposed sediment management measures have been included in the last section. This report represents the final report for Study No. 3.1.3.

[1] The final annual monitoring report was filed with FERC on December 1, 2015.
[2] FirstLight filed its Updated Study Report for Study No. 3.1.3 on September 14, 2015
[3] The December 2015 annual monitoring report combined with this report satisfied this requirement

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2-D	Two Dimensional
3-D	Three Dimensional
ADCP	Acoustic Doppler Current Profiler
CFD	Computational Fluid Dynamics
cfs	cubic feet per second
CHA	CHA Consulting, Inc.
CY	Cubic yard
EOW	Edge-of-water
EWI	Equal Width Increment
FERC	Federal Energy Regulatory Commission
FirstLight	FirstLight Hydro Generating Company
ft.	feet
ft^2	Square foot
Gomez and Sullivan	Gomez and Sullivan Engineers, DPC
GIS	Geographic Information System
HYDROs	LISST Hydro North and HYDRO South
ILP	Integrated Licensing Process
km	kilometer
LISST	Laser In-situ Transmissometry
MADEP	Massachusetts Department of Environmental Protection
Mg/L	milligrams per liter
mi^2	Square mile
msl	Mean Sea Level
NAD83	North American Datum of 1983
NAVD88	North American Vertical Datum of 1988
NGVD29	National Geodetic Vertical Datum of 1929
NOI	Notice of Intent
Northfield Mountain Project	Northfield Mountain Pumped Storage Project
Ocean & Coastal	Ocean and Coastal Consultants, Inc.
PAD	Pre-Application Document
PSP	Proposed Study Plan
PSD	Particle Size Distribution
QA	Quality Assurance
QAPP	Quality Assurance Project Plan
QC	Quality Control
ROV	Remotely Operated Vehicle
RSP	Revised Study Plan
Rt.	Route
RTK GPS	Real-Time Kinematic Global Positioning System
SeaVision	SeaVision Underwater Solutions
SSC	Suspended Sediment Concentration
SD1	Scoping Document 1
SD2	Scoping Document 2
SPDL	Study Plan Determination Letter
StreamSide	LISST StreamSide
Study No. 3.1.3	Northfield Mountain Pumped Storage Project Sediment Management Plan
TC	Total Concentration

TFI	Turners Falls Impoundment
the Commission	Federal Energy Regulatory Commission
the Plan	Northfield Mountain Pumped Storage Project Sediment Management Plan
the Project	Northfield Mountain Pumped Storage Project
TIN	Triangular Irregular Network
TSS	Total Suspended Solids
Turners Falls	Turners Falls Hydroelectric Project
Project	Turners Falls Hydroelectric Project
µl/L	microliters per liter
USEPA	U.S. Environmental Protection Agency
V	Volts
Vernon	Vernon Hydroelectric Project
VY	Vermont Yankee Nuclear Power Plant

1 INTRODUCTION

FirstLight Hydro Generating Company (FirstLight) is the current licensee of the Northfield Mountain Pumped Storage Project (Northfield Mountain Project, FERC No. 2485) and the Turners Falls Hydroelectric Project (Turners Falls Project, FERC No. 1889). FirstLight has initiated with the Federal Energy Regulatory Commission (FERC, the Commission) the process of relicensing the Northfield Mountain and Turners Falls Projects using FERC's Integrated Licensing Process (ILP). The current licenses for Northfield Mountain and Turners Falls Projects were issued on May 14, 1968 and May 5, 1980, respectively, with both set to expire on April 30, 2018.

As part of the ILP, FERC conducted a public scoping process during which various resource issues were identified. On October 31, 2012, FirstLight filed its Pre-Application Document (PAD) and Notice of Intent (NOI) with FERC. The PAD included FirstLight's preliminary list of proposed studies. On December 21, 2012, FERC issued Scoping Document 1 (SD1) and preliminarily identified resource issues and concerns. On January 30 and 31, 2013, FERC held scoping meetings for the Northfield Mountain and Turners Falls Projects. FERC issued Scoping Document 2 (SD2) on April 15, 2013.

FirstLight filed its Proposed Study Plan (PSP) on April 15, 2013 and, per the Commission regulations, held a PSP meeting at the Northfield Visitors Center on May 14, 2013. Thereafter, FirstLight held ten resource-specific study plan meetings to allow for more detailed discussions on each PSP and on studies not being proposed. On June 28, 2013, FirstLight filed with the Commission an Updated PSP to reflect further changes to the PSP based on comments received at the meetings. On or before July 15, 2013, stakeholders filed written comments on the Updated PSP. FirstLight filed a Revised Study Plan (RSP) on August 14, 2013 with FERC addressing stakeholder comments.

Prior to FirstLight initiating the FERC relicensing process for the Northfield Mountain and Turners Falls Projects, the U.S. Environmental Protection Agency (USEPA) issued an Administrative Order dated August 4, 2010, which requested a report identifying measures to prevent discharges of sediments associated with draining the Northfield Mountain Upper Reservoir. Subsequently, by letter dated January 20, 2011, FERC staff requested a plan to avoid or minimize the entrainment of sediment into the Northfield Mountain Project (the Project) works during reservoir maintenance drawdowns. In response to these requests, FirstLight filed the *Northfield Mountain Pumped Storage Sediment Management Plan* (the Plan) on July 15, 2011.

The Plan was developed in consultation with the USEPA and the Massachusetts Department of Environmental Protection (MADEP). The Plan contained proposed methods to assess sediment dynamics in the Project's Upper Reservoir and the Connecticut River from 2011 through 2014. These proposed methods included conducting annual bathymetric surveys in the Upper Reservoir to determine annual changes in sediment volume and collecting turbidity and total suspended solids (TSS) data routinely at the Route (Rt.) 10 Bridge (spanning the Connecticut River) and at the Northfield Mountain Project.

In its letter of February 16, 2012, the USEPA provided several comments related to the scope of the sampling and requested that FirstLight develop a Quality Assurance Project Plan (QAPP). In response, FirstLight agreed to develop a QAPP in cooperation with the USEPA; the initial draft of which was submitted on June 28, 2012. The initial draft of the QAPP included several modifications to the original Plan, most notably the addition of continuous suspended sediment monitoring equipment to be installed upstream of the Rt. 10 Bridge and at the Northfield Mountain Project. The USEPA provided FirstLight with comments pertaining to the initial QAPP on July 31, 2012, which FirstLight addressed. FirstLight submitted revision 1 of the QAPP to the USEPA on October 19, 2012.

In 2013, as part of the study scoping process associated with the relicensing of the Northfield Mountain and Turners Falls Projects, the USEPA requested that FirstLight incorporate the *Sediment Management Plan* into its relicensing studies. As such, FirstLight included the *Sediment Management Plan* in the RSP as Study No. 3.1.3 *Northfield Mountain Project Sediment Management Plan* (Study No. 3.1.3).

In accordance with the *Sediment Management Plan* and Study No. 3.1.3 RSP, Upper Reservoir bathymetry surveys were conducted annually (starting in 2011) and suspended sediment was monitored continuously in the vicinity of the Rt. 10 Bridge and at the Northfield Mountain Project (2012 – mid-2015). In addition, grab samples were collected throughout the study area during this time (2012-2015). Over the course of this time period, the continuous monitoring program was modified several times due to technical challenges encountered with the monitoring equipment. In 2013, following a status update meeting with USEPA and MADEP personnel, FirstLight announced that sediment monitoring activities would be extended for an additional year through the fall of 2015 due to these technical challenges.

Also in 2013, FirstLight expanded the scope of Study No. 3.1.3 to include various modeling components. Modeling efforts implemented as part of this study included the development of a Computational Hydrodynamic Sedimentation model of the Upper Reservoir, a Computational Fluid Dynamics (CFD) sedimentation model of the Project tailrace, and a physical model of the Project area. Furthermore, in 2015 FirstLight commissioned a pilot dredge of the Upper Reservoir.

As of the date of this report all components of this study have been completed. The results of the various study components have been reviewed and management measures to minimize the entrainment of sediment into Project works and the Connecticut River have been developed (Section 5). As discussed in Section 5, the proposed sediment management measures follow an adaptive approach and, as such, may change over time as the current understanding of the sediment dynamics in the Upper Reservoir and Northfield Mountain tailrace evolves and technological advancements occur. This report marks the final report for Study No. 3.1.3.

Information discussed in this report includes: (1) a general overview and status update of all study components; (2) analyses and results pertaining to the annual Upper Reservoir Bathymetry Surveys (2011-2015); (3) analyses and results of the suspended sediment monitoring efforts (2013-2015); and (4) proposed sediment management measures. Report sections relevant to this discussion include:

- Section 2: Field Studies and Data Collection;
- Section 3: Data Analyses;
- Section 4: Results and Discussion;
- Section 5: Proposed Sediment Management Measures; and
- Various Appendices (A-F)

2 FIELD STUDIES, DATA COLLECTION, AND MODELING

Various field studies, data collection, and modeling efforts associated with this study occurred from 2011 to 2016. These efforts included:

- Annual Upper Reservoir bathymetry surveys (2011-2015) – Section 2.1;
- Continuous suspended sediment monitoring upstream of the Rt. 10 Bridge and at the Northfield Mountain Project (2012-2015) – Section 2.2;
- Periodic cross-sectional suspended sediment monitoring at the Rt. 10 Bridge and Northfield Mountain tailrace boat barrier buoy line (2013) – Section 2.2;
- Grab sample collection upstream of the Rt. 10 Bridge, across the Rt. 10 Bridge, and at the Northfield Mountain tailrace (2012-2015) – Section 2.2;
- Development of an Upper Reservoir Computational Hydrodynamic Sedimentation model (2013-2014) – Section 2.3;
- Development of a Northfield Mountain tailrace CFD Sedimentation model (2014) – Section 2.3;
- Development of a physical model of the Northfield Mountain tailrace and surrounding area (2015-2016) – Section 2.3; and
- A pilot dredge of the Upper Reservoir (2015) – Section 2.4

This section provides an overview of each study component listed above. In depth discussion pertaining to data analysis and results of the annual bathymetry surveys and suspended sediment monitoring can be found in Sections 3 and 4, respectively.

2.1 Upper Reservoir Bathymetry Surveys

Northfield Mountain Upper Reservoir bathymetry surveys have been conducted annually since 2011 to approximate the sediment volume accumulated in the Upper Reservoir, and more specifically the amount of sediment accumulated in the intake channel. Figure 2.1-1 shows the Northfield Mountain Upper Reservoir, including the intake channel, where the surveys occurred. Table 2.1-1 provides a summary of the relevant information from each survey including which firm collected the survey data, the vertical datum of the survey, whether a single or multi-beam echosounder was used, and relevant notes (if any).

For each survey a vessel was equipped with either a single or multi-beam echosounder used to record the reservoir water depth. The echosounder was linked to a Real-Time Kinematic Global Positioning System (RTK-GPS) which was used to record the vertical and horizontal positioning of the echosounder during all survey operations. All horizontal positions were referenced to the North American Datum of 1983 (NAD83) Massachusetts Mainland State Plane, U.S. Survey feet coordinate system while all vertical positions referenced the Northfield Mountain Pumped Storage Facility vertical datum or the National Geodetic Vertical Datum of 1929 (NGVD29).

At the conclusion of each survey, the bathymetric data were used to create a Triangular Irregular Network (TIN) which depicted Upper Reservoir bed elevations. The TINs were then used in “cut-fill” and “raster-minus” operations to determine the sediment volume change between each year as well as the relative changes in bed elevation. A contour plan and sounding plan were created for each annual survey (Appendix A).

Additional information pertaining to the data analysis and results for each bathymetry survey can be found in Section 3.1 and 4.1, respectively.

Table 2.1-1. Summary of Upper Reservoir Bathymetric Data Collection[4]

Date of Bathymetric Survey	Bathymetry Collected by	Vertical Datum	Single or Multi-beam Echosounder	Comments
November 5, 2011	Ocean and Coastal Consultants Inc., with SeaVision Underwater Solutions	Northfield Mountain Pumped Storage Facility vertical datum	Single beam	
September 29-30, 2012	Ocean and Coastal Consultants Inc., with SeaVision Underwater Solutions	Northfield Mountain Pumped Storage Facility vertical datum	Multi-beam	Multi-beam surveys collect larger swaths of sounding data which allows for greater resolution
October 5-6, 2013	CHA Consulting, Inc.	Northfield Mountain Pumped Storage Facility vertical datum	Single beam	
October 11-12, 2014	SeaVision Underwater Solutions	Northfield Mountain Pumped Storage Facility vertical datum	Multi-beam	In addition to the multi-beam survey, gravity cores were utilized at six locations within the intake channel to better ascertain the sediment thickness in this area.
October 3-4, 2015	SeaVision Underwater Solutions	Northfield Mountain Pumped Storage Facility vertical datum	Multi-beam	In addition to the multi-beam survey, vibracores were collected at six locations within the intake channel to better ascertain the sediment thickness in this area. Note that the bathymetry survey was conducted after initiation of the pilot dredge study.

[4] As part of the proposed sediment management measures outlined in Section 5, a bathymetric survey of the Upper Reservoir will be conducted in October 2016.

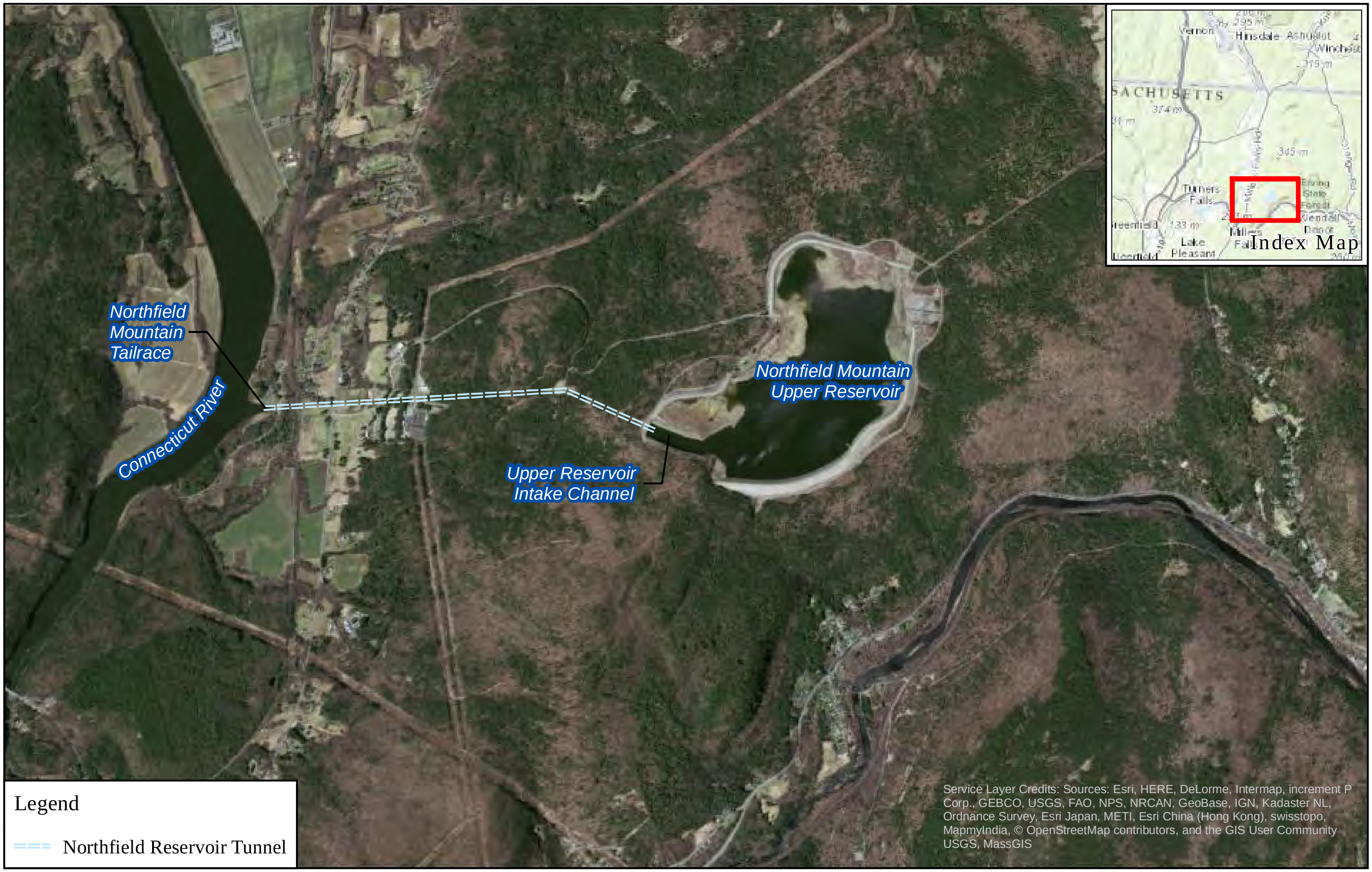

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Figure 2.1-1 Northfield Mountain Upper Reservoir and Tailrace

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2.2 Suspended Sediment Monitoring

From 2012 to 2015, FirstLight operated continuous suspended sediment monitors at three locations in the Project area (Figure 2.2-1), except during the winter period (freezing temperatures). Continuous suspended sediment monitoring equipment used as part of this study included two Laser In-situ Scattering Transmissometry (LISST) HYDRO units (HYDROs) and one LISST-StreamSide (StreamSide) unit. The LISST HYDROs were installed at the Northfield Mountain Project (initially in the powerhouse and then relocated to the tailrace in 2013) while the StreamSide was installed just upstream of the Rt. 10 Bridge in Northfield, MA. Additional LISST equipment that was utilized during this study included the LISST-100X which was used to collect cross-sectional data at the Rt. 10 Bridge and Northfield Mountain tailrace boat barrier buoy line in 2013.

In addition to the LISST instruments, grab samples were taken from the drain hoses of the HYDROs and StreamSide (2012-2015), from the edge-of-water at each LISST instrument (2015), and across the Rt. 10 Bridge (2015).

This section provides a detailed discussion of each of the suspended sediment monitoring methods employed as part of this study.

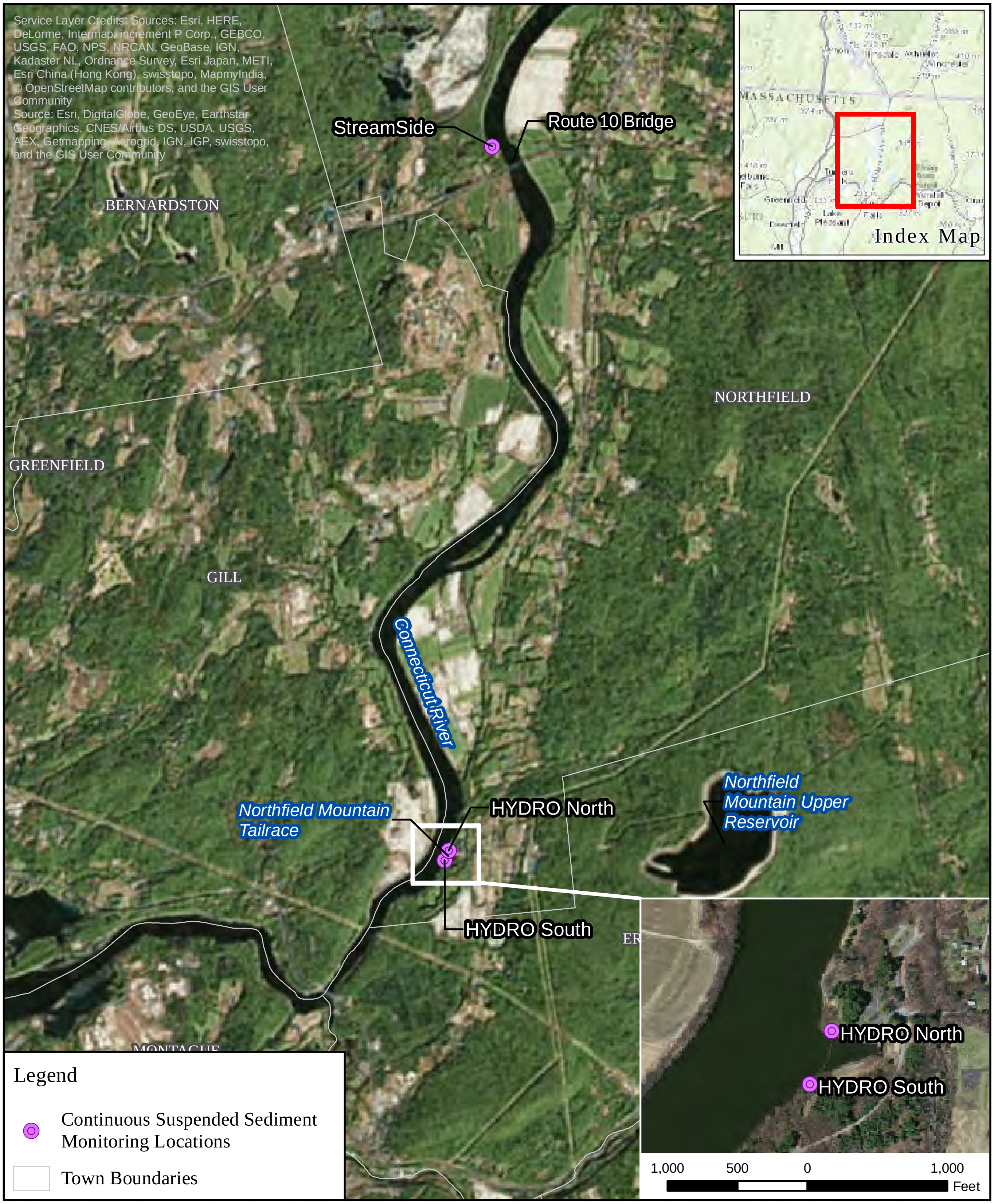

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Figure 2.2-1
Locations of Continuous Suspended Sediment Monitors

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2.2.1 LISST Equipment

LISST-StreamSide

Starting in 2012, a continuous suspended sediment monitor (LISST-StreamSide) was installed in a secure closet on the right bank of the Connecticut River (Turners Falls Impoundment) upstream of the Rt. 10 Bridge in Northfield, MA. Figure 2.2.1-1 shows the location of the instrument relative to the Rt. 10 Bridge. The StreamSide was installed annually (2012-2015) by April 1 (or as soon as flow conditions allowed) and remained in place until late November when it was removed for the season. Figure 2.2.1-2 depicts the cabinet setup which housed the StreamSide.

The StreamSide was connected to a pump installed at a fixed location in the river approximately 10-15 feet offshore and suspended about 2 feet from the river bottom. Water was pumped from the river through the instrument where particle size distribution (PSD) (microns) and total concentration (µl/L) values were measured using laser diffraction technology. After flowing through the instrument the water was returned to the river; a water sample was not retained. Prior to each measurement, distilled water was run through the instrument to automatically "zero" it prior to the next recorded measurement. All data were stored on the instrument's hard drive until they were downloaded to a computer by field technicians.

Measurements were typically recorded at the top of every hour with the average sampling duration lasting 60 seconds. Each measurement consisted of a 60 second clean water flush, 300 second intake flush (river water from the pump), and a 20 second post measurement clean water flush.[5] Clean water background readings were taken and stored every three measurements by subtracting the measurement of light scattering in clean water from that resulting from the turbid sample water. The instrument then compared the field recorded clean water background with the manufacturer preset clean water reading. For the device to be working properly, these readings should be similar.

The StreamSide was serviced on a weekly schedule during which time the data was downloaded, the clean water tank was refilled (this occurred twice a week), the optical cells were cleaned, the battery voltage was checked, and, if necessary, the connectors, casing, and hoses were cleaned.

Over the course of the study, StreamSide data collection efforts were affected by equipment malfunctions and electrical issues which resulted in sporadic data gaps. Instrument issues ranged from electrical malfunctions, pump malfunctions, and instrument failures which resulted in the instrument being taken offline and shipped to the manufacturer for repairs. Limited usable data were collected in 2012 as a result of these instrument issues. As such, data analysis and results presented in this report focus on the 2013-2015 period. Following the challenging 2012 season, FirstLight and the equipment manufacturer worked closely to troubleshoot the equipment malfunctions. Modifications were made to the electrical components, instrument settings, and closet which housed the instrument. At the request of FirstLight, the equipment manufacturer visited the site during the 2013 field season to review and certify the instrument setup (Appendix B).

In spite of the equipment manufacturers certification that the instrument was properly installed, equipment malfunctions and electrical issues continued to plague data collection efforts during the 2013, 2014, and 2015 field seasons resulting in sporadic data gaps. FirstLight continued to work closely with the equipment manufacturer, however, instrument issues continued to persist. Following a major equipment malfunction in early 2015 which resulted in the instrument being taken offline, shipped to the manufacturer, and rebuilt, and following consultation with USEPA, FirstLight curtailed continuous suspended sediment monitoring at the StreamSide.

[5] These settings represent the final data settings used during the 2014 and 2015 field seasons. The final instrument settings were refined during the 2012 and 2013 field seasons and determined in collaboration with the equipment manufacturer.

Discussion pertaining to the StreamSide data analysis and results can be found in Section 3.2 and 4.2, respectively.

LISST-HYDROs

To monitor Suspended Sediment Concentration (SSC) moving into and out of the Northfield Mountain Upper Reservoir, two continuous suspended sediment monitors (LISST-HYDROs) were installed in the Northfield Mountain powerhouse in 2012. The HYDROs were installed directly inline to two separate 30-inch service water lines using available service water taps. The 30-inch service water lines tie into the draft tube area which contains the same water that is flowing through the pump/turbines. The LISST Hydro North instrument was installed to monitor Units 1 and 2, while the LISST HYDRO South was installed to monitor Units 3 and 4. The goal of the powerhouse HYDRO configuration was to measure SSC and PSD values observed during Project pumping and generating cycles via laser diffraction technology.

Data collection inside the powerhouse was attempted from June-December 2012 with limited success. After extensive troubleshooting by FirstLight and the equipment manufacturer, it was determined that the pressure from the service water line was too great for the HYDROs to adequately record measurements and that maintaining the configuration in the powerhouse was not going to yield sufficient usable data. Following extensive investigation by FirstLight and the equipment manufacturer it was determined that relocating the HYDROs to the banks of the Project tailrace would allow for representative measurements to be recorded during pumping and generating cycles without the difficulties encountered in the powerhouse.

Starting in 2013, the HYDRO instruments were relocated to the left (HYDRO South) and right (HYDRO North) banks of the Project tailrace where they remained in place through 2015. These locations allowed for representative measurements to be recorded during both pumping and generating cycles. During pumping, the water within the tailrace may contain sediment that is pulled into the system from the Connecticut River through the intake while during generation, the water that is being discharged from the Upper Reservoir back to the river may similarly contain sediment. Due to the fact that suspended sediment may vary laterally across the tailrace and/or vertically within the water column depending on Project operations two HYDROs were utilized at the tailrace. By installing HYDROs on either bank of the tailrace, combined with cross-sectional data collected by the LISST-100X, a representative dataset was developed. Figure 2.2.1-3 shows a typical cabinet setup used to house the LISST HYDRO instruments while Figure 2.2.1-4 depicts their locations at the tailrace.

HYDRO instruments, and their associated equipment, were installed annually (2013-2015) by April 1 (or as soon as flow conditions allowed) and remained in place until mid to late November when they were removed for the season. Each HYDRO instrument was connected to a pump installed at a representative location within the tailrace. The HYDRO North and South pumps was installed approximately 50 ft. from each shore (far enough offshore so as to be in the intake channel) and approximately 2 ft. off the bed.

Total concentration (µl/L) and PSD (microns) were measured at each location using laser diffraction technology at 20-minute intervals. After flowing through the instrument, the river water was released through a drain hose. A water sample was not retained except for periodic grab samples that were collected. Clean-water background readings were taken from filtered potable water and stored prior to each sample to automatically "zero" the instrument by subtracting the measurement of light scattering in clean water from that resulting from the turbid sample water. The instruments operated on a 30-second clean water flush, a 300-second pre flush, a 30-second clean water flush and automatic optical lens cleaning.[6]

The instruments were visually inspected and cleaned on a weekly basis to ensure proper working order and clean optic cells. Data downloads from the instruments were not necessary because each HYDRO

[6] These settings represent the final data settings used during the 2014 and 2015 field seasons. The final instrument settings were refined during the 2013 field seasons and determined in collaboration with the equipment manufacturer.

instrument transmitted the data directly to FirstLight's historian computer system. Data was downloaded from the historian computer system on a weekly basis.

Similar to the StreamSide, HYDRO data collection efforts from 2012-2015 were affected by repeated equipment malfunctions and electrical issues which resulted in data gaps. No useable data were collected in 2012 when the instruments were located inside the powerhouse. As such, data analysis and results presented in this report focus on the 2013-2015 period. After relocating the HYDRO instruments to the tailrace in 2013 FirstLight requested the manufacturer visit the site during the field season to review and certify the instrument setup (Appendix B).

In spite of the equipment manufacturers' certification that the instruments were installed properly, equipment malfunctions and electrical issues continued to affect data collection efforts during the 2013, 2014, and 2015 field seasons resulting in sporadic data gaps. FirstLight continued to work closely with the equipment manufacturer, however, instrument issues continued to persist. Following a major equipment malfunction in early 2015 which resulted in the instrument being taken offline, shipped to the manufacturer, and rebuilt, and following consultation with USEPA, FirstLight curtailed continuous suspended sediment monitoring at the HYDRO locations.

Discussion pertaining to the HYDRO data analysis and results can be found in Section 3.2 and 4.2, respectively.

LISST-100X

Cross-sectional data at the Rt. 10 Bridge and the Northfield Mountain tailrace boat barrier buoy line were collected via a LISST-100X in 2013 over a range of flow and operating conditions. The cross-sectional data were collected for a variety of reasons, including: (1) to determine total concentration and PSD variation across the cross-section over a range of flow and operating conditions; (2) to determine if the StreamSide and HYDRO pumps were installed at locations representative of the cross-section; and (3) as a check on the data collected at the StreamSide and HYDROs.

Data were collected using a crane and reel setup from the Rt. 10 Bridge and from a barge at the Northfield Mountain tailrace. Figure 2.2.1-5 shows the configuration of the barge at the tailrace while Figure 2.2.1-6 shows the configuration of the LISST-100X. As observed in Figure 2.2.1-6, a sounding weight with fins was attached to the LISST-100X to orient the instrument against the current and hold it in a constant position. Sampling stations were identified at evenly spaced intervals using the Equal-Width Increment Method (EWI) along transects at each location prior to sampling. Eleven (11) stations, spaced at 50-foot intervals, and 9 stations, at ~30-foot intervals, were identified at the Rt. 10 Bridge and the Northfield Mountain tailrace boat barrier buoy line, respectively (Figures 2.2.1-1 and 2.2.1-4). Total concentration (µl/L) and PSD (microns) measurements were collected via laser diffraction technology at the surface and 5-foot depth intervals at each increment until approximately one foot from the bottom was reached. At each station, the instrument was held in place for a minimum of 60 seconds with a measurement being recorded every second. Clean-water backgrounds were collected using distilled water before and after sampling at each transect to "zero" the instrument. Following completion of a transect, the data were downloaded to a computer. The instrument did not require maintenance except for regular cleaning of the optical lenses.

Over the course of the study it was observed that each LISST instrument (StreamSide, HYDRO North, HYDRO South, and LISST-100X) was unique, given that each contained its own unique lenses for measuring laser scatter. As a result of this, preliminary analyses revealed different total concentration measurements between the LISST-100X and the other LISST instruments. After discussion with the manufacturer, it was determined that the values provided by the LISST-100X were not directly comparable to the other LISST instruments due to limitations in instrument capability. Essentially, each instrument could measure particles from the same water and provide a different value. The only way to standardize the data would be to convert the LISST measurements to mg/L using grab sample data. This conversion was not performed for the LISST-100X due to the fact that too few laboratory samples were collected that corresponded to the cross-sectional sampling effort. Although the LISST instruments were not directly comparable, general patterns observed at each instrument were comparable. Therefore, the LISST-100X data were only used to describe general cross-sectional patterns rather than quantitative comparison against the other LISST instruments.

Discussion of the LISST-100X data analysis and results can be found in Section 3.2 and 4.2, respectively.

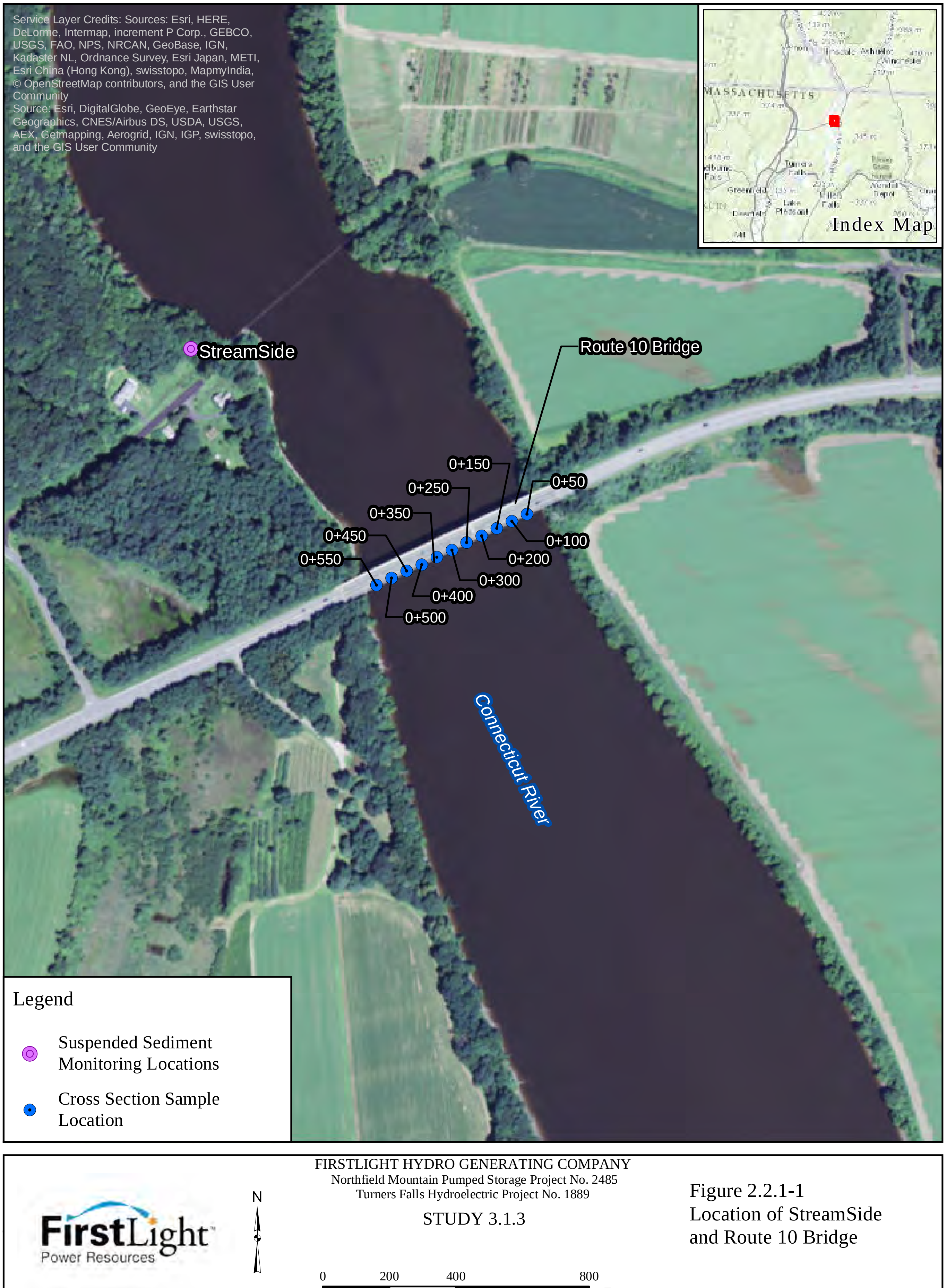

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Figure 2.2.1-1
Location of StreamSide and Route 10 Bridge

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Figure 2.2.1-2 LISST StreamSide Equipment Cabinet Configuration

Figure 2.2.1-3 LISST-HYDRO Cabinet Configuration (typical)

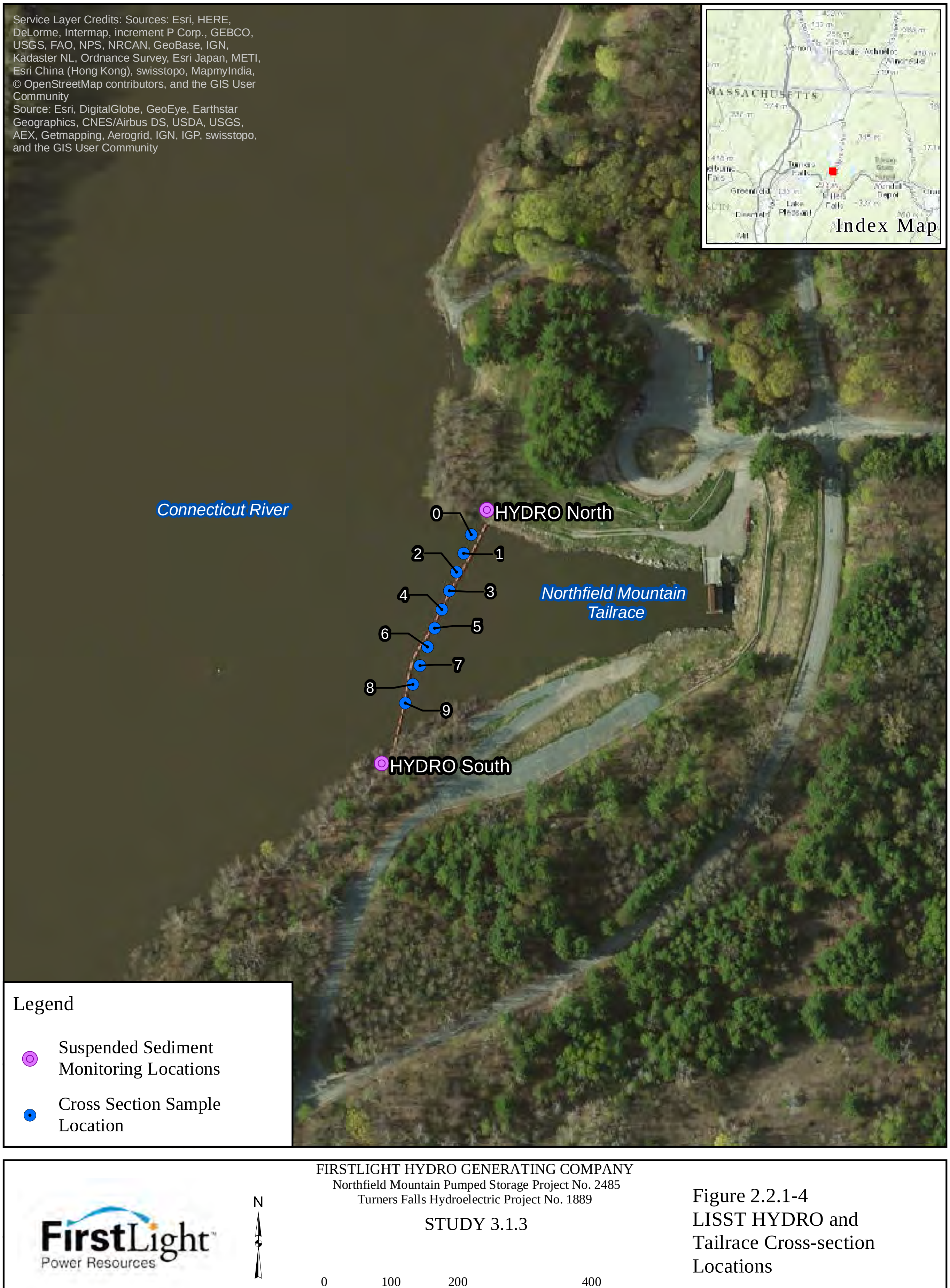

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Figure 2.2.1-4
LISST HYDRO and Tailrace Cross-section Locations

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Figure 2.2.1-5 LISST-100X Collection from barge at the Northfield Mountain Tailrace

Figure 2.2.1-6 LISST-100X Configuration

2.2.2 Grab Sample Collection

In the original *Sediment Management Plan* filed July 15, 2011, FirstLight proposed a four-year sediment monitoring study in which turbidity and TSS data were to be collected quarterly and during targeted periods of high flow in various locations throughout the Turners Falls Impoundment (TFI) and the Northfield Mountain Upper Reservoir. TSS and turbidity grab samples were collected on two occasions during 2011 in accordance with the original plan.

Based on the data collected in 2011, and in order to accomplish the study goals, FirstLight proposed changing the data collection methods and protocols to rely on the LISST continuous suspended sediment monitors in place of periodic grab samples starting in 2012. These proposed modifications were discussed in the *Updated Sediment Management Plan* and *QAPP Revision 1*. At the request of the USEPA, periodic grab samples continued to be collected during the 2012-2015 monitoring periods to supplement the continuous suspended sediment data. From 2012-2014 grab samples were collected periodically over a range of flow and operating conditions from the StreamSide and HYDRO drain hoses. The grab sample program was expanded in 2015 to include LISST drain hose samples, edge-of-water samples collected in the vicinity of the LISST pumps, and cross-section samples collected at the Rt. 10 Bridge and Northfield Mountain tailrace boat barrier (if safely possible). Data collected as part of the expanded 2015 grab sampling program includes:

- Daily grab samples were collected from the LISST drain hoses (StreamSide and HYDROs) from April 7, 2015 until the continuous suspended sediment monitoring portion of the program was discontinued in June. Drain hose grab samples were collected at the same time as a LISST measurement, when possible. Samples were not collected when the instrument was offline due to various equipment malfunctions.

- Daily grab samples were collected from the edge-of-water in the vicinity of the LISST pumps (StreamSide and HYDROs) starting April 7, 2015 until October 30, 2015 at which time the program was discontinued.

- Cross-section grab samples were collected via a Kemmerer at predetermined stations (equal-width, 50 foot interval) across the Rt. 10 Bridge on four occasions over a range of flows during the spring freshet (20,000-60,000 cfs). Cross-section stations used in 2015 were identical to the stations used in 2013 for the LISST-100X data collection effort. Samples were collected following the EWI method at three depth increments at each station (~1 ft. below the surface, middle of the water column, and ~2 ft. from the bed). Each individual sample was submitted to an independent analytical laboratory for analysis. Figure 2.2.2-1 shows the configuration of the Kemmerer used to collect the samples. One cross-section composite was also collected and submitted to the laboratory for analysis.

- FirstLight intended to collect grab samples across the Northfield Mountain tailrace during the spring freshet; however, flow and operating conditions deemed this effort to be unsafe. As such, 2015 cross-section data were not collected at this location.

Figure 2.2.2-2 shows the grab sampling locations. All grab samples collected during this study were submitted to an independent analytical laboratory for analysis of TSS (SM 2540D) and SSC (ASTM D3977).

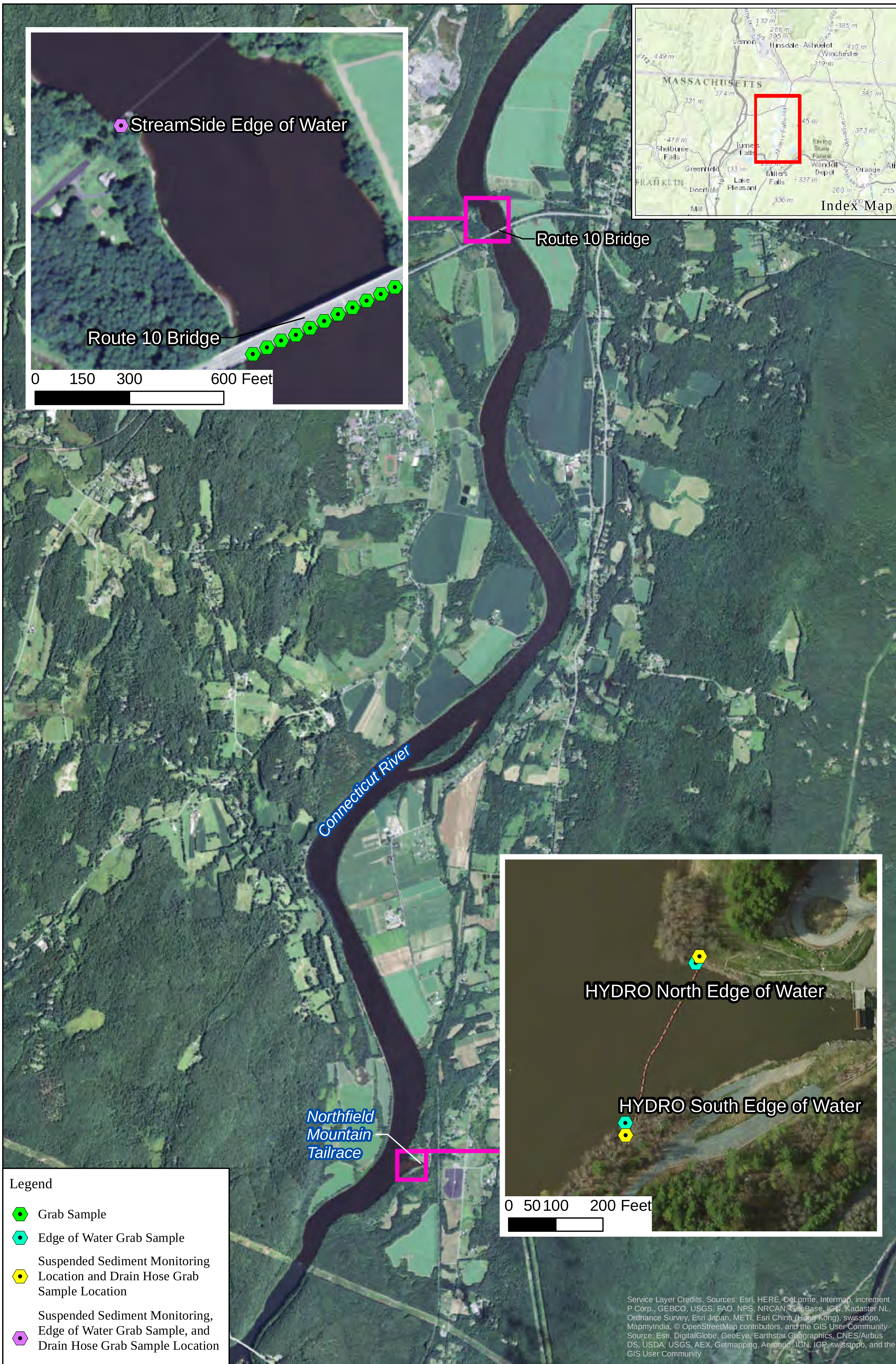
Although not directly comparable with the LISST measurements[7], the grab sample data serve two important purposes, (1) to develop a quantitative dataset over a range of flow and operating conditions to complement

[7] Total concentration (TC) measurements collected by the LISST instruments are in units of µl/L (volume) while the SSC grab sample results are in units of mg/L (mass). These datasets cannot be compared unless the LISST data is converted to mg/L.

or supplement the LISST data, and (2) to develop a correlation between the LISST data and grab sample data to either confirm or adjust the LISST data.

Discussion pertaining to the grab sample data analysis and results can be found in Section 3.2 and 4.2, respectively.

Figure 2.2.2-1 Configuration of Rt.10 Bridge Grab Sample Collection



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N

0 0.25 0.5 1 Miles

Figure 2.2.2-2
Grab Sampling Locations

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2.3 Modeling

In 2013, Study No. 3.1.3 was expanded to include several modeling efforts to better understand suspended sediment dynamics in the study area and to determine how operational or structural modifications could affect the entrainment of sediment in Project works and the Connecticut River. Specific modeling components developed as part of this study included a Computational Hydrodynamic Sedimentation model of the Upper Reservoir (Section 2.3.1), a CFD sedimentation model of the tailrace and surrounding areas (Section 2.3.2), and a physical model of the tailrace and surrounding areas (Section 2.3.3). At this time, all modeling efforts have been completed and the results have been reviewed and analyzed. The results from these analyses, combined with the other components of this study, were taken into consideration when developing the proposed sediment management measures found in Section 5. Background information pertaining to each modeling effort is found in the sections below while results are discussed in Section 4.3.

2.3.1 Computational Hydrodynamic Sedimentation Modeling of the Upper Reservoir

In late 2013, FirstLight contracted with Alden Research Laboratory, Inc. (Alden) to study suspended sediment dynamics in the Upper Reservoir. As part of this effort, Alden developed a 2-dimensional (2-D) Computational Hydrodynamic Sedimentation model to understand the process of sedimentation in the Upper Reservoir and to evaluate long-term sediment management alternatives in that area. The model Alden used was the commercially available MIKE21C (DHI) 2-D numeric model. The modeling effort had two main objectives:

1. Determine the root cause of sedimentation in the Upper Reservoir; and

2. Investigate methods for decreasing sedimentation in the Upper Reservoir. Options considered for minimizing sediment accumulation by increasing the transport of sediment from the Upper Reservoir during generating phases included: (a) operational changes – lower minimum water surface in the Upper Reservoir during generation phases, and (b) a structural modification intended to manipulate Upper Reservoir currents and increase flow velocity (and sediment entrainment) in the intake channel during generating phases.

Model runs were executed using: (1) the current FERC operational drawdown limit of the Upper Reservoir of 938 feet (mean sea level (msl))[8] (Case 1); (2) lowering the Upper Reservoir drawdown to 928 ft. msl (Case 2); (3) lowering the Upper Reservoir drawdown to 920 feet msl (Case 3); and (4) physically reducing the intake channel width (Case 4).The May 2014 Alden report describing the modeling was submitted on December 1, 2014 as part of the *Sediment Management Plan – 2014 Summary of Annual Monitoring*. The model was field validated using an Acoustic Doppler Current Profiler (ADCP) to document flow field patterns induced in the Upper Reservoir during both pumping and generating operating conditions. The field collected data were then compared to the model output. The results of this modeling effort are discussed in Section 4.3.

2.3.2 Computational Fluid Dynamics Sediment Modeling of the Northfield Mountain Project Intake/Tailrace

In 2014, FirstLight again contracted with Alden to study the suspended sediment dynamics in the Northfield Mountain intake/tailrace area. The tailrace modeling effort focused on the entrained sand and fine material from the Connecticut River which is transported to the Upper Reservoir during operational pumping phases as well as potential solutions in the tailrace to reduce sediment transport to the Upper Reservoir. The ultimate objective of this modeling effort was to determine if physical modifications to the Northfield

[8] NGVD29 is commonly referred to as mean sea level. For the purpose of this report those two datum's should be considered identical.

Mountain tailrace intake/tailwater area could reduce sediment entrained to the Upper Reservoir during pumping operations and hence reduce sediment accumulation in the Upper Reservoir.

To accomplish the modeling objectives, Alden developed a 3-Dimensional (3-D) Computational Fluid Dynamics (CFD) model of the Northfield Mountain tailrace and surrounding area (500 feet upstream and downstream from the tailrace). The 3-D model was developed, validated, and used to simulate sediment mobilization under a range of Connecticut River discharges, TFI water levels, and operational pumping schemes (1, 2, 3, or 4 pumps moving water to the Upper Reservoir). A series of three CFD sediment simulations were used to compute sediment uptake under the existing configuration and to quantify the effectiveness of a convex sediment exclusion structure (Alternative 1) and a longer concave sediment exclusion structure (Alternative 2) both of which were positioned outside the exclusion zone. Figures 2.3.2-1 and 2.3.2-2 denote the location of the modeled sediment exclusion structures 1 and 2, respectively.

The results of this modeling effort are discussed in Section 4.3 and detailed in the September 2016 Alden report titled *Engineering Studies of Sediment Uptake at the Northfield Mountain Connecticut River Intake/Tailwater*. The September 2016 Alden report is included in Appendix C.

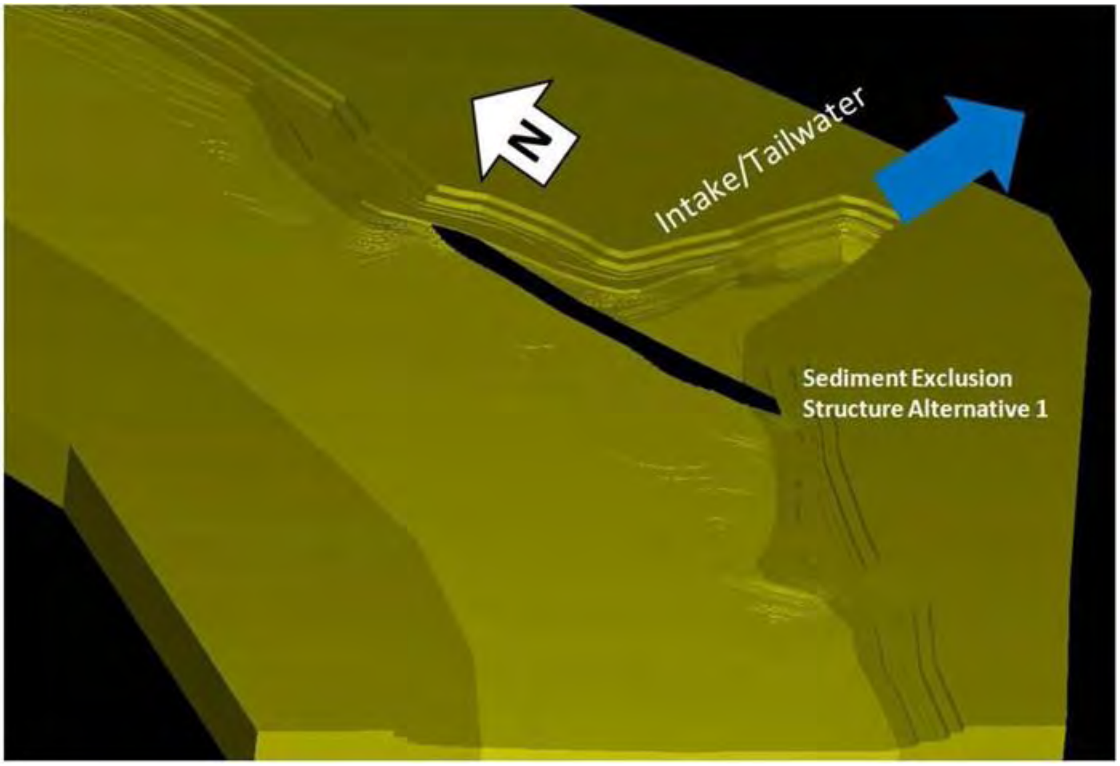

Figure 2.3.2-1 Tailrace/intake CFD Model – Sediment Exclusion Alternative 1

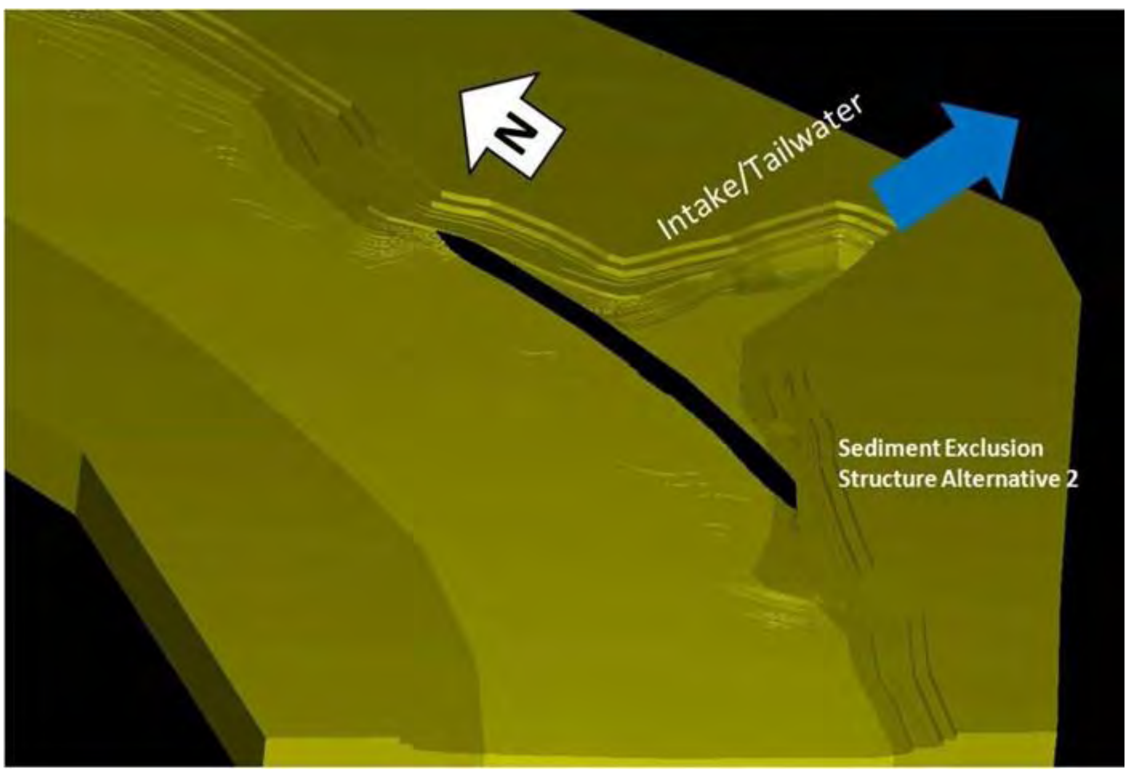

Figure 2.3.2-2 Tailrace/intake CFD Model – Sediment Exclusion Alternative 2

2.3.3 Physical Model of the Project Area

In 2015, FirstLight expanded the modeling component of Study No. 3.1.3 to include the development of a physical model of the Northfield Mountain tailrace/intake and Connecticut River in the vicinity of the tailrace. The purpose of the physical model was to reproduce the river conditions (flows, currents, sediment load) in the study area and to investigate new civil works that could be constructed at the existing Project tailrace/intake structure.[9] The goal of this modeling effort would be to help determine if changes to the intake structure would be significantly reduce the intake of sediment during the pump cycle at the Project. FirstLight again contracted with Alden for this effort. All modeling activities were completed during the summer of 2016. The final report for this modeling effort is included in Appendix C.

Tasks associated with this modeling effort included: (1) the collection of relevant data and information (including topographical, hydraulic, operational, and sediment data); (2) the construction and calibration of the physical model based on existing conditions; (3) the modeling and testing of the new intake structure; and (4) reporting. The model allowed for:

1. The ability to reproduce steady state water surface profiles (calibration process with no operation);
2. The ability to reproduce sediment transport through the intake during pump operations; and
3. The investigation of the effect of changes in the intake structure on sediment transport.

The physical model represents the Northfield Mountain tailrace/intake area as well as the Connecticut River in the vicinity of the tailrace. Specifically, the physical boundary conditions of the model were:

- Upstream section approximately 3.2 km from the intake following the river centerline;
- Downstream section approximately 0.8 km from the intake following the river centerline;
- Approximate total river length of 4.0 km following the river centerline, which corresponds to an approximate North-South length of 3.7 km and East-West length of 1.2 km; and
- The Northfield Mountain tailrace and intake structure

Figure 2.3.3-1 depicts the extent of the physical model.

Prior to the development of the model FirstLight provided Alden with multiple datasets to support the modeling effort. These datasets included: bathymetric data for the TFI (including the Northfield Mountain tailrace), tailrace/intake drawings, flow and water elevation data, Project operations data, and suspended sediment data collected throughout the TFI. In addition to the data provided by FirstLight, Alden collected supplemental data in 2015 including: (1) the installation of a water level logger on the east bank near the intake, (2) additional bathymetry at the tailrace/intake, (3) collection of water samples for analysis of suspended sediment in the river, and (4) collection of bed material samples in the Upper Reservoir and the river at predetermined locations. Figure 2.3.3-2 depicts the locations where supplemental field data were collected.

The physical model was used to compare sediment intake associated with any modeled intake structural modifications to the existing intake structure. The modeled change to the existing intake structure consisted of a deviation/deflection structure upstream of the existing intake structure to mobilize the river secondary currents and divert the sediment away from the intake structure. Figure 2.3.3-3 shows the general layout of

[9] Intake structure modifications referred to herein were designed and constructed for the physical model only. As indicated in Section 5, and based on the work in this and other studies, FirstLight is not proposing physical modifications as a measure to minimize the entrainment of sediment in the Project works and Connecticut River.

the deflection structure. The modeled structure was designed to allow free overflow toward the existing intake with a weir level set at an elevation where most of the coarse sediments are not present (lower depths). Figures 2.3.3-4 and 2.3.3-5 depict the physical model. The results from this modeling effort are discussed in Section 4.3.

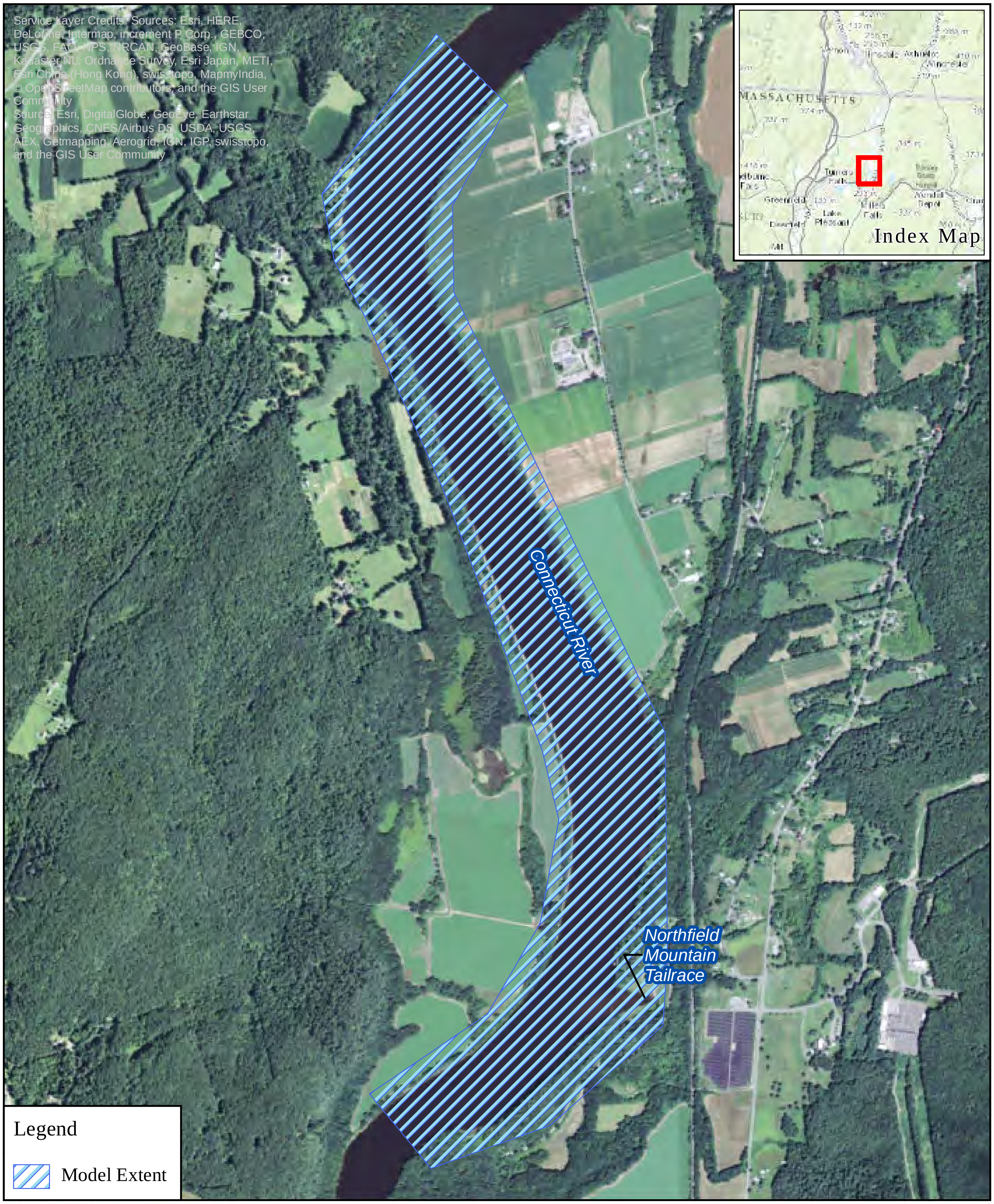

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Figure 2.3.3-1
Extent of Physical Model

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N

0 750 1,500 3,000 Feet

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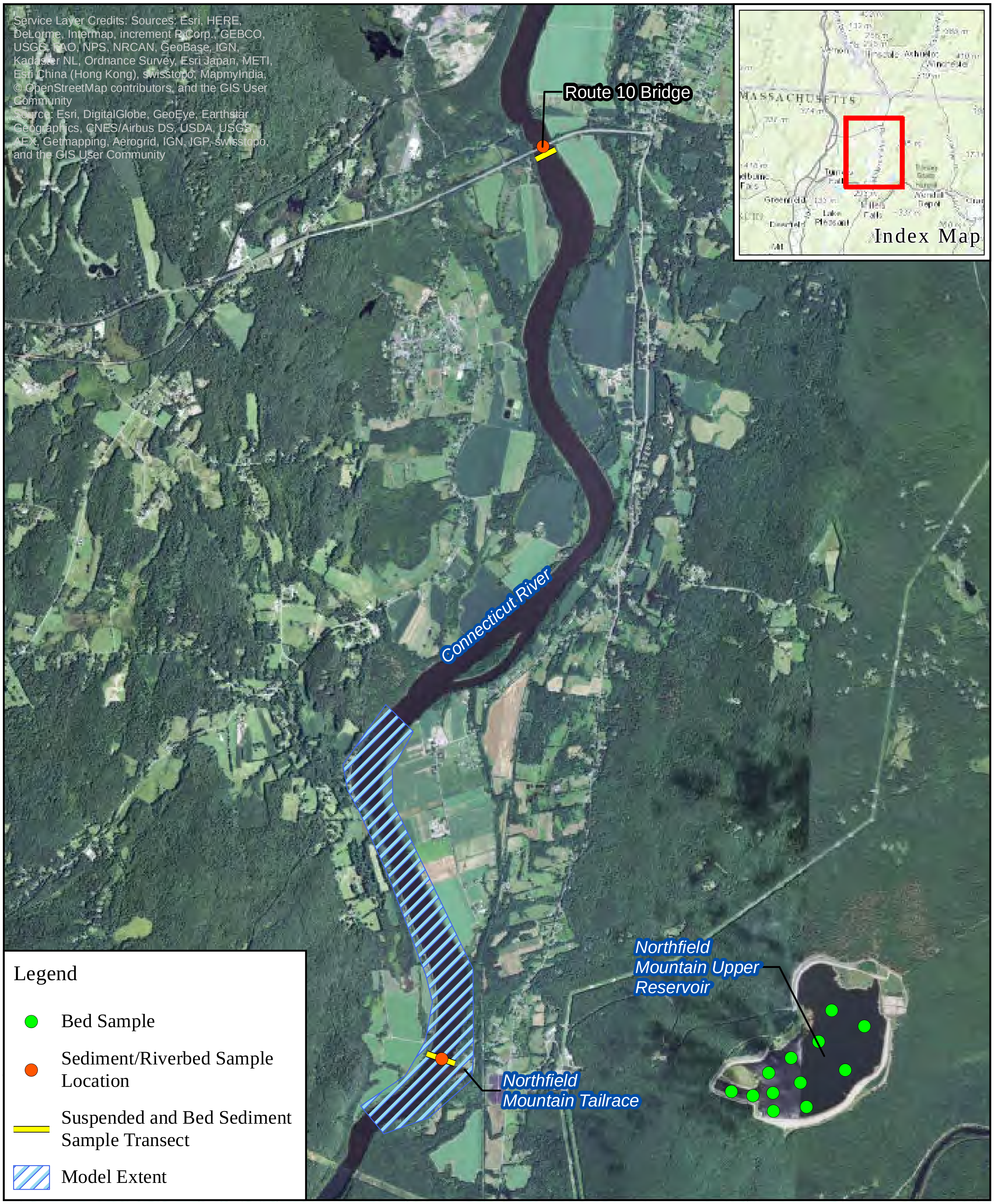

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FirstLight Power Resources

N

0 0.375 0.75 1.5 Miles

Figure 2.3.3-2
Location of Supplemental Data Collection Efforts Related to the Physical Model

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Figure 2.3.3-3
Approximate Location of Physical Model Structure

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Figure 2.3.3-4 Physical Model of Turners Falls Impoundment - Northfield Tailrace Area

Figure 2.3.3-5 Physical Model of Northfield Tailrace Area- Bend in River is at the Tailrace

2.4 Upper Reservoir Pilot Dredge

As part of FirstLight's assessment of sediment management techniques for the Project, Dredge America, Inc. was retained to assess and perform limited dredging of the Upper Reservoir in April 2015. Physical activities associated with the pilot dredge were completed in early November 2015. The pilot dredge was conducted to assess whether deep water hydraulic dredging is a viable option for removing excess accumulated sediment in the Upper Reservoir. The periodic removal of excess accumulated sediment could reduce the entrainment of accumulated silt into the Project works and the Connecticut River at harmful levels during drawdown or dewatering activities. Use of marine deep water hydraulic dredging is not proven in pumped storage facilities, which is why FirstLight conducted a pilot or a test dredge.

One of the potential advantages of deep water hydraulic dredging appears to be that it can occur while the Project is available for generation or pumping allowing for removal of sediments without the need for the Project to be offline. In contrast, other mechanical means of sediment removal may require dewatering of the Upper Reservoir and would likely require an extended outage. The technology employed by Dredge America also inherently avoids disturbance of sediments outside the small area undergoing active dredging. Pilot dredge program activities occurred within and immediately upstream of the intake channel. Figure 2.4-1 depicts the approximate location of the dredging activities.

The pilot dredging project consisted of a boat-mounted deep water dredge as the main platform. The unit utilized a special Ellicot 370 horsepower dredge. Approximately 80 feet of additional flotation was added to the front of the dredge in order to extend the ladder line to a maximum depth of 120 feet. This depth of dredging required an underwater pump to lift the slurry off the bottom of the reservoir. The power unit was set on a second dredge platform positioned next to the main dredge. Figure 2.4-2 depicts the dredge setup.

The hybrid dredge setup ran from a static cable spanning the Upper Reservoir and anchored on opposing shores. The dredge rode along the cable and slowly suctioned an area approximately 8 feet wide per pass. The dredge made passes back and forth across the limited dredging area similar to a lawn mower cutting the grass within a large field. The depth of the suction was limited to approximately 3 feet so that the sediment on the reservoir bottom remained stable.

The dredged slurry mixture was incorporated with a polymer additive while being pumped into the Geotube dewatering system, which was located adjacent to the Upper Reservoir. Sediments from the sediment-water mixture were substantially captured in the Geotubes, with the filtered effluent flowing back into the Upper Reservoir at a controlled flow rate. Figure 2.4-3 shows the Geotube dewatering system.

The results of the pilot dredge are discussed in Section 4.3.

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Figure 2.4-1
Location of Upper Reservoir
Pilot Dredging Activities

Legend

- Approximate Limit of Dredging Operations
- Staging Area
- Temporary Sediment Basin - 10 ft Deep

N

Service Layer Credits: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community
Content may not reflect National Geographic's current map policy.

0 100 200 400 Feet

1 inch = 200 feet

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Figure 2.4-2 Dredge Equipment Setup

Figure 2.4-3 Geotube Dewatering System

3 BATHYMETRIC AND SUSPENDED SEDIMENT DATA ANALYSES

This section provides a detailed discussion of the data analysis methods used for the annual Upper Reservoir bathymetry surveys and the suspended sediment monitoring efforts discussed in Section 2. Section 3.1 discusses the data analysis methods associated with the Upper Reservoir Bathymetry Surveys. These methods typically included the creation of Triangular Irregular Networks (TINs) and cut/fill calculations to estimate the total sediment volume flux within the reservoir. Section 3.2 discusses the data analysis methods associated with suspended sediment monitoring efforts, including data collected at the StreamSide, HYDROs, LISST-100X, and grab samples. Data analysis protocols typically followed three steps: (1) Quality Assurance (QA)/Quality Control (QC) of all data; (2) conversion of the LISST volume concentration (µl/L) to mass concentration (mg/L) using available grab sample data; and (3) analysis of results.

3.1 Upper Reservoir Bathymetry Surveys

As noted in Section 2.1, Upper Reservoir bathymetry surveys have been conducted annually since 2011 as part of this study. The 2011 and 2012 surveys were conducted by Ocean and Coastal Consultants Inc. (Ocean & Coastal) with SeaVision Underwater Solutions (SeaVision). In 2013 the survey was conducted by CHA Consulting, Inc. (CHA). The 2014 and 2015 surveys were conducted by SeaVision. This section provides an overview of the data analysis methods employed for each year's survey. The ultimate goal of the data analysis was to compare the current year's survey with the previous year's survey to estimate the total sediment volume flux within the reservoir.

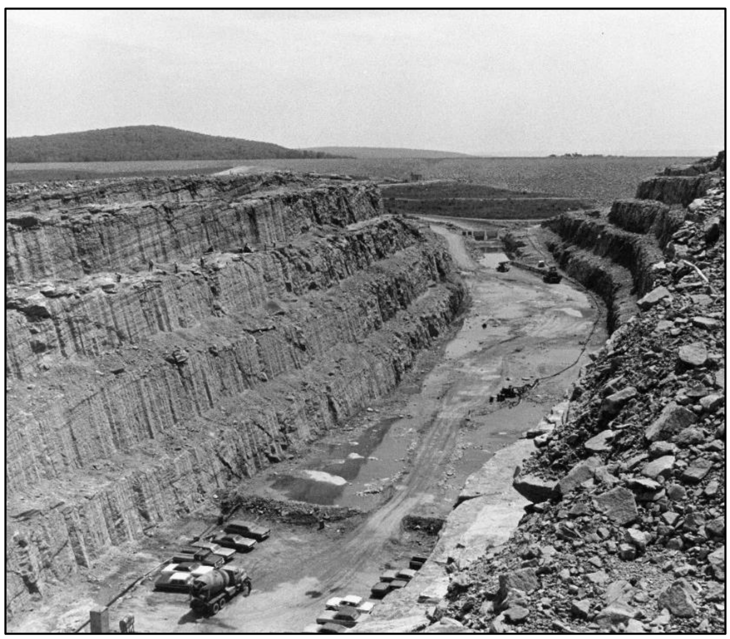
In 2011 and 2012, once all field collected data had been post processed, Ocean & Coastal and SeaVision conducted a QA/QC review of the dataset. The final QA'd data was then uploaded to a Geographic Information System (GIS) database which was used to organize and analyze the data. Once in GIS, the survey data was used to generate a contour plan of the reservoir from which a TIN was created. Cut/fill calculations were then performed by comparing the TIN created for that year's survey with the TIN(s) from the previous year(s). Differences observed between the current TIN with the past year(s) TIN(s) indicated where sediment deposition or erosion had occurred. In addition, the results of the cut/fill calculations provided net sediment accumulation or loss quantities from year to year.

In 2013, 2014, and 2015, all post processing of the hydrographic survey data was performed using the HYPACK software package. In 2013, CHA downloaded the data to an office desktop computer with the raw unedited data backed up for archival purposes. Latency test computations were performed to determine latency factors for the hydrographic survey system. Velocity corrections were made to the data from the velocity profiles observed during the field surveys. Each survey line was edited for spurious depth readings such as drop outs and spikes. All positioning data and water level corrections were reviewed for consistency. Any check lines run were compared with the sounding lines at their cross over points. Once the hydrographic data was edited, the data was sorted at a spacing of 5 ft. and 10 ft. and exported to ASCII data files for further processing.

Volume calculations were performed to assess the amount of material deposited or eroded throughout the intake channel and entire Upper Reservoir since the 2012 survey performed by Ocean & Coastal and SeaVision. The computational process involved the following steps: (1) a 2013 existing conditions TIN was created based on the hydrographic survey performed by CHA during the planned outage on October 5 and 6, 2013; (2) a 2012 existing conditions TIN was created based on the 2012 multi-beam hydrographic survey data provided by SeaVision; (3) multi-beam data was then sampled from the 2012 TIN along the sounding lines observed during 2013 survey; (4) a TIN was then created based on the sampled data and was used for volume calculations; and 5) the 2012 and 2013 TIN's were compared and volume surface was generated using Autodesk AutoCAD Land Desktop 2009.

In 2014 and 2015, SeaVision processed the multi-beam bathymetric survey data following a four phase process. In the first phase, position, orientation, water level, and sound velocity profiles for all survey lines were loaded and reviewed for errors. In the second phase, individual survey files were reviewed in a series of sweeps (usually 50 to 200 at a time) in order to review the swath data and identify any noise, spurious points, or erroneous soundings that may exist in the data. Manual editing of stray data points, and some automatic filters that search for and remove erroneous data, were then performed on all data. In the third phase of processing, all data was delivered into a matrix and reviewed as "area-based" such that cross-sections throughout the entire survey area were reviewed simultaneously. This allowed for the review of overlaps between adjacent survey lines and to confirm that the data at the overlaps was consistent (thus building in a quality assurance step to the processing phase). At the end of the third phase of processing, the data was binned for export to a grid. In the case of this work, the data grid was generated based on 3-feet by 3-feet spacing such that the sounding assigned to each grid cell represented the average of all soundings collected inside of that cell. In the final phase of processing, the ASCII XYZ grid file (with cells sized at 3-feet by 3-feet) was subjected to a TIN surface algorithm to generate color-shaded relief imagery and contours. Additionally, the TIN network was used in order to generate decimated grids with soundings spaced at 10-feet, 25-feet, and 50-feet.

Volume calculations were then performed to assess the amount of material deposited or eroded throughout the Upper Reservoir intake channel since the 2012 survey. To define the intake channel, the original as-built drawings of the facility were referenced to define the base of the channel. It is believed that this is the most appropriate means of assessing the sediment volume behavior in the intake channel while reducing the impacts that the sheer, bounding, sidewalls (i.e., the cut rock wall faces on the north and south sides of the intake channel- see inset during original construction) can have on the survey data and thus the volume calculations. Using HYPACK, TINs were generated for the 2012-2015 surveys for comparison of surface changes to calculate volumes and to estimate the change in elevation between each surface model.



In addition to the multi-beam surveys conducted in 2014 and 2015, gravity cores (2014) and vibracores (2015) were utilized at six locations within the Upper Reservoir intake channel to better ascertain the sediment thickness in this area. The 2015 cores were not collected at the same exact locations as the 2014 cores, however, they were in the same general vicinity which allowed for indirect comparisons of sediment thickness between years. For both the gravity core and vibracore collection a similar methodology was employed. A four or six foot rigid plastic barrel was lowered to the bottom of the intake channel at each location at which time the sampling unit was deployed from the survey vessel. The rigid plastic barrel was pre-marked with black electrical tape at the 2 ft. elevation mark so that once the sampler had been lowered to the reservoir bottom and driven into the sediments a Remotely Operated Vehicle (ROV) could be deployed to identify the degree of penetration into the bottom sediments. Figure 3.1-1 depicts still video grabs showing gravity core collection at two locations in the intake channel.

Table 2.1-1 shows that the 2011 and 2013 Upper Reservoir bathymetry surveys were conducted using a single beam echosounder while the 2012, 2014, and 2015 surveys were collected using a multi-beam unit.

For the purpose of this report, and to get an approximate estimate of annual deposition or erosion rates, special emphasis was placed on the results of the 2012 survey as compared with the 2014 survey given that each of the surveys conducted during those years utilized a multi-beam echosounder. The results of the 2012 to 2014 comparison were further bolstered by the use of the gravity core data collected in the intake channel. Changes in bed elevation were also analyzed comparing 2014 to 2015; however, due to the removal of ~46,000 CY of sediment during the pilot dredge the 2014 to 2015 analysis could not be used to determine annual deposition or erosion rates in the vicinity of the intake channel. Further discussion pertaining to the 2014 bathymetry analyses is discussed in Section 4.1.

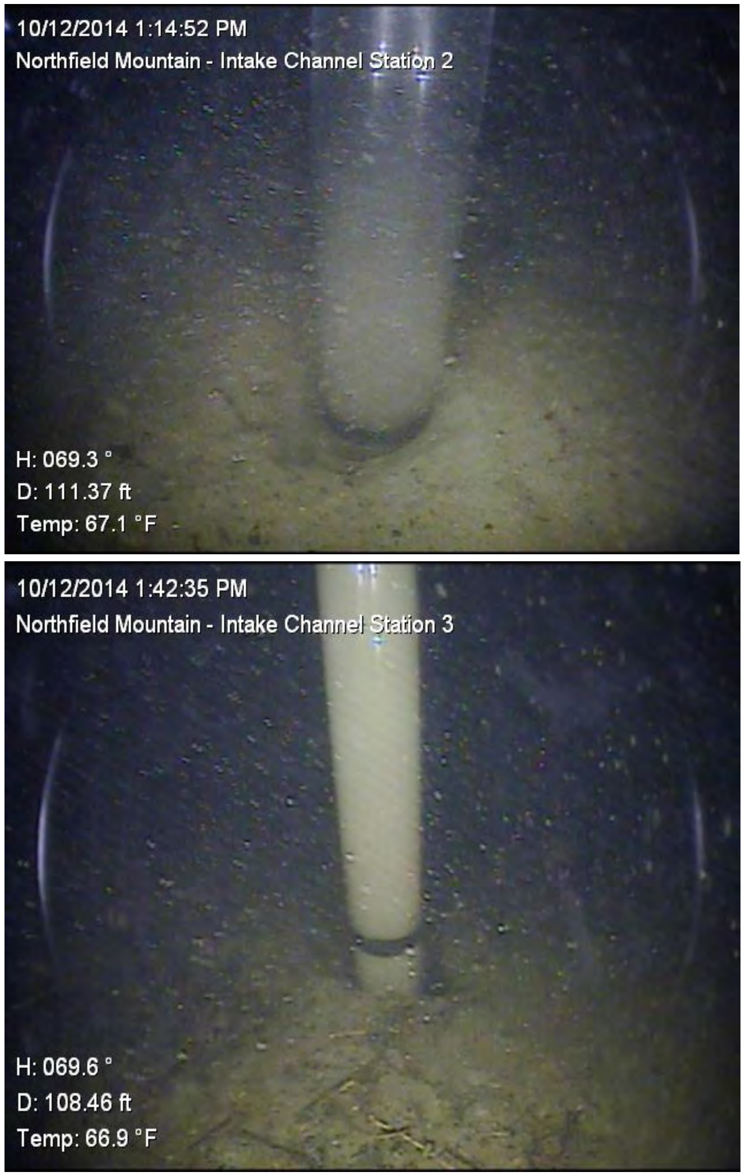


Figure 3.1-1 2014 Upper Reservoir Intake Channel Gravity Core Collection (2014)

3.2 Suspended Sediment Monitoring

As previously discussed, the suspended sediment monitoring component of this program consisted of three main tasks: (1) continuous monitoring of suspended sediment at three locations within the Turners Falls Impoundment (2013-2015); (2) cross-sectional data collection from the Rt. 10 Bridge and Northfield Mountain tailrace boat barrier buoy line via the LISST-100X (2013) and grab sample collection (2015); and (3) grab sample collection at the StreamSide, HYDRO North, and HYDRO South locations over a range of flows and operating conditions (2013-2015). Once all data were collected, or laboratory results received, FirstLight conducted a thorough QA/QC review of all data. Data that did not pass the QA/QC measures were flagged or removed from the dataset. The final grab sample dataset was then used to convert the LISST data (StreamSide and HYDROs) from volume concentration (µl/L) to mass concentration (mg/L) in order to be directly comparable. Various data analyses were then conducted on the final, converted datasets in order to better understand suspended sediment dynamics throughout the study area over a range of flow and operating conditions.

This section provides a detailed discussion of the QA/QC protocols followed for the LISST and grab sample data (Section 3.2.1), the protocols followed for the conversion of volume concentration (µl/L) to mass concentration (mg/L) (Section 3.2.2), and the analyses which were then conducted on the final dataset (Section 3.2.3).

3.2.1 QA/QC of data

Once all field data were collected, or laboratory results were received, each dataset went through a thorough QA/QC process before being accepted as final. Data which passed the QA/QC protocols were considered final while the remaining data were flagged and excluded from analyses. QA/QC measures performed for each dataset are described below.

Continuous LISST Data

The StreamSide and HYDRO instruments measured total volume concentration (µl/L) and particle size distribution (microns) using laser diffraction technology. Data were downloaded from the StreamSide on a weekly basis in .CSV format. The .CSV files were then brought into Microsoft Excel where all post processing occurred. The HYDRO instruments were programmed to automatically transmit the collected data to the Project historian computer system which was programmed to record the data in Excel format. Data were reviewed in Excel on a weekly basis.

As previously described, over the course of this study (2012-2015) operational issues with the equipment were encountered which resulted in the exclusion of many measurements. Due to the challenges associated with using the continuous LISST equipment, FirstLight worked closely with the equipment manufacturer to ensure the data collected were correct and usable. Through this collaboration, the manufacturer performed QA/QC on the 2013 data and provided FirstLight with the specific QA/QC protocols to be followed when reviewing the 2014 and 2015 data. These protocols included:

1. **Review of the instrument Optical Transmission**: According to the manufacturer, the operational range of optical transmission for the LISST instruments is 0.3 to 0.98. Samples with optical transmission outside of this range were not included in analyses because resulting total concentration and mean size were likely inaccurate. The most common reason for data exclusion was high optical transmission (i.e. >0.98), which indicated that the water was too clear for the instrument to accurately measure sediment from that water sample.

2. **Review of the instrument battery voltage**: Insufficient battery power to the LISST instruments resulted in faulty data values. Samples with low battery voltage (<10 V) were not included in analyses.

3. **Review of the instrument clean water level**: The LISST instruments required occasional clean water measurements to "zero" the instrument and account for fouling on the lenses or scratches that may occur over time. If the clean water tank, which contained distilled water, was empty, adequate clean water backgrounds were not obtained. Data values taken when the clean water tank was determined to be empty were not included in analyses.

4. **Removal of the largest particle size bins due to the presence of "rising tails"[10]:** The manufacturer recommended excluding the largest size bins from the raw data due to the presence of rising tails.[11] This recommendation was based on the observed particle size distribution patterns found in the data. The values in the five largest bins were not likely attributed to the measurement of actual sediment particles, but instead resulted from laser scattering due to bubbles or thermal effects (i.e., scintillation). It was generally observed that the five largest bins were resulting in rising tails and erratic measurements. Total concentration and mean size were recalculated for all samples from the LISST instruments without including the top five particle size bins.

5. **Review of the dataset for duplicate samples**: For the LISST HYDRO instruments, data were initially stored on FirstLight's historian database, which would fill any data gaps with the last recorded measurement (e.g., if an equipment malfunction occurred and the instrument was not collecting data, the historian would automatically fill this gap with the last measured value). Given that these duplicates were not actually collected during the time given by the data historian, they were not included in the analyses.

6. **Review of the dataset for extreme outliers**: Occasionally, total concentration measurements were provided that were very high relative to previous and subsequent measurements, but were not flagged or excluded using the QA measures outlined above. The manufacturer suggested that these values be removed on a case-by-case basis and were likely due to an instrument issue (i.e., faulty clean water background). These measurements were relatively uncommon, typically few data points among many, and were not included in analyses if they were not within the realm of patterning observed in the dataset.

If erroneous data points were still observed, further investigation into these values via collaboration with the manufacturer occurred.[12] As an additional QA check, the final continuous LISST total concentration dataset was plotted against the grab sample dataset to determine if the general patterns observed were similar for each dataset (e.g., if the grab sample data showed a rise, peak, and fall one would expect the LISST data to show the same pattern).

LISST-100X Data

All LISST-100X data required post-processing and were derived using a spherical particle model, which assumes that particles within the sample that scattered light are all spheres. The manufacturer recommends a randomly-shaped model for most applications, unless comparisons with other laser diffraction instruments

[10] "Rising Tails" occur when there are an increasing number of occurrences on the ends of a sample distribution, indicating that the distribution may be multi-modal but that the entire distribution beyond the ends was not measured or apparent. From a particle size distribution perspective, it refers to higher values in the smallest or largest particle size bins. Given the indirect nature of the LISST measurements and the issues encountered (i.e., bubbles and scintillation), it was determined by the LISST manufacturer that the largest size bins should be removed from the dataset because the values in those bins were not the result of actual sediment particles.
[11] The LISST equipment measures the particle size and concentration in a number of logarithmically spaced size classes or bins. Each size class has a manufacturer defined lower and upper size limit. Often times rising tails can occur in the smallest or largest size classes or bins.
[12] Additional investigation beyond the steps listed often resulted in FirstLight sending the data to the manufacturer for its review.

could occur. Therefore, the spherical model was chosen over a randomly-shaped model because there was the potential to compare samples from the different LISST instruments.

Clean water backgrounds were recorded in advance of, and at the completion of, field data collection efforts. During post processing, the data were processed separately using the preliminary and final clean water backgrounds at which time the backgrounds were averaged to account for biological fouling and dirty lenses. Similar to the continuous LISST monitors, and at the recommendation of the equipment manufacturer, the largest size bins were removed from the dataset due to some minor rising tails and the data were recalculated. Operational issues encountered by the continuous LISST monitors were not typically encountered by the LISST-100X; however, the absence of laboratory grab sample data corresponding to the same water that the LISST-100X measured precluded the conversion of volume (µl/L) to mass concentration (mg/L). Therefore, the use of data from the LISST-100X has been restricted to cross-section patterns and general observations, rather than quantitative comparison to the other LISST instruments.[13]

Project Operations Data

FirstLight records flow information at the Vernon Hydroelectric Project (Vernon) and Northfield Mountain as well as information pertaining to Northfield Mountain Project operations (e.g., number of units pumping, number of units generating, flow associated with those operations, etc.). In order to fully understand the suspended sediment dynamics in the study area, suspended sediment data collected as part of this study were analyzed against FirstLight's flow and operations data. For the purpose of this report, flow data which were utilized in the mainstem analyses focused solely on Vernon discharge and did not take into account inflow from the Ashuelot River, unless specifically noted.[14]

Gomez and Sullivan obtained 15-minute Project operations and flow data from FirstLight's historian database over the course of this study. Upon receipt of the data, Gomez and Sullivan performed a thorough QA/QC on the dataset. Each parameter was plotted and quality assured through the removal of extreme outliers and values duplicated for extended periods.[15] Erroneous data that did not pass QA/QC measures were excluded from the dataset.

Grab Sample Data

Over the course of the study, grab samples were collected from the drain hoses of the LISST equipment (StreamSide and HYDROs) and/or from the edge-of-water in the vicinity of each instrument's pump. In 2015, grab samples were also collected at EWI stations across the Rt. 10 Bridge. All grab samples were submitted to an independent laboratory for analysis of SSC and TSS. The goal of the grab sample data was to collect instrument-independent measurements to complement and compare to the LISST data.

Upon receipt of the laboratory results, the dataset was manually quality-assured to identify samples with missing information. If information matches could not be made to chain of custody forms, field notes, or laboratory reports, the sample was removed. The dataset was also reviewed for any erroneous data or outliers. Few extreme outliers, possibly due to contaminated samples, were observed that were flagged and excluded from analyses.

[13] LISST-100X data was also not quantitatively comparable to the StreamSide or HYDRO instruments due to the indirect (laser scattering) nature of sampling and because each instrument measured scatter uniquely (i.e. different lenses).
[14] The Ashuelot River (drainage area ~420 mi^2) is a tributary to the TFI whose confluence is located downstream of Vernon.
[15] Duplication of data values was the result of data gaps being filled with the last measured value in the FirstLight historian database.

3.2.2 Conversion of Volume Concentration to Mass Concentration

StreamSide and HYDRO data collected from 2013-2015 were converted from volume concentration (µl/L) to mass concentration (mg/L) using conversion factors developed in 2015. Without conversion, LISST data would not have been quantitatively comparable among units due to the indirect (laser scattering) nature of sampling and because each instrument measured scatter uniquely (i.e., different lenses).

The LISST instruments measured total sediment concentration using laser diffraction technology which provided an estimate of the amount of sediment in the water as a measure of volume concentration. Volume concentration was recorded by the LISST instruments in the units of micro-liters per liter (µl/L). In order to facilitate the conversion of the dataset from µl/L to mg/L (mass concentration), as previously requested by the USEPA, grab samples were collected from the drain hoses of the LISST instruments and/or the edge-of-water in the vicinity of the LISST instrument pumps to be paired with LISST measurements. Paired sampling refers to the collection of a grab sample at the same time a measurement is recorded at the LISST instrument(s), and was recommended by the manufacturer to develop a conversion factor. In 2015, the grab sampling program was expanded to include daily collection of grab samples at both the drain hose (when possible) and the edge-of-water. Grab samples collected during the previous years of the study (2012-2014) were infrequent.

Given the variability observed among LISST measurements, and because particle density could also vary, the density conversion factor was developed using all available paired samples with linear regression. During the conversion development phase, it was noted that the LISST instruments did not reliably measure if sediment concentrations were extremely low; therefore, the y-intercept of the regression equation was set to zero and the density conversion was the slope of the line.

Due to operational issues at the StreamSide, too few grab samples were collected from the drain hose in 2015 to provide a reliable correlation; edge-of-water samples were used in place of drain samples. The results of the edge-of-water samples were appropriate to use given that they were collected in the vicinity of the StreamSide pump on a daily basis. This regression provided a strong correlation and therefore a reliable conversion factor to mass concentration for the StreamSide (Figure 3.2.2-1).

For the LISST HYDRO instruments, a sufficient number of grab samples were collected from the monitor drain hoses in 2015 such that strong correlations were observed and reliable conversion factors were developed (Figures 3.2.2-2 and 3.2.2-3).[16]

Grab samples were not available for all LISST-100X data, and the measurements from this instrument were not converted to mass concentration values. Because the LISST-100X data were primarily used for cross-sectional patterning, relative values of total volume concentration were considered sufficient.

[16] The conversion factors are instrument-specific, rather than location specific. Because the instruments were swapped and installed on different banks each year, the conversion factors were applied appropriately to the instrument.

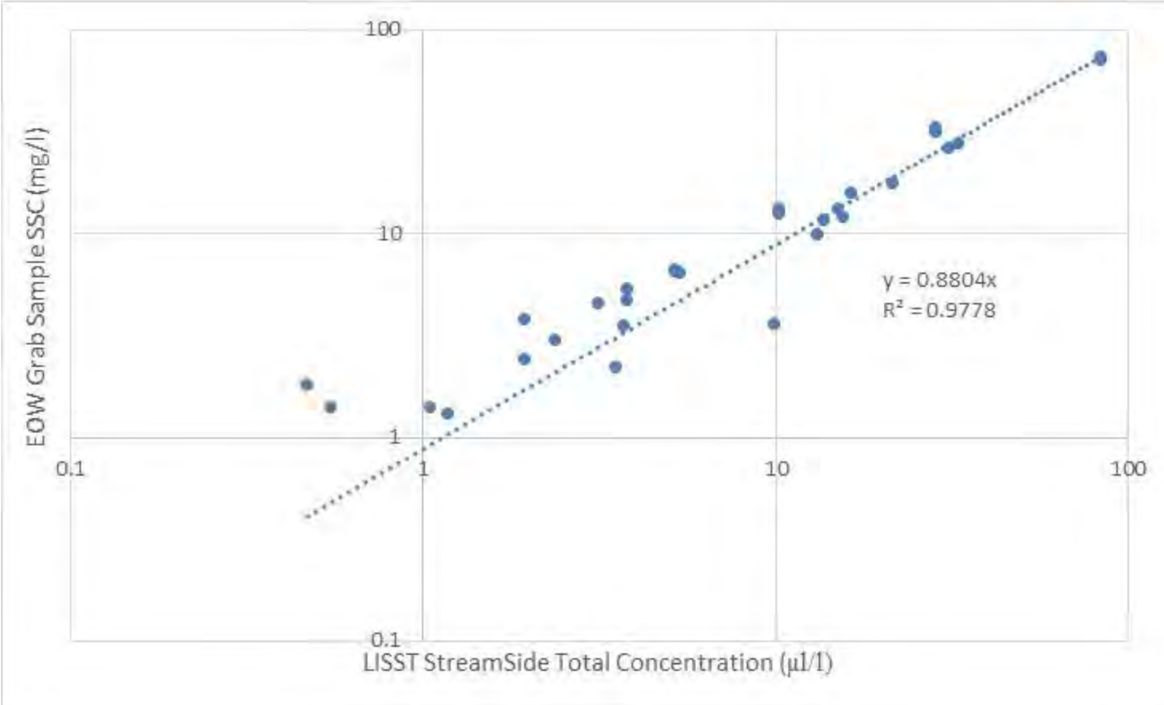


Figure 3.2.2-1 StreamSide Unit Conversion Equation

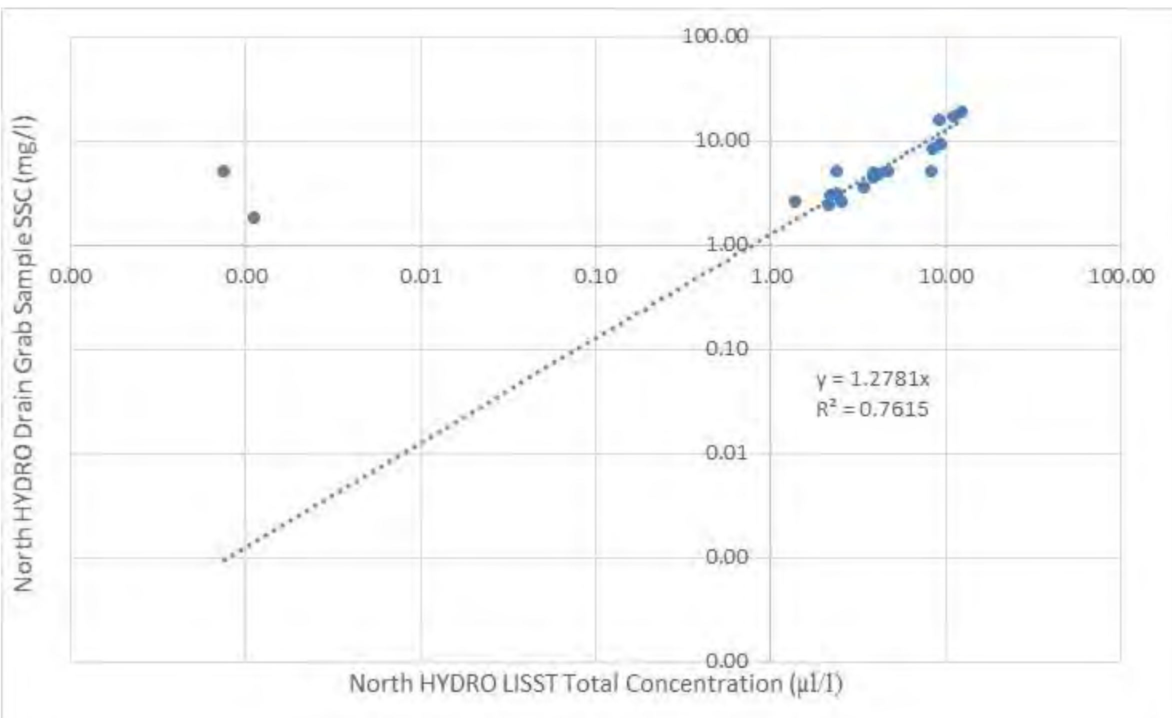


Figure 3.2.2-2 HYDRO North Unit Conversion Equation

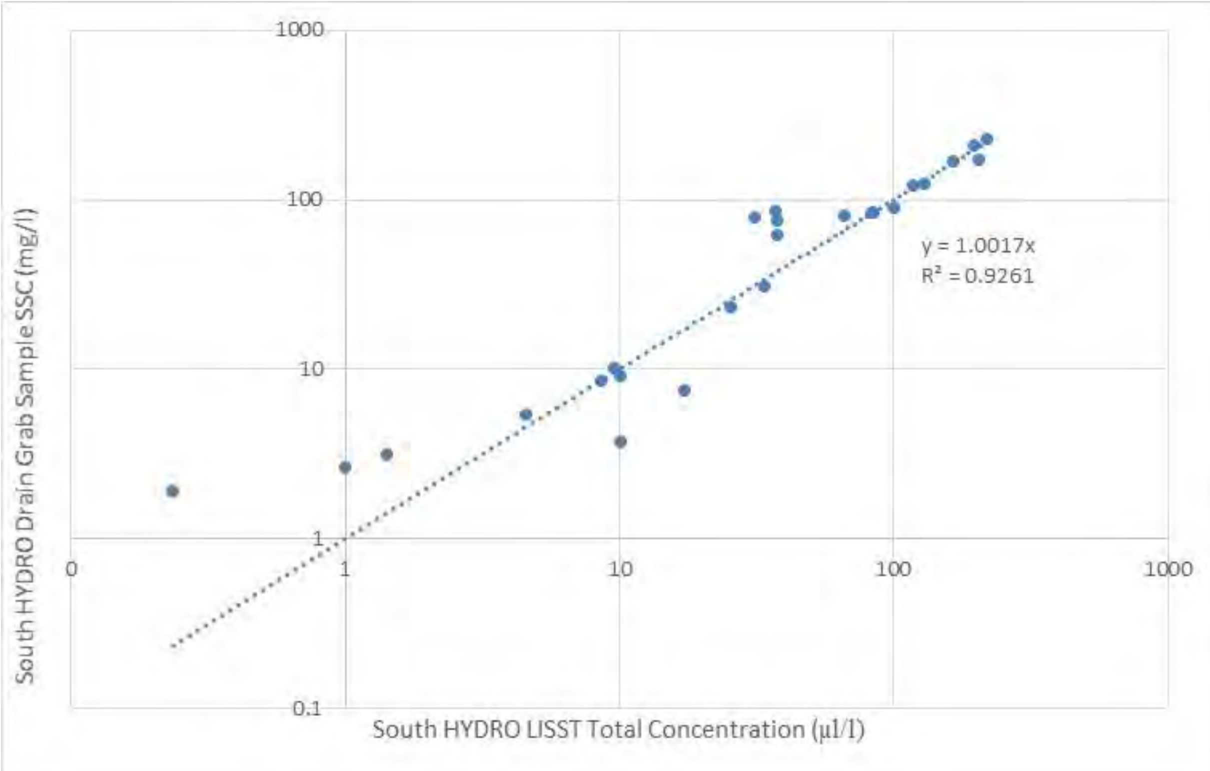


Figure 3.2.2-3 HYDRO South Unit Conversion Equation

3.2.3 Analyses

Following the completion of the QA processes and the conversion of the LISST data from volume to mass concentration, various suspended sediment analyses were performed.[17] Suspended sediment concentrations were compared with flow and Project operations data (Vernon and Northfield Mountain) over a range of seasonal, and operational conditions. Data collected from the Rt. 10 Bridge cross-section and the Northfield Mountain tailrace cross-section were also examined to better understand the suspended sediment dynamics across the river and tailrace, as well as throughout the water column. Cross-sectional data were also compared to the point data collected (StreamSide, HYDROs, and grab samples) to determine if the continuous sampling locations were representative of the larger cross-section and if any data adjustments would be needed. This section describes each of the analyses conducted while Section 4 discusses the results.

Comparison of Point and Continuous Measurements to Flow and Operations

Continuous total concentration measurements were analyzed to examine the relationships with river flow and Project operations (Vernon and Northfield Mountain). Timeseries (hourly basis) plots of SSC, river flow at Vernon Dam, and Northfield Mountain Project operational flow data were developed on a monthly or 10-day time step for the duration of the study (Appendix D and E).[18] The goals of the timeseries plots were to identify SSC patterns on an annual, seasonal, and Project operations basis. From these analyses, several periods of interest were then identified for further analysis on a finer scale. The finer scale plots were analyzed to specifically understand the dynamics of SSC and flow in relation to the generating and pumping operations at the Project.

Time periods of interest that were examined on a finer scale included: low (2,000-12,000 cfs), moderate (12,000-20,000 cfs), and high flow (30,000-70,000 cfs) periods when Northfield Mountain was pumping and generating over a range of units (1-4). The spring freshet was also captured during the high flow period of interest. The goals of this analysis were to determine: (1) how varying SSC levels could impact the Project (i.e., sediment entrainment in Project works); (2) if an increase in SSC values were observed during pumping and/or generating conditions; (3) if an increase in SSC values were observed depending on the number of units online (1-4), (4) if there was a difference between the SSC values observed from the north bank to the south bank of the tailrace over a range of flow and operating conditions; and (5) how the SSC levels of the mainstem impacted the tailrace and, potentially, the Upper Reservoir. The results of the edge-of-water grab samples, the StreamSide, and HYDROs were used for these analyses. Section 4.2 contains a detailed discussion of these results.

Cross-sectional Rt. 10 Bridge

LISST-100X data were collected in 2013 over a range of flows (1,697 cfs – 31,382 cfs) in order to better understand how total concentration varied across the cross-section and throughout the water column. The LISST-100X data were also used to determine if the StreamSide pump location was representative of the cross-section or if adjustments needed to be made to the StreamSide data. Various plots depicting the LISST-100X data were developed and analyzed as part of this effort (Appendix F). However, because the LISST-100X data were not able to be converted to mass concentrations, they were not analyzed quantitatively and were only used to describe the general patterns in that area of the river.

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[17] Although the LISST instruments recorded PSD measurements, given the indirect nature of the laser scattering and a lack of confidence in the accuracy of the particle size distributions provided by the LISST instruments, no analyses were performed on particle size data. As such, suspended sediment analyses were limited to suspended sediment concentration.

[18] When reviewing the plots contained in these Appendices it is important to note that the y-axis may vary from plot to plot. Additionally, in Appendix D, gaps observed in the LISST data represent periods of time when the instruments were offline due to equipment malfunctions or data that was removed from the final dataset during the QA/QC process.

In 2015, grab sample data were collected from the Rt. 10 Bridge over a range of flows (19,112 cfs – 59,700 cfs). The 2015 Rt. 10 Bridge data were plotted by depth and station in order to examine whether SSC varied across the river, with depth, or both. Flows, and any changes in flow, were also noted given that the sampling events occurred over multiple hours. Grab samples were also collected from the edge-of-water in the vicinity of the StreamSide pump before or after (sometimes both) cross-sectional data collection occurred. Measurements from grab samples taken near the StreamSide were then compared to the cross-sectional data in order to evaluate whether the StreamSide sampling location was representative of the river in that area. Results were compared to patterns from data collected in 2013 with the LISST-100X.

Table 3.2.3-1 denotes the pertinent information regarding the Rt. 10 Bridge cross-section data collection efforts of 2013 and 2015. Section 4.2 contains a detailed discussion of these results.

Cross-sectional Northfield Tailrace

LISST-100X data were collected over a range of operating conditions (1-3 units pumping and generating) at the Northfield Mountain tailrace boat barrier buoy line in 2013 to evaluate whether sediment concentrations differed by depth and/or station across the Northfield Mountain tailrace. The LISST-100X data were also used to determine if the HYDRO pump locations were representative of the cross-section or if adjustments needed to be made to the HYDRO data. Various plots depicting the LISST-100X data were developed and analyzed as part of this effort (Appendix F); however, because the LISST-100X data were not able to be converted to mass concentrations, they were not analyzed quantitatively and were only used to describe the general cross-sectional pattern in the tailrace.

Additionally, paired grab samples collected in 2015 from each bank were analyzed using a two sample Kolmogorov-Smirnov test, which compares the median and cumulative distribution of samples. Using this test, low p-values ($p < 0.05$) would indicate that samples from each bank differ in median, variability, or distribution. This test was performed on the complete paired dataset, along with pumping and generation subsets.

FirstLight also planned on collecting cross-sectional grab samples in 2015 at the same stations where LISST-100X data were measured in 2013 during moderate to high flow events over a range of operating conditions. Due to safety concerns associated with collecting samples from a boat at the tailrace while the Project was operating and river flows were moderate to high, this was not possible.

Table 3.2.3-1 denotes the pertinent information regarding the Northfield Mountain tailrace cross-section data collection effort in 2013. Section 4.2 contains a detailed discussion of these results.

Table 3.2.3-1 Cross-sectional Data Collection – 2013 and 2015

Date	Location	Method	Flow (cfs)	Northfield Mtn. Operations	Notes
4/18/2013	Rt. 10 Bridge	LISST-100X (EWI)	33,483	N/A – sampling point upstream of Station	Naturally Routed Flow[19]
4/26/2013	Rt. 10 Bridge	LISST-100X (EWI)	15,980	N/A – sampling point upstream of Station	Naturally Routed Flow
5/2/2013	Rt. 10 Bridge	LISST-100X (EWI)	10,707	N/A – sampling point upstream of Station	Naturally Routed Flow
5/10/2013	Rt. 10 Bridge	LISST-100X (EWI)	10,070	N/A – sampling point upstream of Station	Naturally Routed Flow
10/3/2013	Rt. 10 Bridge	LISST-100X (EWI)	3,363	N/A – sampling point upstream of Station	Naturally Routed Flow
10/11/2013	Rt. 10 Bridge	LISST-100X (EWI)	5,450	N/A – sampling point upstream of Station	Naturally Routed Flow
10/16/2013	Rt. 10 Bridge	LISST-100X (EWI)	4,490	N/A – sampling point upstream of Station	Naturally Routed Flow
10/24/2013	Rt. 10 Bridge	LISST-100X (EWI)	4,278	N/A – sampling point upstream of Station	Naturally Routed Flow
10/10/2013	NFM Boat Barrier	LISST-100X (EWI)	6,782	Idle	Naturally Routed Flow
10/15/2013	NFM Boat Barrier	LISST-100X (EWI)	4,171	1 Unit Gen	Naturally Routed Flow
10/23/2013	NFM Boat Barrier	LISST-100X (EWI)	4,640	2 Units Gen	Naturally Routed Flow
10/26/2013	NFM Boat Barrier	LISST-100X (EWI)	4,955	2 Units Pump	Naturally Routed Flow
10/26/2013	NFM Boat Barrier	LISST-100X (EWI)	4,955	3 Units Gen	Naturally Routed Flow
4/14/2015	Rt. 10 Bridge	Grab Sample (EWI)	50,536-59,700	N/A – sampling point upstream of Station	Vernon Discharge
4/17/2015	Rt. 10 Bridge	Grab Sample (EWI)	47,970-52,591	N/A – sampling point upstream of Station	Vernon Discharge
4/20/2015	Rt. 10 Bridge	Grab Sample (EWI)	41,282-42,172	N/A – sampling point upstream of Station	Vernon Discharge
4/28/2015	Rt. 10 Bridge	Grab Sample (EWI)	20,437-19,112	N/A – sampling point upstream of Station	Vernon Discharge

[19] Turners Falls Impoundment Naturally Routed Flow is the sum of Vernon discharge and inflow from the Ashuelot and Millers Rivers.

4 RESULTS & DISCUSSION

Over the course of the study, the *Northfield Mountain Project Sediment Management Plan* included multiple field data collection, modeling, and analysis components. The results of the various data collection, modeling, and analysis efforts which occurred from 2011-2016 are presented in this section. Section 4.1 presents the findings of the annual bathymetry surveys including estimations of the total sediment volume flux within the Upper Reservoir. Section 4.2 discusses the findings of the suspended sediment monitoring portion of the program based on the data collected at the StreamSide, HYDROs, LISST-100X, and from the grab samples. Results discussed in Section 4.2 include analysis of SSC timeseries vs. flow and Project operations (Vernon and Northfield Mountain) and review of specific periods of interest which exhibit a range of river and operations conditions. Section 4.3 presents a summary discussion of the various modeling efforts and pilot dredge.

4.1 Upper Reservoir Bathymetry Surveys

As mentioned in Section 3.1, the results of each annual Upper Reservoir bathymetry survey were compared against the previous year's bathymetry survey to determine the total sediment volume flux in the Upper Reservoir as well as the intake channel. TINs demonstrating the change in sediment volume (i.e., areas of deposition and erosion) from year to year were developed based on the results of the bathymetry analysis. Figures depicting the annual changes across the entire Upper Reservoir for the period 2011-2013 are included in Appendix A.[20] When reviewing the figures in the Appendix, it is important to note that these figures contain comparisons of single beam vs. multi-beam echosounder surveys. While it is possible to conduct such a comparison using GIS or CAD software, it is not appropriate to do so as the accuracy of such a comparison is unknown and could vary greatly in some areas. Similarly, it is not appropriate to compare a single beam vs. single beam period (2011 and 2013) with a multi-beam vs. multi-beam period (2012 and 2014) as the multi-beam echosounders collect data at a higher resolution. Changes in sediment volume between 2011 and 2013 depicted in the figures found in Appendix A, which are based on comparison of single and multi-beam echosounders, should be considered approximate at best.

In order to better understand the changes in sediment volume of the Upper Reservoir intake channel between surveys, in-depth data analysis focused on the results of the 2012 survey as compared with the 2014 survey. The results of these bathymetry surveys were selected for comparison given that each survey utilized a multi-beam echosounder, were conducted by the same company, and followed the same methodology. Furthermore, the results of the 2012 to 2014 comparison were checked against gravity core data collected in the intake channel in 2014 and vibracore data collected in 2015.

When comparing the results of the 2012 and 2014 bathymetry surveys it was observed that a net total of 16,077 cubic yards of sediment accumulated in the Upper Reservoir intake channel over the two year period between surveys or an average of ~8,000 cubic yards/year. As a means of comparison, the net change in sediment volume at the intake channel was also calculated based on the sediment depth observed at each gravity core location. Given that the overall area of the intake channel is approximately 210,135 ft^2, and the average depth of sediment accumulation was found to be approximately 2 ft. (as observed at the six gravity core locations), then the total volume of sediment at the bottom of the intake channel is approximately 15,566 cubic yards. Due to the fact that the Upper Reservoir was dewatered in 2010 and silt was mechanically removed from the intake channel, the calculated net change of 15,566 cubic yards based on gravity core data represents the net deposition over the four year period, November 2010 to October 2014, or an average of ~4,000 cubic yards/year. Based on these two calculation methods the annual sediment

[20] Analysis of the 2014 bathymetry survey data only compared changes in sediment volume at the intake channel and not the entire Upper Reservoir. The 2015 survey was conducted after the completion of the pilot dredge program and as such is not directly comparable to the 2011-2014 results.

deposition rate in the Upper Reservoir intake channel was observed to range from ~4,000 to ~8,000 cubic yards/year.

The difference between the bathymetry and gravity core comparisons could be due to a number of reasons including, but not limited to: (1) accuracy limitations of the echosounder during each bathymetry survey; (2) echosounder interference caused by the geometry of the intake channel; (3) an underestimation of the amount of sediment found in the intake channel by the gravity cores; (4) varying flow, SSC, or operational conditions from year to year; or (5) a combination of all four. Because it is not possible to definitively determine the reason for the difference in the sediment deposition rate between the two calculation methods, for the purposes of this report, the annual deposition rate is reported as a range between the two calculation methods.

Figure 4.1-1 depicts the change in sediment volume of the Upper Reservoir intake channel from 2012 to 2014. Figure 4.1-2 shows the results of the 2014 survey as well as the locations where gravity cores were collected in the intake channel. Results of the 2014 Upper Reservoir bathymetry survey for the entire reservoir are depicted in Figure 4.1-3, 4.1-4, and 4.1-5.

During the 2015 bathymetry survey vibracores were collected at six locations as a spot check against the bathymetry data collected and as a means of comparison to the gravity core data collected in 2014. Based on observations made in the field during the 2014 survey the decision was made to switch from gravity cores to vibracores in order to achieve better penetration and recovery. Comparison of the gravity core information collected in 2014 with the vibracore information collected in 2015 found that the sediment thickness at the gravity core locations ranged from 2.0 to 2.5 ft. while the vibracores ranged from 0.3 to 5 ft.[21] The low end of the range observed in 2015 represents areas where the pilot dredge occurred between surveys while the high end of the range observed in 2015 represents areas that were not dredged. The difference in the high end of the range from 2014 to 2015 may be due to: (1) differences in core collection methodology (i.e., the vibracores were able to achieve better penetration and recovery than the gravity cores); (2) cores were collected at slightly different locations in 2014 and 2015; (3) sediment deposition since the 2014 survey; or (4) some combination of all three. Based on the analysis conducted, it appears that the vibracore data collected in 2015 generally correlates with the results of the bathymetry survey comparisons made from 2012 to 2014 and the finding that the annual deposition rate in the Upper Reservoir intake channel ranges from ~4,000 to ~8,000 cubic yards/year.

The results of the 2014 and 2015 bathymetry surveys were also compared to determine changes in the amount of sediment present in the intake channel. As previously stated, the pilot dredge occurred between surveys thus making it impossible to determine an annual deposition rate. While it was not possible to determine an annual deposition rate, calculations of the amount of sediment present in the intake channel were still possible. As stated in Section 2.4, ~46,000 CY of sediment were dredged from within and immediately upstream of the intake channel in 2015. While the majority of the dredging activity occurred immediately upstream of the intake channel, comparison of the 2014 to the 2015 multi-beam surveys found that approximately 13,500 CY of sediment was removed from the intake channel between surveys as a result of the dredging activities.[22] Figure 4.1-6 shows the change in bed elevation at the Upper Reservoir intake channel from 2014 to 2015. The areas of net sediment loss observed in the figure are indicative of the pilot dredge.

Figure 4.1-7 shows the results of the 2015 survey as well as the locations where the vibracores were collected in the intake channel. Note that the core locations are in the same general vicinity as those

[21] The 2015 cores were not collected at the same exact locations as the 2014 cores; however, they were in the same general vicinity which allowed for indirect comparisons of sediment thickness between years.
[22] This finding was checked against observations made during the dredging operation which found that approximately 15,000 CY of sediment had been removed from the intake channel.

collected in 2014. Results of the Upper Reservoir bathymetry survey for the entire reservoir are depicted in Figure 4.1-8, 4.1-9, and 4.1-10.

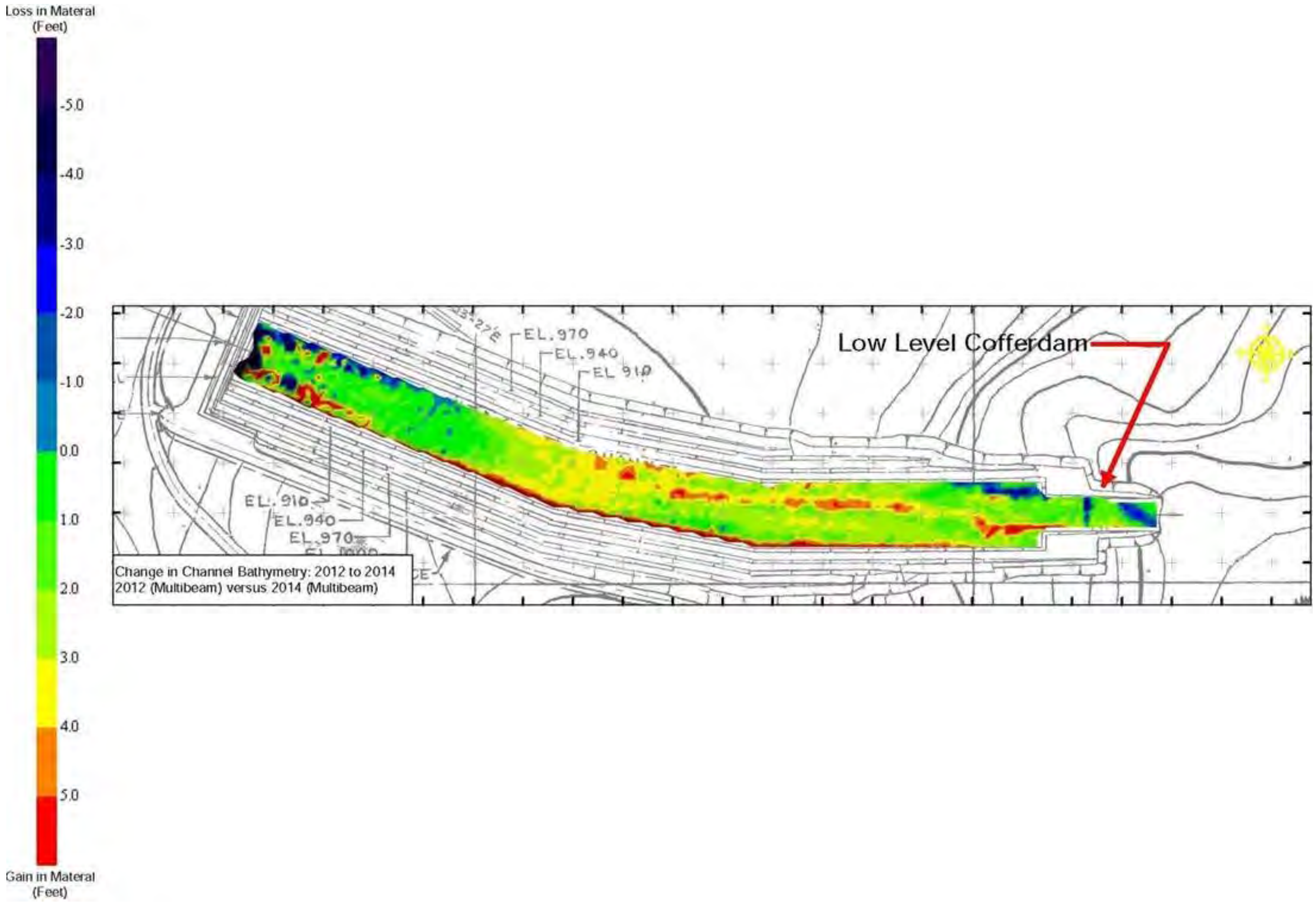
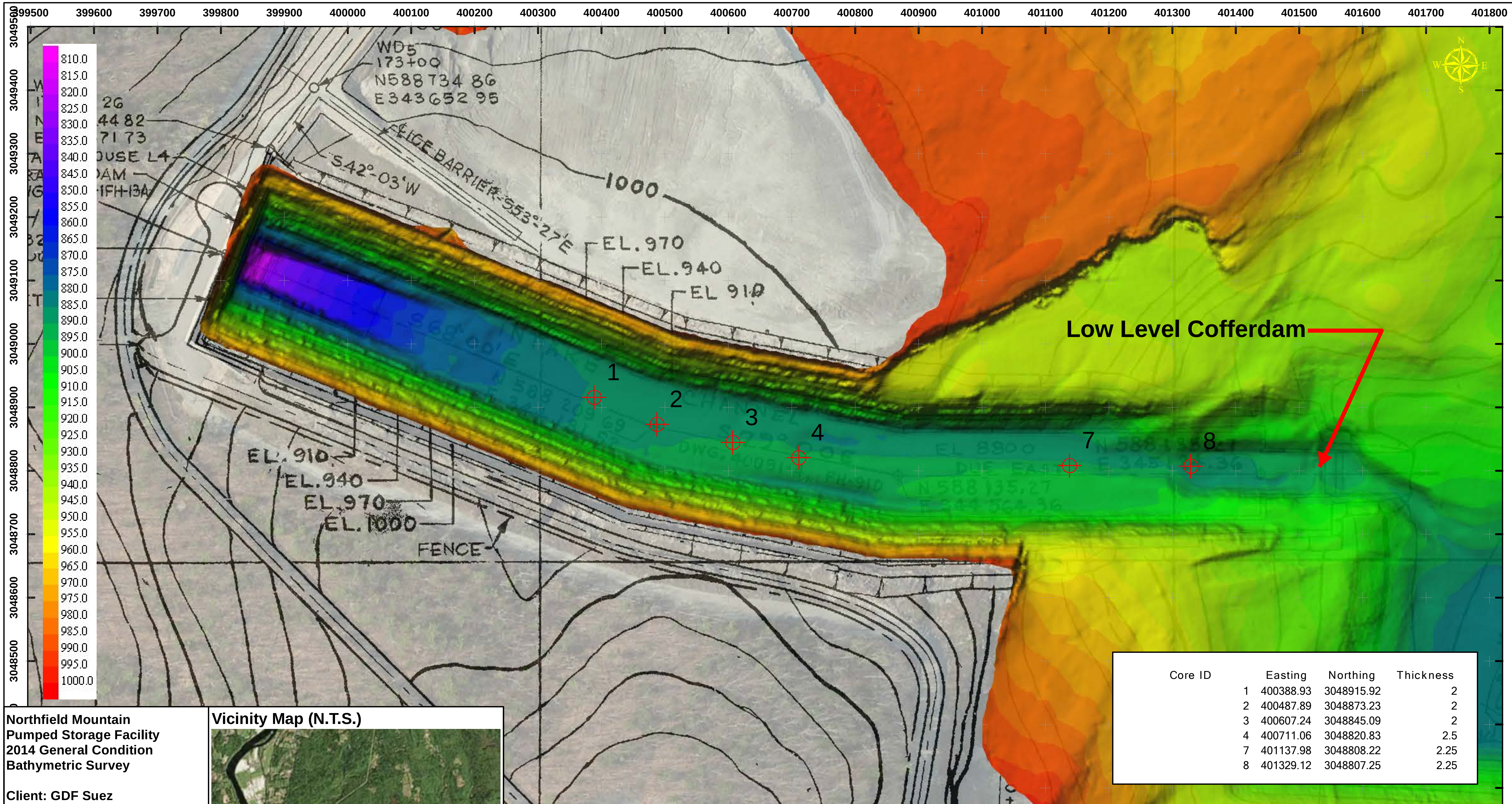


Figure 4.1-1 Upper Reservoir Intake Channel Bathymetric Survey – 2012 to 2014 Change



Core ID	Easting	Northing	Thickness
1	400388.93	3048915.92	2
2	400487.89	3048873.23	2
3	400607.24	3048845.09	2
4	400711.06	3048820.83	2.5
7	401137.98	3048808.22	2.25
8	401329.12	3048807.25	2.25

Northfield Mountain Pumped Storage Facility 2014 General Condition Bathymetric Survey

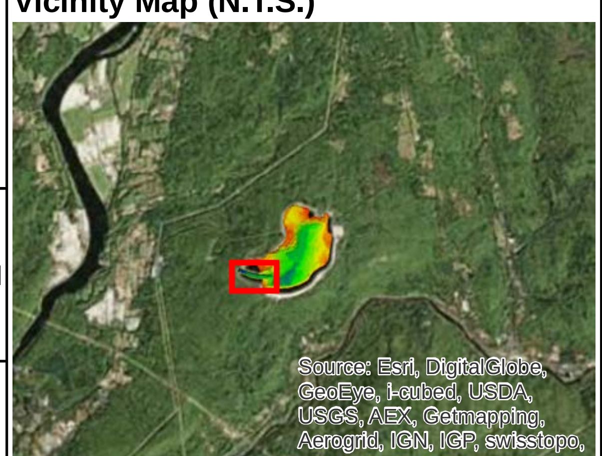
Client: GDF Suez

Figure 4.1-2

Upper Reservoir Intake Channel Multibeam Bathymetric Survey Core Sample Locations

SeaVision Figure 14-051-02
Drawn by: J. Snyder
Date: 11/4/2014

Vicinity Map (N.T.S.)



Notes

1. The bathymetry depicted on this drawing represents the results of a survey performed by SeaVision Underwater Solutions, Inc. on October 12, 2014 and can only be considered to indicate the general conditions existing at that time.

2. The multibeam bathymetry data was collected using a SBG Ekinox Intertial Navigation / Global Positioning System with Real-Time Kinematic corrections transmitted from the KeyNet GPS Virtual Reference Station Network. SeaVision utilized a Norbit 455 kHz WBMS Multibeam Echosounder to collect the data.

3. Horizontal positioning is expressed in feet and references the North American Datum of 1983, Massachusetts (Mainland) State Plane (Feet). Elevations are expressed in feet and reference the Northfield Mountain Pumped Storage Facility (NMPSF) Site Datum.

4. The NMPSF Site Datum is assumed to be an elevation of +0.389 eet relative to the North American Vertical Datum of 1988 (NAVD 1988).

5. Background aerial photographs have been taken from the publicly available digital imagery available through MassGIS and from electronic drawings provided by GDF Suez / FirstLight.

Scale

0 75 150 300
Feet

1 inch = 150 feet

Check Graphic Scale

SEAVISION UNDERWATER SOLUTIONS
151 Martine Street, Suite 103
Fall River, MA 02723
Phone 508-250-0650
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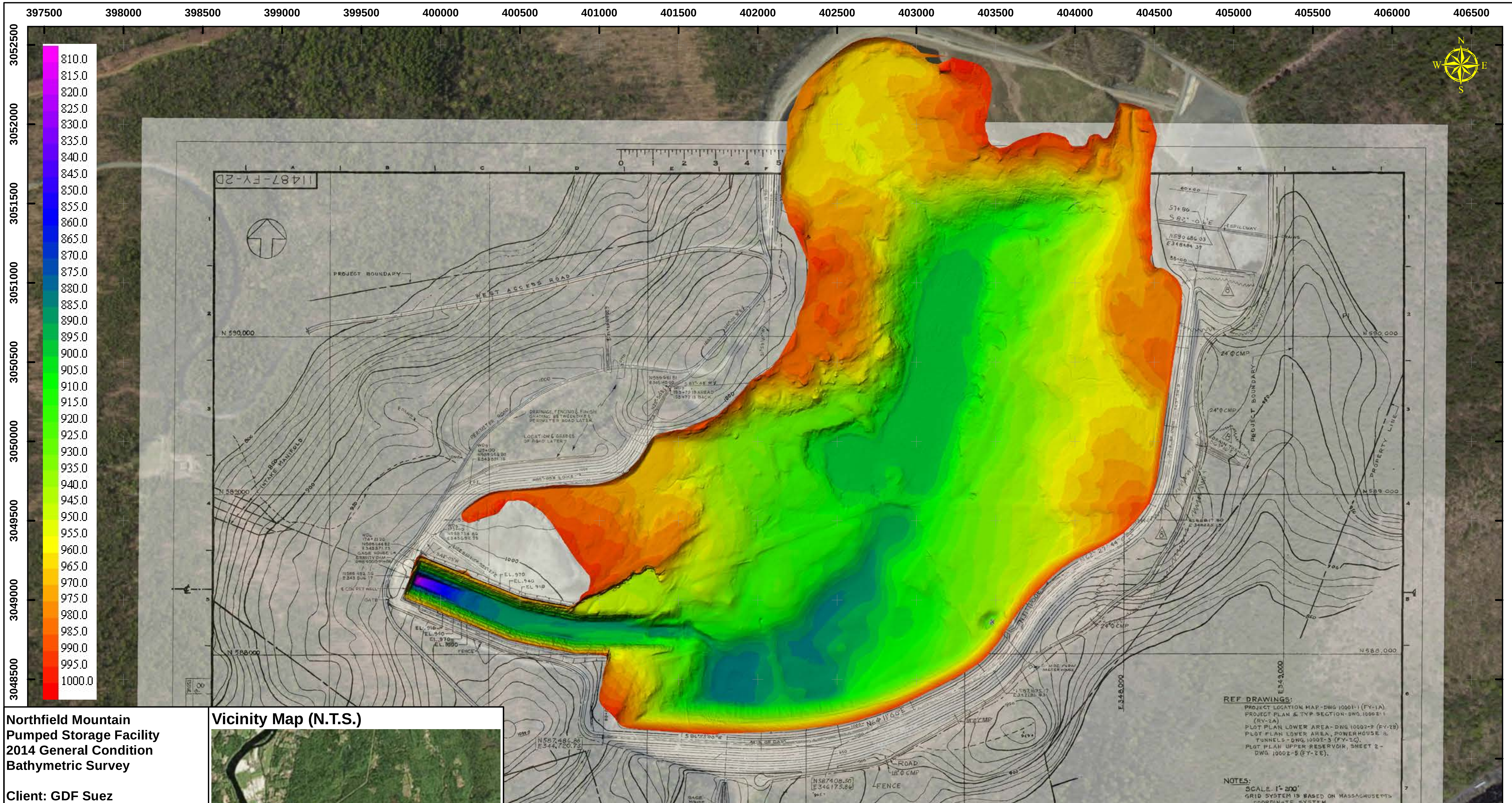
http://www.seavisionmarine.com



Northfield Mountain Pumped Storage Facility 2014 General Condition Bathymetric Survey

Client: GDF Suez

Vicinity Map (N.T.S.)

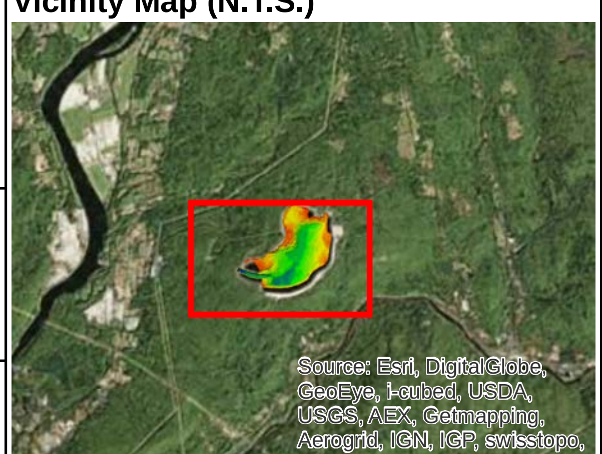


Figure 4.1-3

General Condition Multibeam Bathymetric Survey Color Shaded Relief

SeaVision Figure 14-051-01
Drawn by: J. Snyder
Date: 11/4/2014

Notes

1. The bathymetry depicted on this drawing represents the results of a survey performed by SeaVision Underwater Solutions, Inc. on October 12, 2014 and can only be considered to indicate the general conditions existing at that time.

2. The multibeam bathymetry data was collected using a SBG Ekinox Intertial Navigation / Global Positioning System with Real-Time Kinematic corrections transmitted from the KeyNet GPS Virtual Reference Station Network. SeaVision utilized a Norbit 455 kHz WBMS Multibeam Echosounder to collect the data.

3. Horizontal positioning is expressed in feet and references the North American Datum of 1983, Massachusetts (Mainland) State Plane (Feet). Elevations are expressed in feet and reference the Northfield Mountain Pumped Storage Facility (NMPSF) Site Datum.

4. The NMPSF Site Datum is assumed to be an elevation of +0.389 eet relative to the North American Vertical Datum of 1988 (NAVD 1988).

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Scale

0 300 600 1,200
Feet

1 inch = 600 feet

Check Graphic Scale

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Fax 401-633-7113
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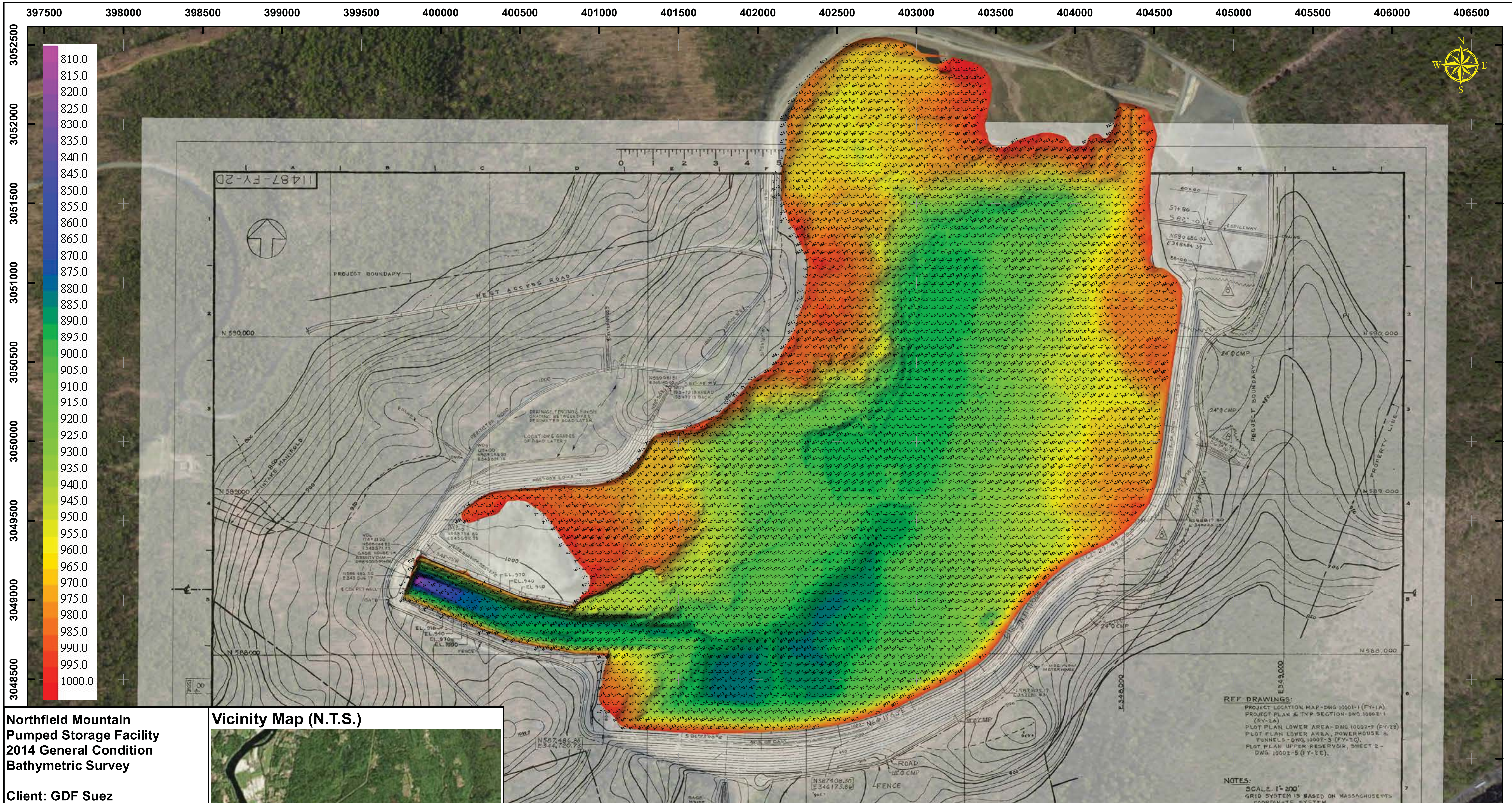

Northfield Mountain Pumped Storage Facility 2014 General Condition Bathymetric Survey

Client: GDF Suez

Vicinity Map (N.T.S.)

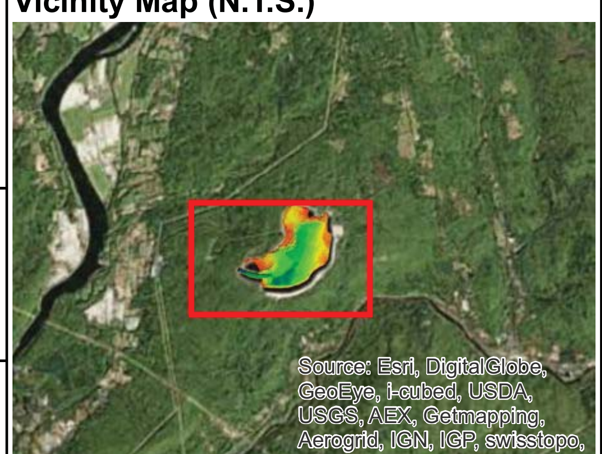

Figure 4.1-4
General Condition
Multibeam Bathymetric Survey
Soundings

SeaVision Figure 14-051-02
Drawn by: J. Snyder
Date: 11/4/2014

Notes

1. The bathymetry depicted on this drawing represents the results of a survey performed by SeaVision Underwater Solutions, Inc. on October 12, 2014 and can only be considered to indicate the general conditions existing at that time.

2. The multibeam bathymetry data was collected using a SBG Ekinox Intertial Navigation / Global Positioning System with Real-Time Kinematic corrections transmitted from the KeyNet GPS Virtual Reference Station Network. SeaVision utilized a Norbit 455 kHz WBMS Multibeam Echosounder to collect the data.

3. Horizontal positioning is expressed in feet and references the North American Datum of 1983, Massachusetts (Mainland) State Plane (Feet). Elevations are expressed in feet and reference the Northfield Mountain Pumped Storage Facility (NMPSF) Site Datum.

4. The NMPSF Site Datum is assumed to be an elevation of +0.389 eet relative to the North American Vertical Datum of 1988 (NAVD 1988).

5. Background aerial photographs have been taken from the publicly available digital imagery available through MassGIS and from electronic drawings provided by GDF Suez / FirstLight.

Scale

0 300 600 1,200
Feet

1 inch = 600 feet

Check Graphic Scale

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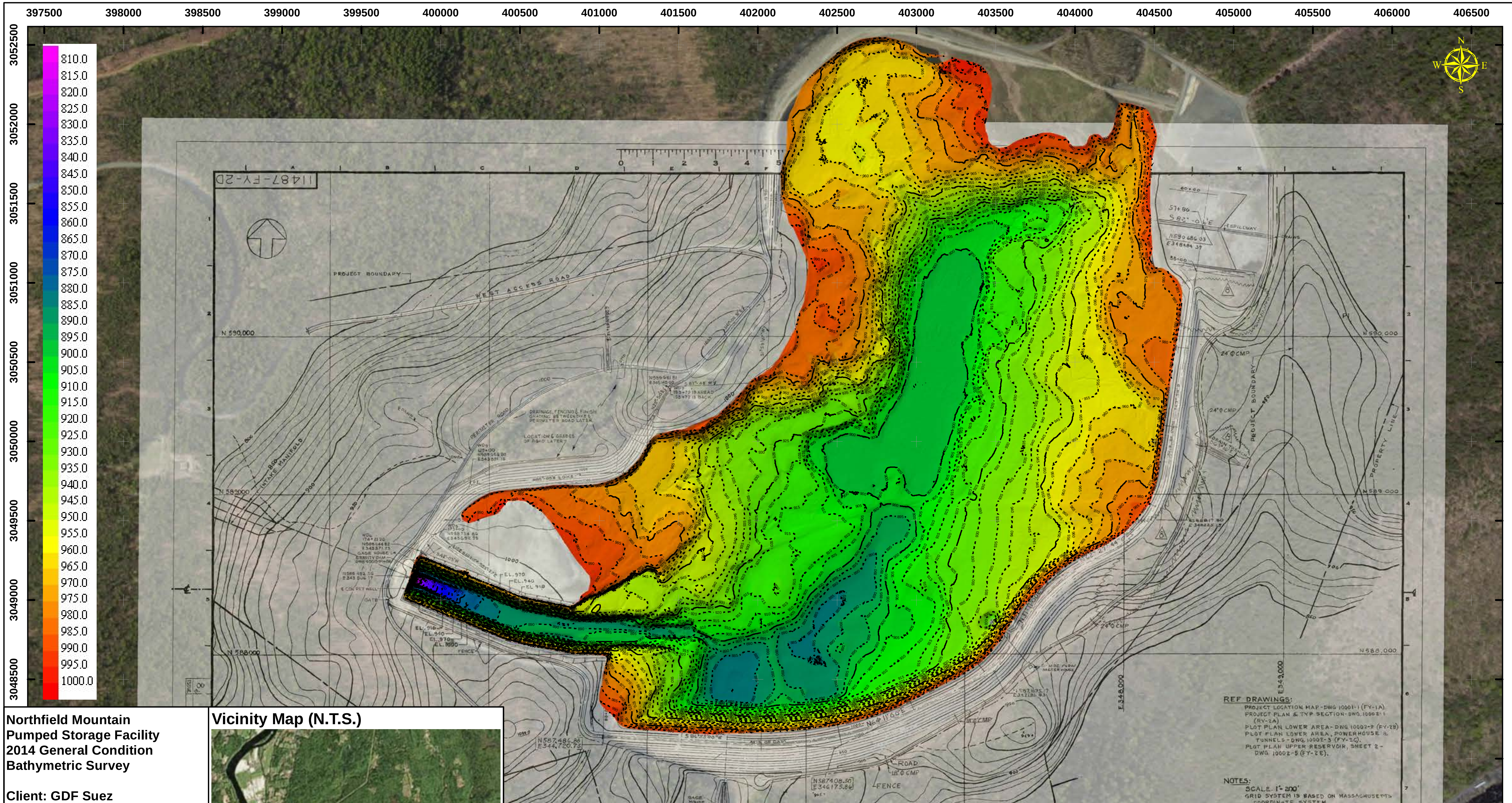


Northfield Mountain Pumped Storage Facility 2014 General Condition Bathymetric Survey

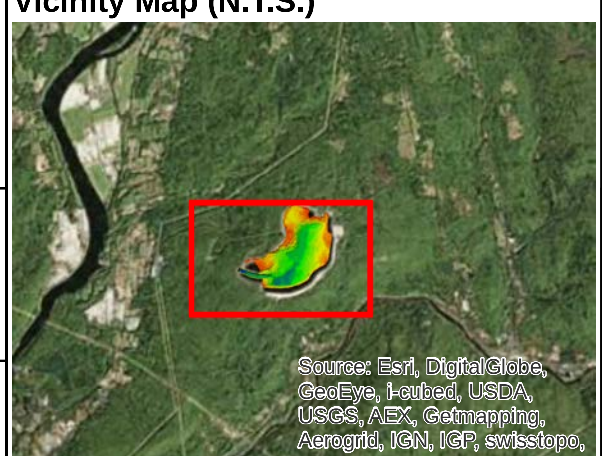
Client: GDF Suez

Figure 4.1-5

General Condition Multibeam Bathymetric Survey Contours

SeaVision Figure 14-051-03
Drawn by: J. Snyder
Date: 11/4/2014

Vicinity Map (N.T.S.)



Notes

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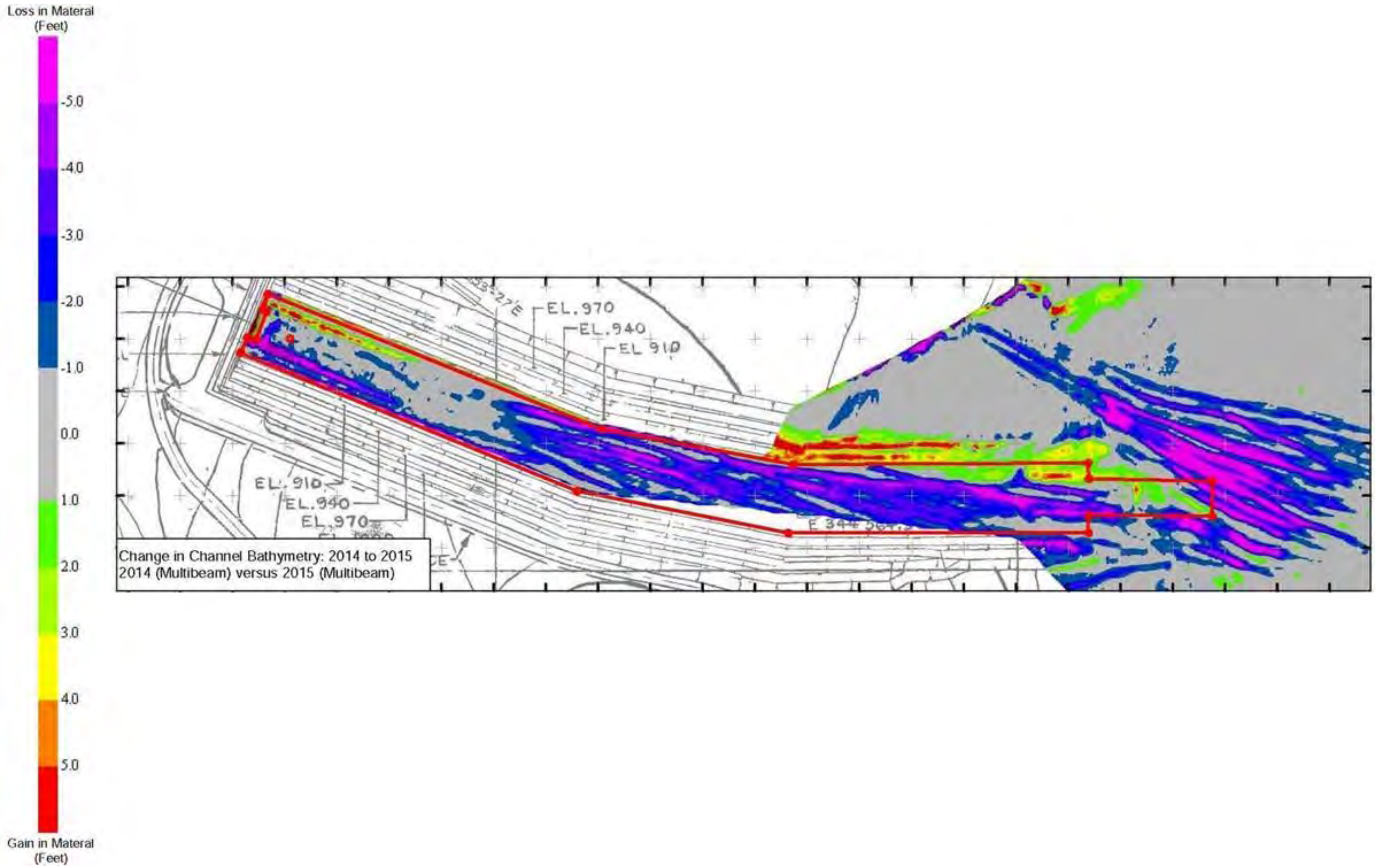
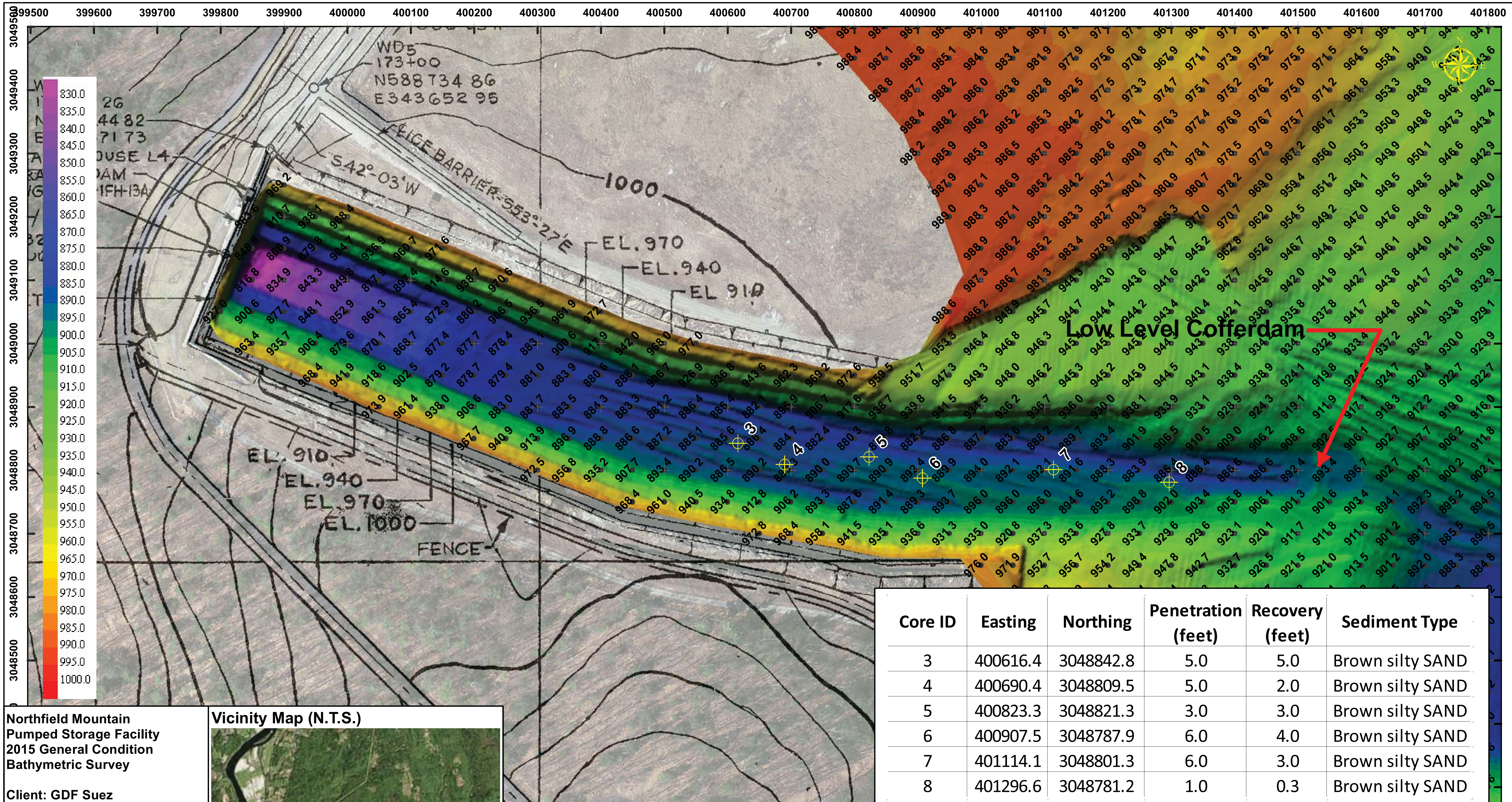


Figure 4.1-6 Upper Reservoir Intake Channel Bathymetric Survey – 2014 to 2015 Change



Core ID	Easting	Northing	Penetration (feet)	Recovery (feet)	Sediment Type
3	400616.4	3048842.8	5.0	5.0	Brown silty SAND
4	400690.4	3048809.5	5.0	2.0	Brown silty SAND
5	400823.3	3048821.3	3.0	3.0	Brown silty SAND
6	400907.5	3048787.9	6.0	4.0	Brown silty SAND
7	401114.1	3048801.3	6.0	3.0	Brown silty SAND
8	401296.6	3048781.2	1.0	0.3	Brown silty SAND

Northfield Mountain Pumped Storage Facility 2015 General Condition Bathymetric Survey

Client: GDF Suez

Figure 4.1-7
Upper Reservoir Intake Channel Multibeam Bathymetric Survey Core Sample Locations

SeaVision Figure 15-044-04
Drawn by: J. Snyder
Date: 11/1/2015

Vicinity Map (N.T.S.)

Notes

1. The bathymetry depicted on this drawing represents the results of a survey performed by SeaVision Underwater Solutions, Inc. on October 4, 2015 and can only be considered to indicate the general conditions existing at that time.

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Scale

0 75 150 300
Feet

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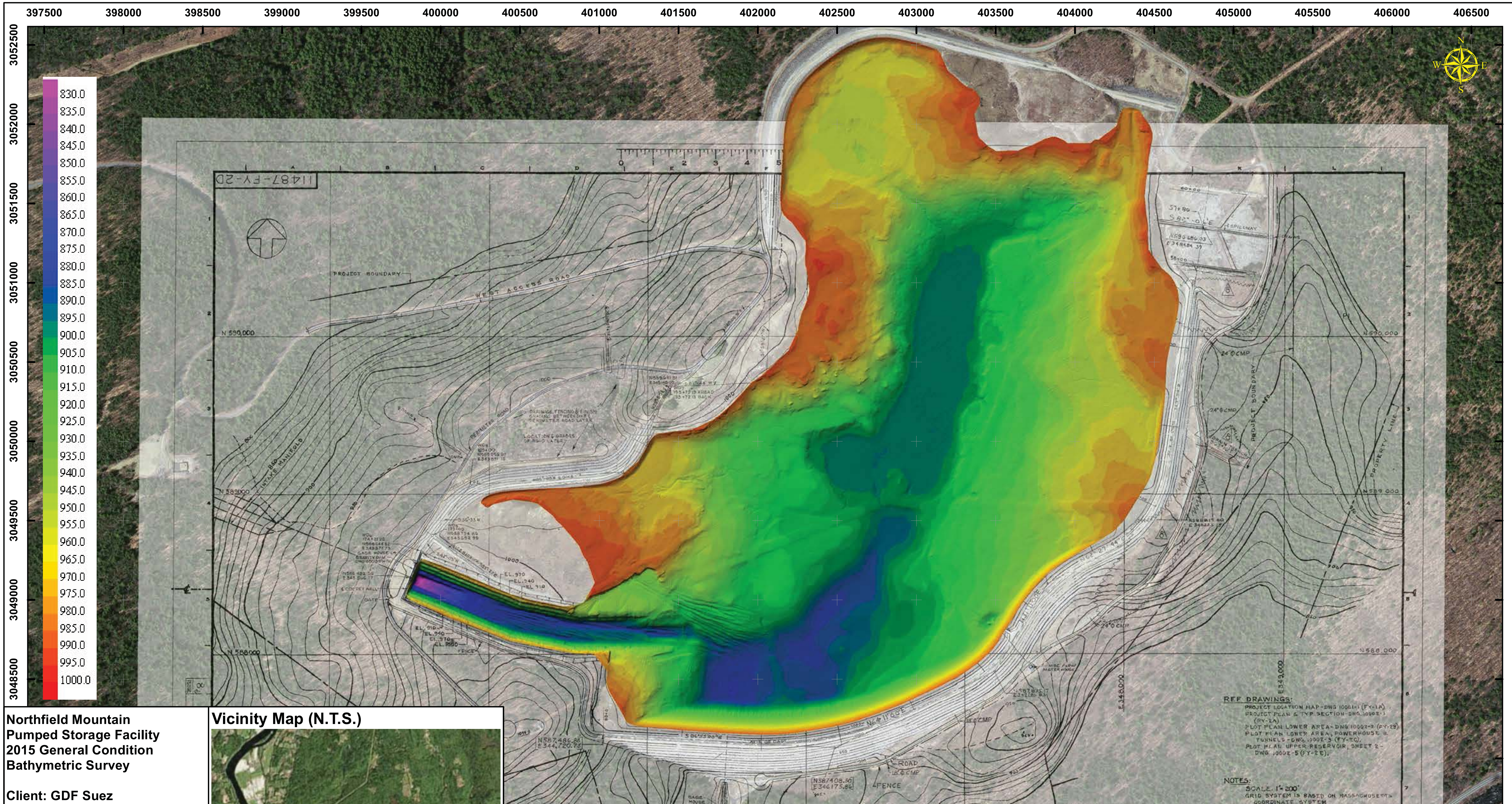

Northfield Mountain Pumped Storage Facility 2015 General Condition Bathymetric Survey

Client: GDF Suez

Vicinity Map (N.T.S.)

Figure 4.1-8
General Condition
Multibeam Bathymetric Survey
Color Shaded Relief

SeaVision Figure 15-044-01
Drawn by: J. Snyder
Date: 11/1/2015

Notes

1. The bathymetry depicted on this drawing represents the results of a survey performed by SeaVision Underwater Solutions, Inc. on October 4, 2015 and can only be considered to indicate the general conditions existing at that time.

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Feet

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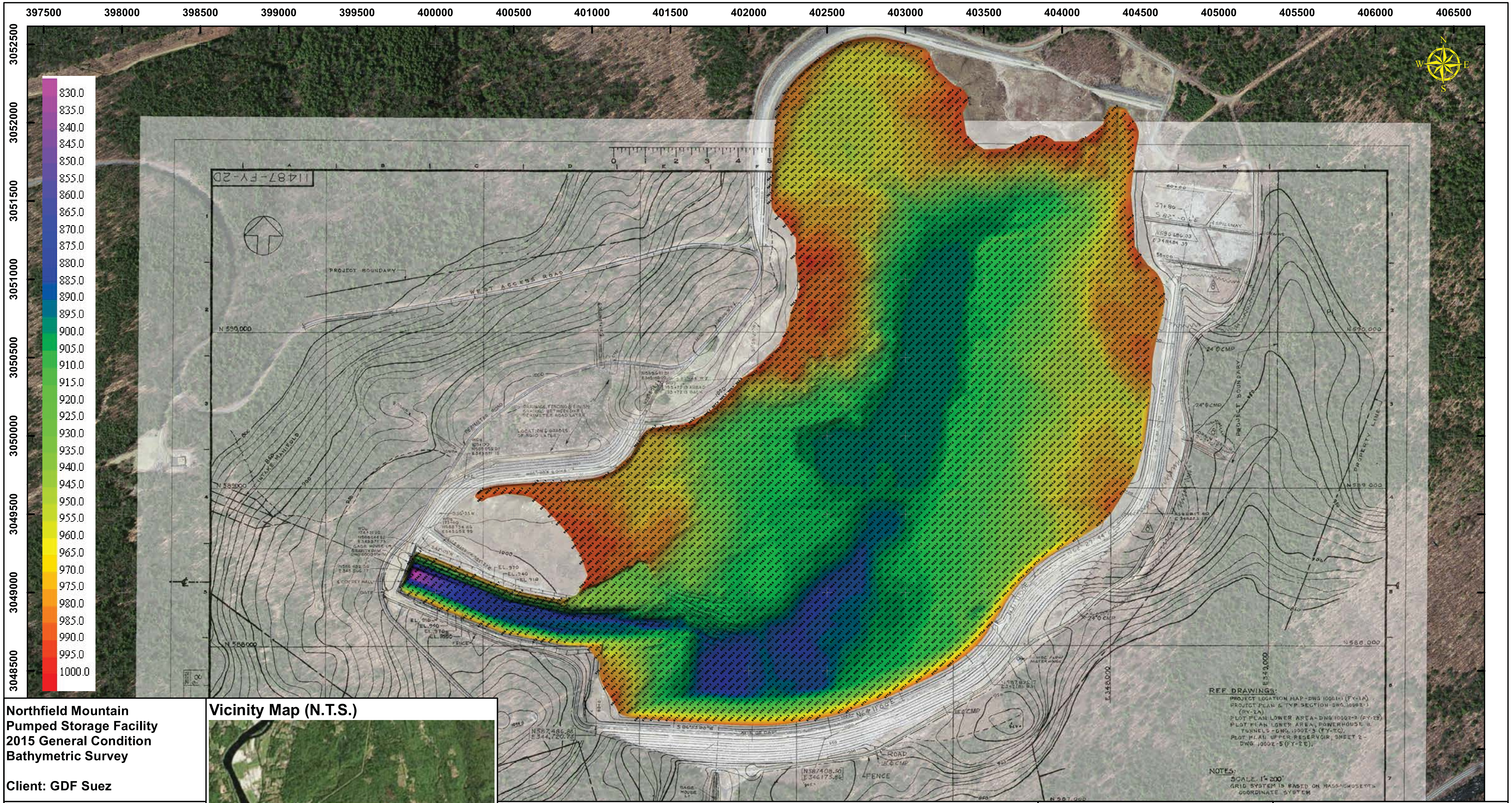

Northfield Mountain Pumped Storage Facility 2015 General Condition Bathymetric Survey

Client: GDF Suez

Figure 4.1-9
General Condition
Multibeam Bathymetric Survey
Soundings

SeaVision Figure 15-044-02
Drawn by: J. Snyder
Date: 11/1/2015

Vicinity Map (N.T.S.)

Notes

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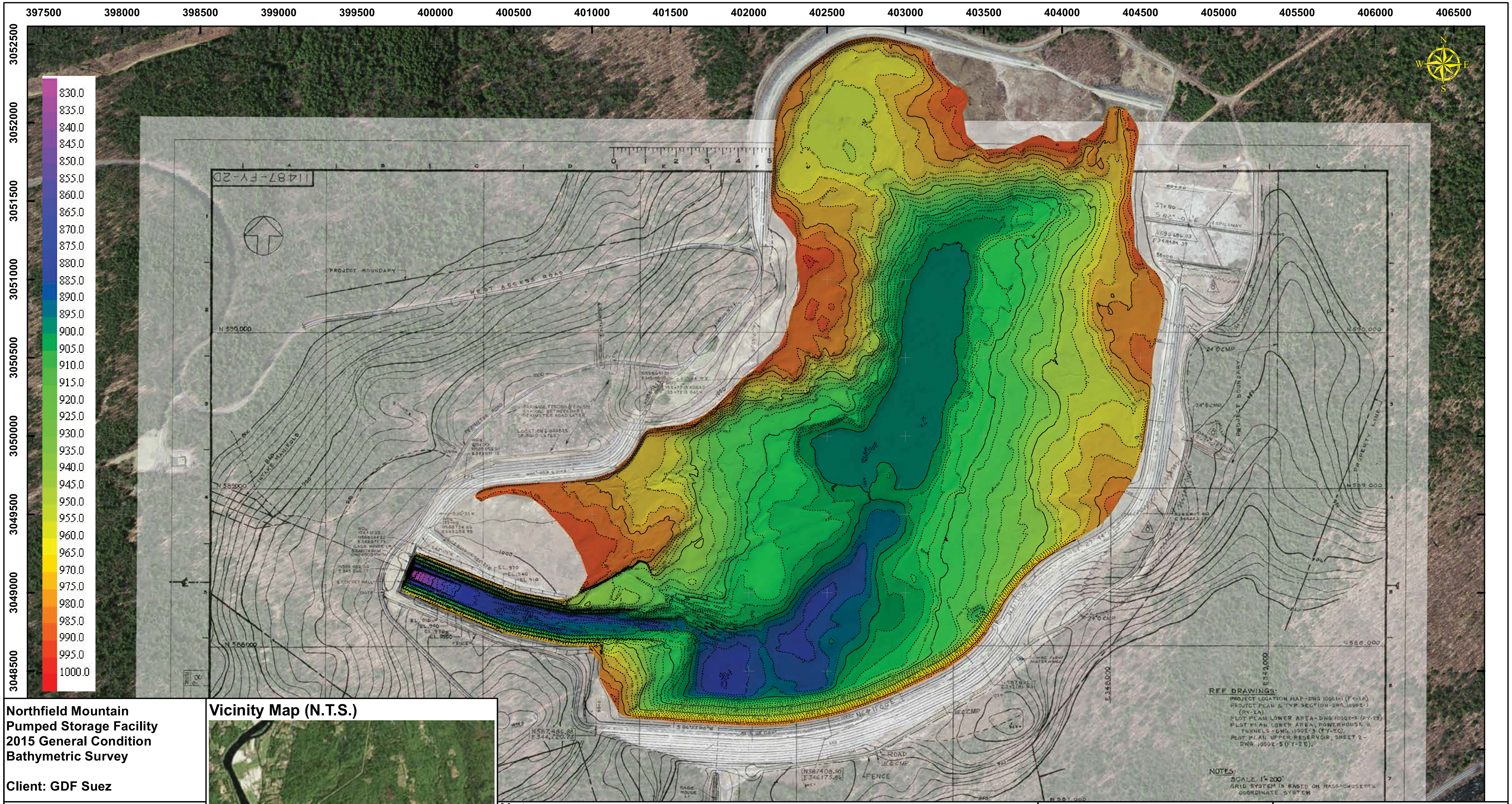

Northfield Mountain Pumped Storage Facility 2015 General Condition Bathymetric Survey

Client: GDF Suez

Figure 4.1-10
General Condition Multibeam Bathymetric Survey Contours

SeaVision Figure 15-044-03
Drawn by: J. Snyder
Date: 11/1/2015

Vicinity Map (N.T.S.)

Notes

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4.2 Suspended Sediment Monitoring

Following successful QA and post processing of the suspended sediment monitoring data (continuous LISST data and grab samples) timeseries plots were developed comparing flow, Project operations (Vernon and Northfield Mountain), and SSC from 2013-2015. The timeseries plots were reviewed to identify annual, seasonal, and Project operations related patterns in SSC when compared against flow (naturally occurring), Vernon Project operations, and Northfield Mountain Project operations. From this initial review, several time periods of interest were then identified for further analyses on a finer scale. Section 4.2.1 discusses the results of these analyses.

In addition to the timeseries plots mentioned above, various plots and graphs depicting the cross-sectional data collected at the Rt. 10 Bridge (LISST-100X and grab samples) and the Northfield Mountain tailrace (LISST-100X) were developed to examine variations in SSC across the cross-section(s) and throughout the water column over a range of flow and operating conditions. Results of these analyses are found in Section 4.2.2.

4.2.1 Comparison of Point and Continuous Measurements to Flow and Operations

This section presents the results of a number of analyses including:

- Seasonal SSC patterns and trends observed in relation to flow;
- SSC patterns and trends observed in relation to flow and Project operating conditions at Vernon; and
- SSC patterns and trends observed in relation to flow and Project operating conditions at Northfield Mountain

Timeseries plots for 2013, 2014, and 2015 are presented in Appendix D and E. Additional plots depicting periods of interest are presented throughout this section of the report. All suspended sediment monitoring data collected from 2013-2015 are included in Appendix G.

Seasonal SSC patterns and trends observed in relation to flow – Connecticut River

Suspended sediment measurements collected by the StreamSide and from grab samples collected in the vicinity of the StreamSide pump demonstrate strong correlations between flow and SSC. Over the course of the study it was observed that as Connecticut River flows increase so too did SSC. That is, the highest SSC values were observed during the highest periods of flow while the lowest SSC values were observed during the lowest period of flows. This was a consistent observation for each year data were collected. Figure 4.2.1-1 demonstrates this relationship.

As shown in Figure 4.2.1-1, SSC values were relatively low and without an apparent trend when flows from Vernon Dam were below 12,000 cfs. 95% of SSC measurements observed when flows were below 12,000 cfs were below 14.5 mg/L with a median of 2.9 mg/L. From 12,000 to 35,000 cfs, SSC values exhibited an increasing trend with a median of 12.45 mg/L. Finally, SSC values associated with flows greater than 35,000 cfs increased more quickly with flow and were significantly higher with a median of 144.61 mg/L. The results of this analysis demonstrate that three flow thresholds generally exist in the TFI in regard to SSC values: <12,000 cfs, 12,000-35,000 cfs, and >35,000 cfs.

Figure 4.2.1-2 depicts the flow duration curve for Vernon discharge from April through November for the years 2013-2015. As shown on the flow duration curve, 63% of the time flows were 12,000 cfs or less, 32% of the time flows were between 12,000-35,000 cfs, and 5% of the time flows were 35,000 cfs or greater during the course of the study.

Furthermore, the hydrology of the Connecticut River in the study area is very much driven by the season. The seasonal hydrology pattern observed in the study area is defined by: (1) a spring freshet typically occurring in late March and into May when the highest annual flows are typically observed (barring a significant basin wide rain event or Hurricane in the summer or fall); (2) moderate flows throughout the early summer as the spring freshet subsides; (3) low flows throughout the summer and early fall; and (4) low to moderate flows during the fall. Significant basin wide or local rain events occasionally cause spikes in flow and SSC during the summer and fall before conditions return to a lower, more steady state. Table 4.2.1-1 denotes the range of flows observed during the course of the study broken out by season. Figures 4.2.1-3 – 4.2.1-5 depict SSC and flow values for the 2013, 2014, and 2015 spring freshet's while Figures 4.2.1-6 and 4.2.1-7 depict a typical summer and fall period, respectively.

SSC patterns and trends observed in relation to Vernon Project operating conditions – Connecticut River

The Vernon Project is a peaking hydroelectric power plant located at the northern extent of the TFI approximately 9 miles upstream of the StreamSide/Rt. 10 Bridge. The hydraulic capacity of Vernon is 17,130 cfs. That is, Connecticut River discharge at or below 17,130 is regulated by Vernon while flows greater than 17,130 cfs spill through the Vernon Dam tainter gates. Figure 4.2.1-8 depicts SSC values as related to a typical Vernon peaking sequence when flows are below 17,130 cfs, as recorded at the Rt. 10 Bridge. Further observations of Vernon peaking operations in relation to Connecticut River SSC values can be found in the timeseries plots contained in Appendix D.

As discussed in the previous section, based on analysis of data collected at the Rt. 10 Bridge, flows below 12,000 cfs typically corresponded to low SSC levels without an increasing trend; however, an increasing pattern of SSC was observed for flows between 12,000 and 17,130 cfs. The increasing pattern of SSC during these periods could be the result of a number of factors which will be explored in greater depth as part of Study No. 3.1.2 *Northfield Mountain/Turners Falls Operations Impacts on Existing Erosion and Potential Bank Instability.*

SSC patterns and trends observed in relation to Northfield Mountain Project operating conditions – Northfield Mountain Tailrace

The StreamSide, HYDROs, and grab sample data were analyzed in relation to flow and Northfield Mountain operating conditions (pumping and generating) to examine the following:

- If an increase in SSC values were observed during pumping or generating cycles (or both) and if the number of units online had an effect;
- How varying levels of SSC in the mainstem could impact the Project during pumping and generating cycles; and
- If differences existed between the SSC values recorded at the north and south banks of the tailrace over a range of flow and operating conditions

Three representative time periods were examined in detail, during which a range of flows and operational conditions were observed. These time periods included:

- A spring freshet when flows increased to a level greater than 35,000 cfs (April 7-21, 2014);
- A moderate flow period when flows were between 12,000 – 35,000 cfs (April 21-28, 2014); and
- A low flow period when flows were less than 12,000 cfs (August 2014)

During the spring freshet time period (Figures 4.2.1-9 and 4.2.1-10) mainstem SSC values (as measured at the StreamSide) increased rapidly with flow, were generally high, and followed a pattern similar to the river flow. During the same spring freshet time period, SSC measurements as recorded at the HYDROs were comparable to those measured in the mainstem (at the StreamSide) when the Project was pumping, meaning that pumping had no discernable impact on mainstem SSC levels at that location. Alternatively, SSC values lower than those observed in the mainstem were observed when the Project was generating. This suggests that the Project was pumping more suspended sediment into the Upper Reservoir than it was transporting back to the river, which is consistent with the bathymetry results discussed in Section 4.1 indicating the accumulation of sediment in the Upper Reservoir over time. There was no clear pattern in relation to the number of units operating. When the Project was idle, or occasionally when only generating one unit, variability in the SSC levels in the tailrace can be observed; this is more likely due to changing currents in the vicinity of the tailrace than effects associated with the Project. During high flow periods, correlations between Project operations and increased mainstem SSC levels were not observed.

Review of the moderate flow scenario plot (Figure 4.2.1-10) demonstrates a similar pattern as was observed when reviewing the high flow scenario, although at lower SSC levels. SSC data measured at the HYDROs tended to be lower than mainstem SSC data measured at the StreamSide when the Project was idle or generating. During pumping operations, higher SSC values more comparable to mainstem SSC values were observed. The relatively lower measurements during generation combined with measurements similar to those observed in the mainstem during pumping suggests that suspended sediment was accumulating in the Upper Reservoir, although in lower quantities than observed during the high flow scenario. During moderate flow periods, correlations between Project operations and increased mainstem SSC levels were not observed.

During the low flow period (Figures 4.2.1-12 – 4.2.1-14), SSC values observed in the river were also very low, and differences in SSC between generation and pumping cycles were negligible, with the exception of a mid-summer rain event that occurred on August 14-15, 2014 (Figure 4.2.1-13). The effects of this rain event lasted for approximately four days until SSC at the Project settled back into a steadier, low flow pattern. This event resulted in suspended sediment accumulation in the Upper Reservoir. Similar to the moderate and high flow periods, correlations between Project operations and increased mainstem SSC levels were not observed.

SSC patterns observed across the Northfield Mountain Tailrace

Data collected at the Northfield Mountain tailrace were also compared to determine if SSC levels differed between locations (north vs. south bank) over a range of flow and operating conditions. During 2015, grab samples were taken from edge-of-water locations that corresponded to the LISST instrument locations. The paired grab samples from the north and south banks of the Northfield Mountain tailrace were then analyzed for differences in suspended sediment concentrations between both banks (Figure 4.2.1-15). For all paired samples, no significant difference was found in suspended sediment concentrations between the north and south banks (K-S test $p = 0.9592$). For paired samples that were taken during the pumping and generating cycle, no differences in suspended sediment concentration on either bank were found (K-S test $p = 0.6208$ and 0.9971 respectively).[23] Similar to cross-sectional results from the LISST-100X sampling, no differences were found from bank to bank. Based on the results of this comparison it was determined that differences between the two banks were negligible. This differs from what was observed from the two HYDRO instruments, which were of the same design. HYDRO measurements provided were often different given that each instrument had unique lenses and the technical difficulties encountered were instrument-specific. Therefore, differences between measurements of the instruments were deemed to be due to instrumental or sampling error (i.e., indirect laser scattering measurements), rather than actual differences in suspended sediment concentration.

[23] The p-value represents the probability that the two groups of samples were collected from the same water over the course of sampling. Further discussion regarding this test can be found in Section 3.2.3

Table 4.2.1-1 Seasonal Range of Flows and SSC (2013-2015)

Season	Months	Flow Range (cfs)	Median Flow (cfs)	SSC Range (mg/L)	Median SSC (mg/L)
Spring 2013	April - June	2,251-55,570	14,751	0.17-163.46	5.28
Summer 2013	July & August	1,318-61,733	8,750	0.29-149.62	5.20
Fall 2013	September-November	1,423-18,769	5,931	0.37-4.40	2.12
Spring 2014	April - June	1,731-68,338	20,080	0.05-449.76	11.47
Summer 2014	July & August	1,535-26,481	6,762	0.49-86.51	3.67
Fall 2014	September-November	1,360-25,450	5,160	0.14-157.3979	6.36
Spring 2015	April - June	1,668-66,725	15,340	2.00-43.02	10.68
Summer 2015	July -August	1,346-27,042	4,718	<0.5-42.7	1.5
Fall 2015	September-October	1,521-32,910	1,949	<0.5-61.2	1.6

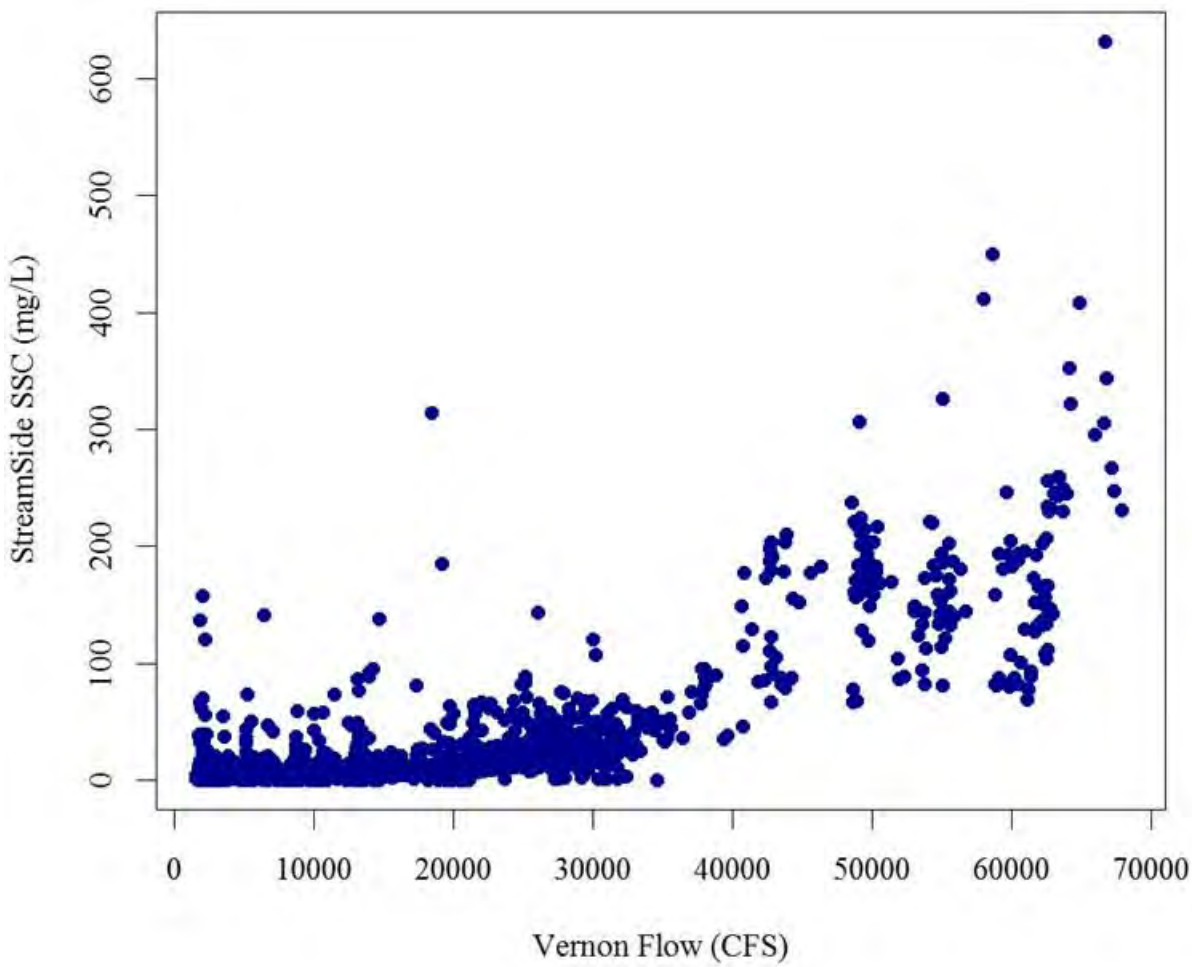

Figure 4.2.1-1 Turners Falls Impoundment SSC vs. Vernon Discharge (2013-2015)

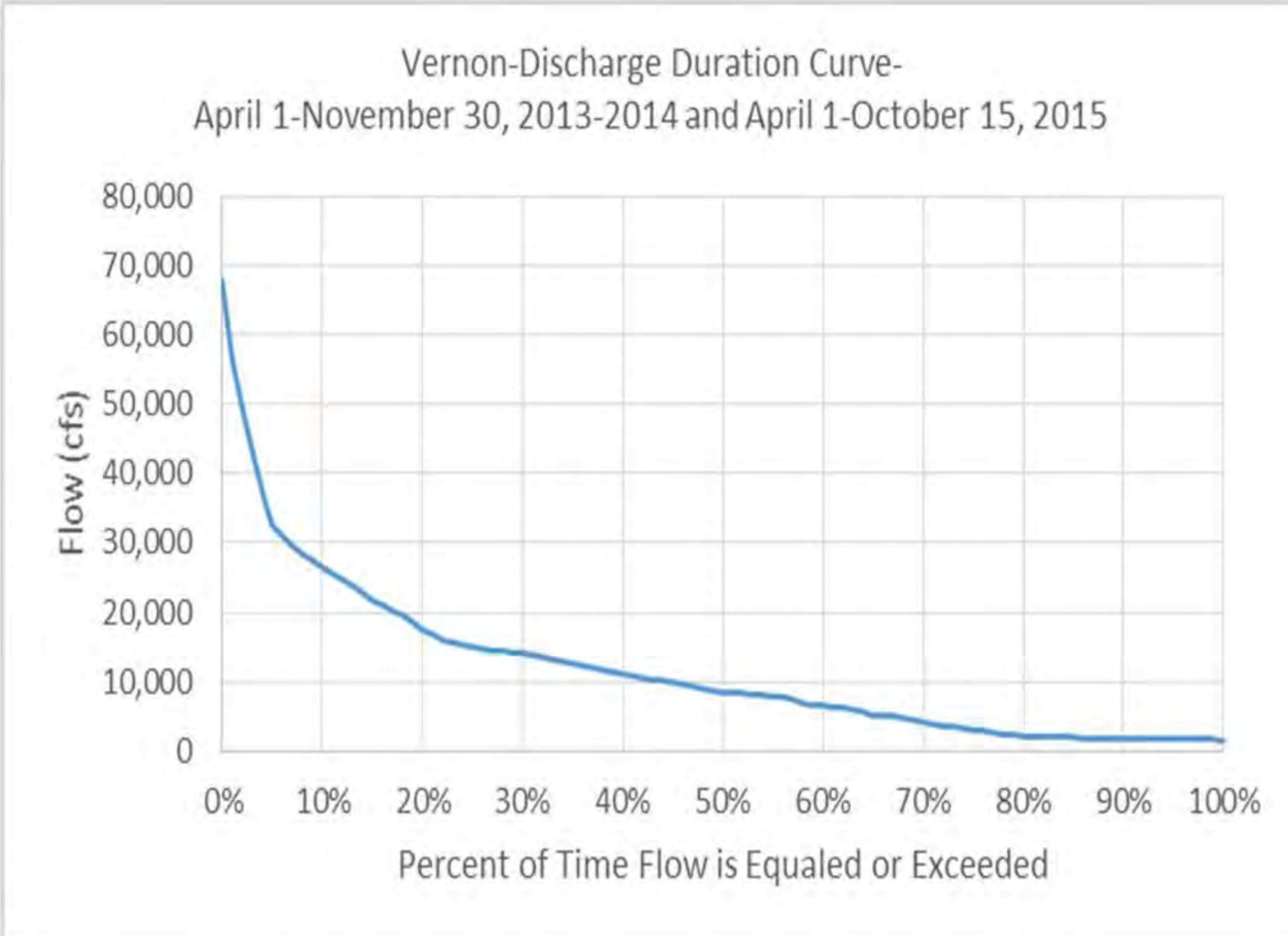

Figure 4.2.1-2 Flow Duration Curve for the Turners Falls Impoundment

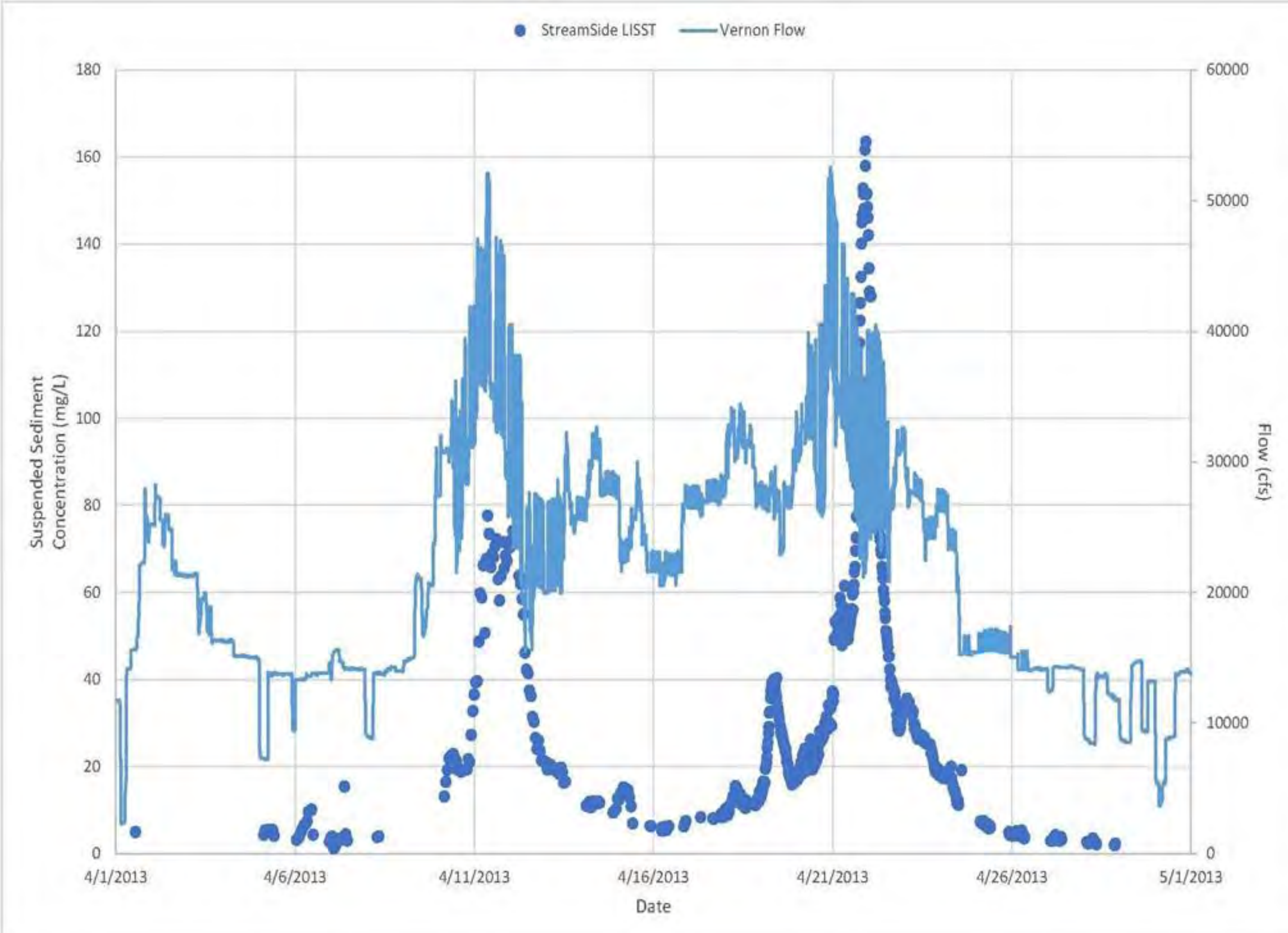

Figure 4.2.1-3 2013 Spring Freshet – SSC vs. Flow (StreamSide)

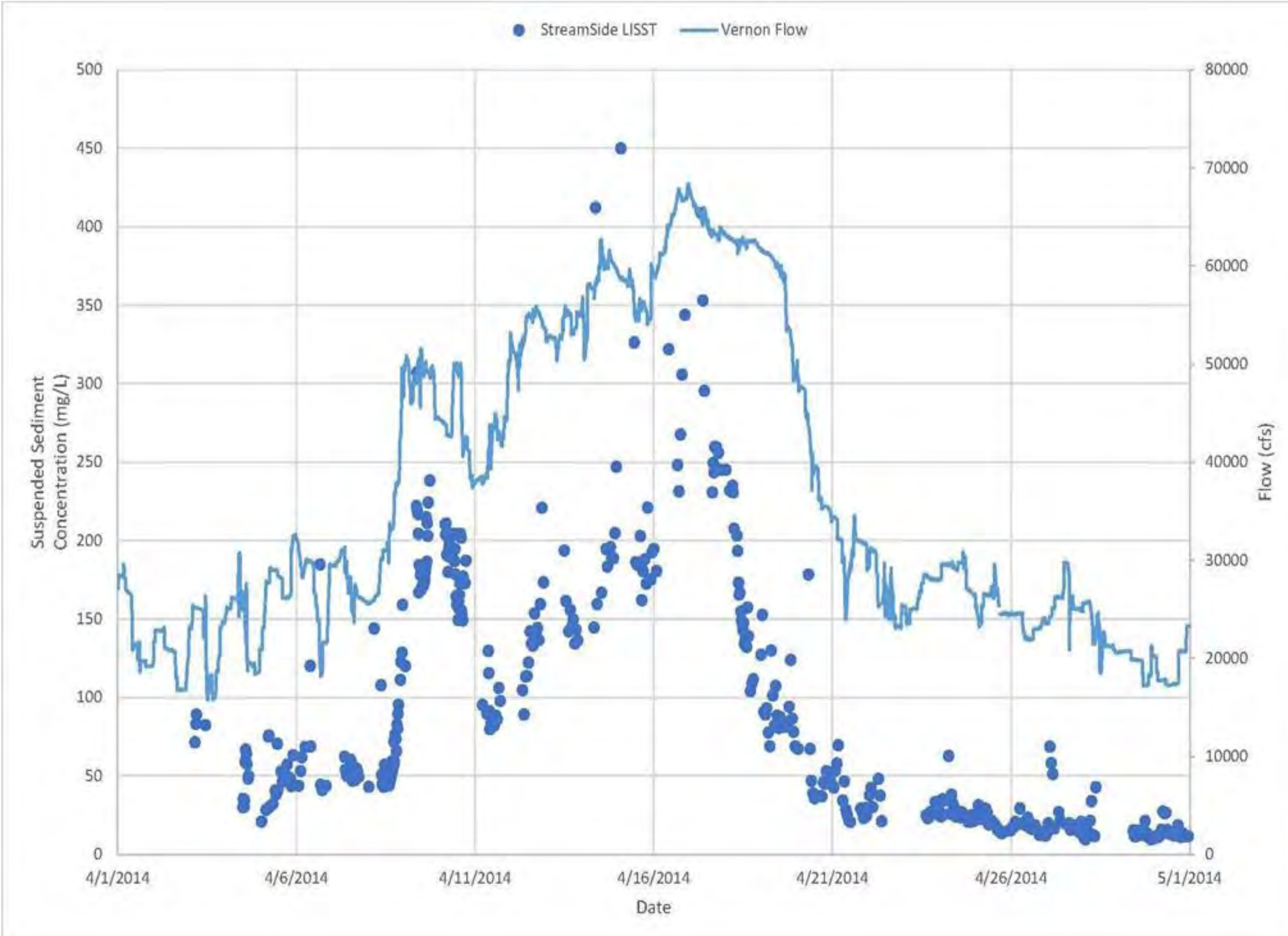

Figure 4.2.1-4 2014 Spring Freshet – SSC vs. Flow (StreamSide)

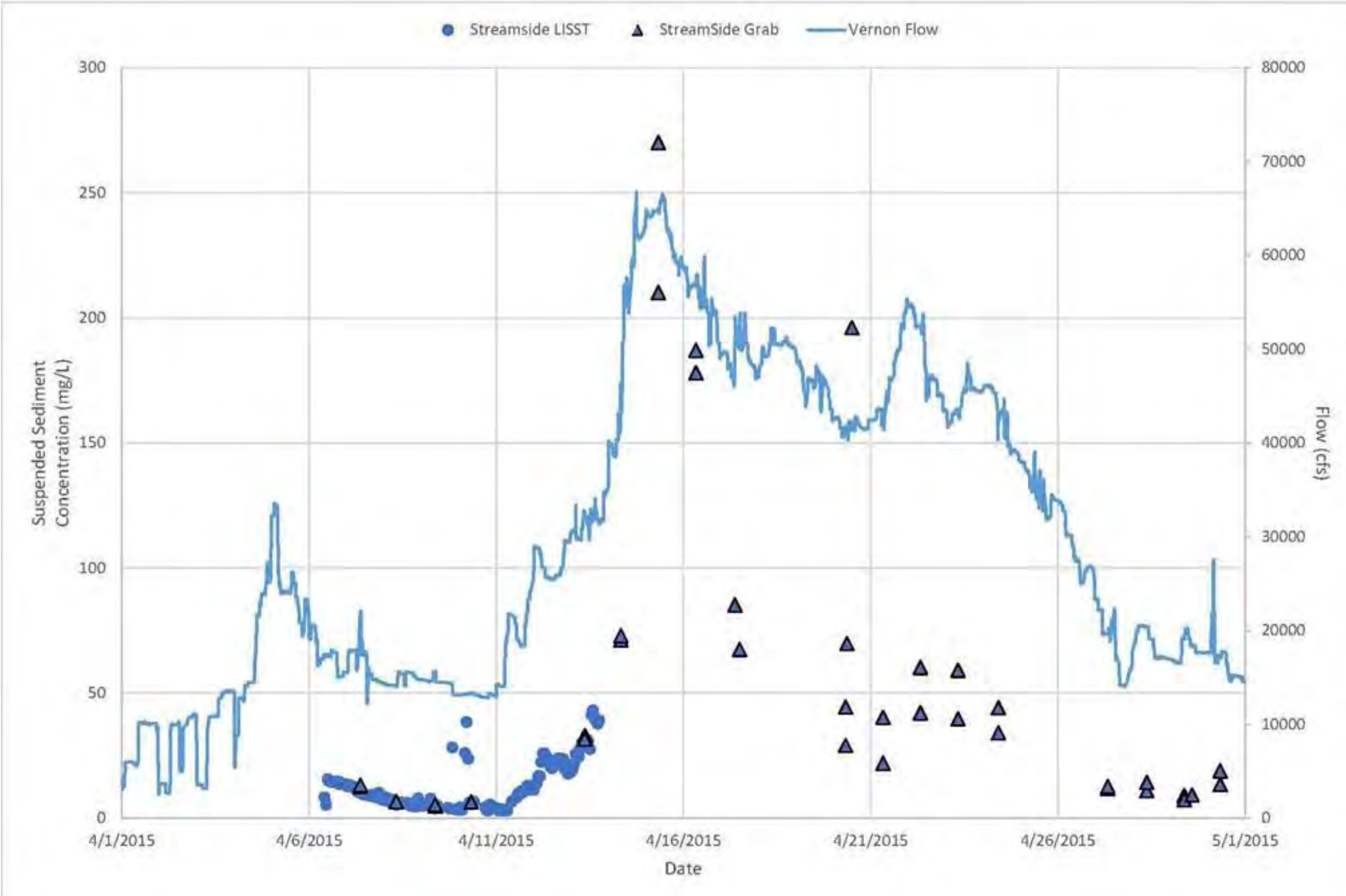

Figure 4.2.1-5 2015 Spring Freshet – SSC vs. Flow (StreamSide)

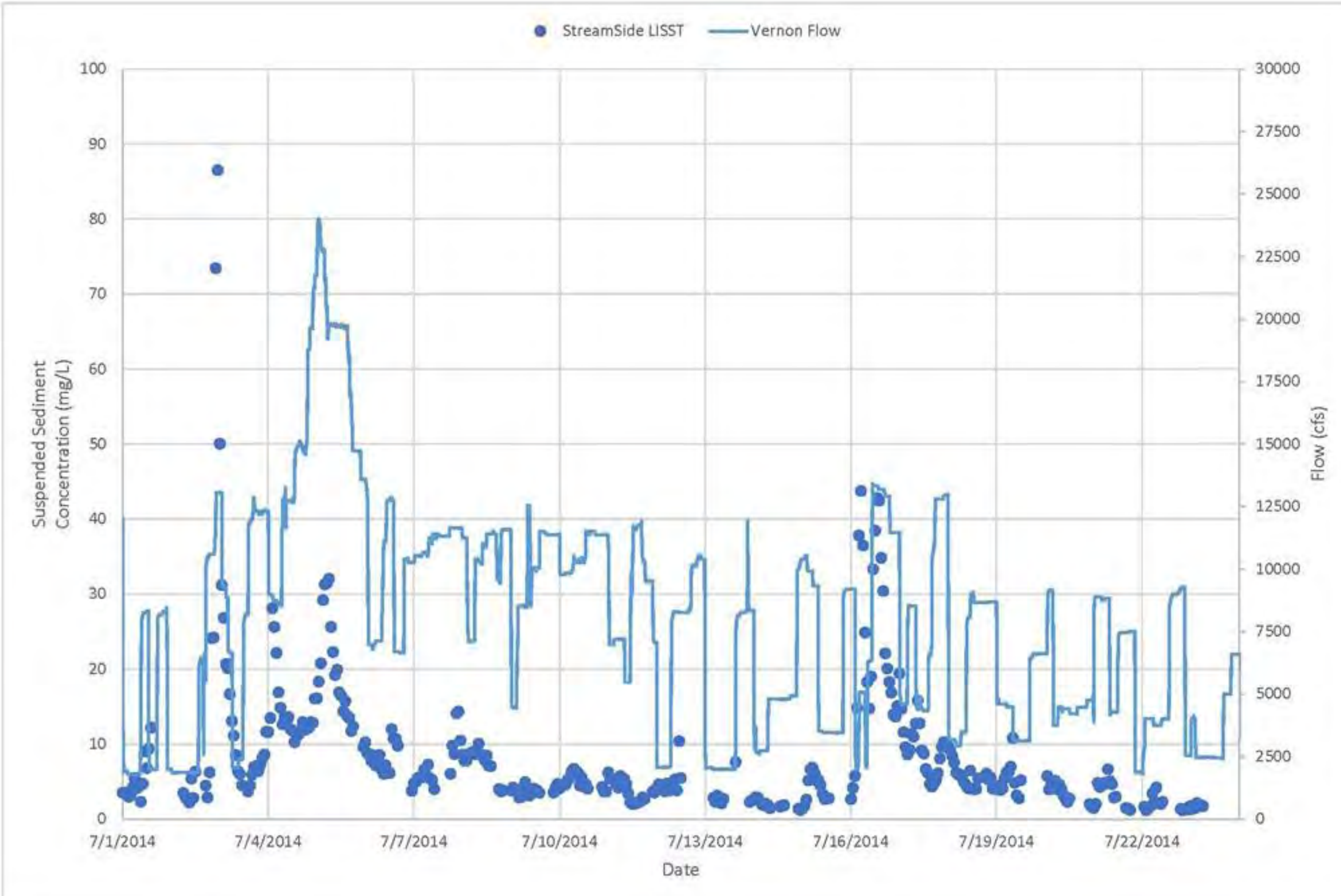

Figure 4.2.1-6 Typical Summer Period – SSC vs. Flow (StreamSide)

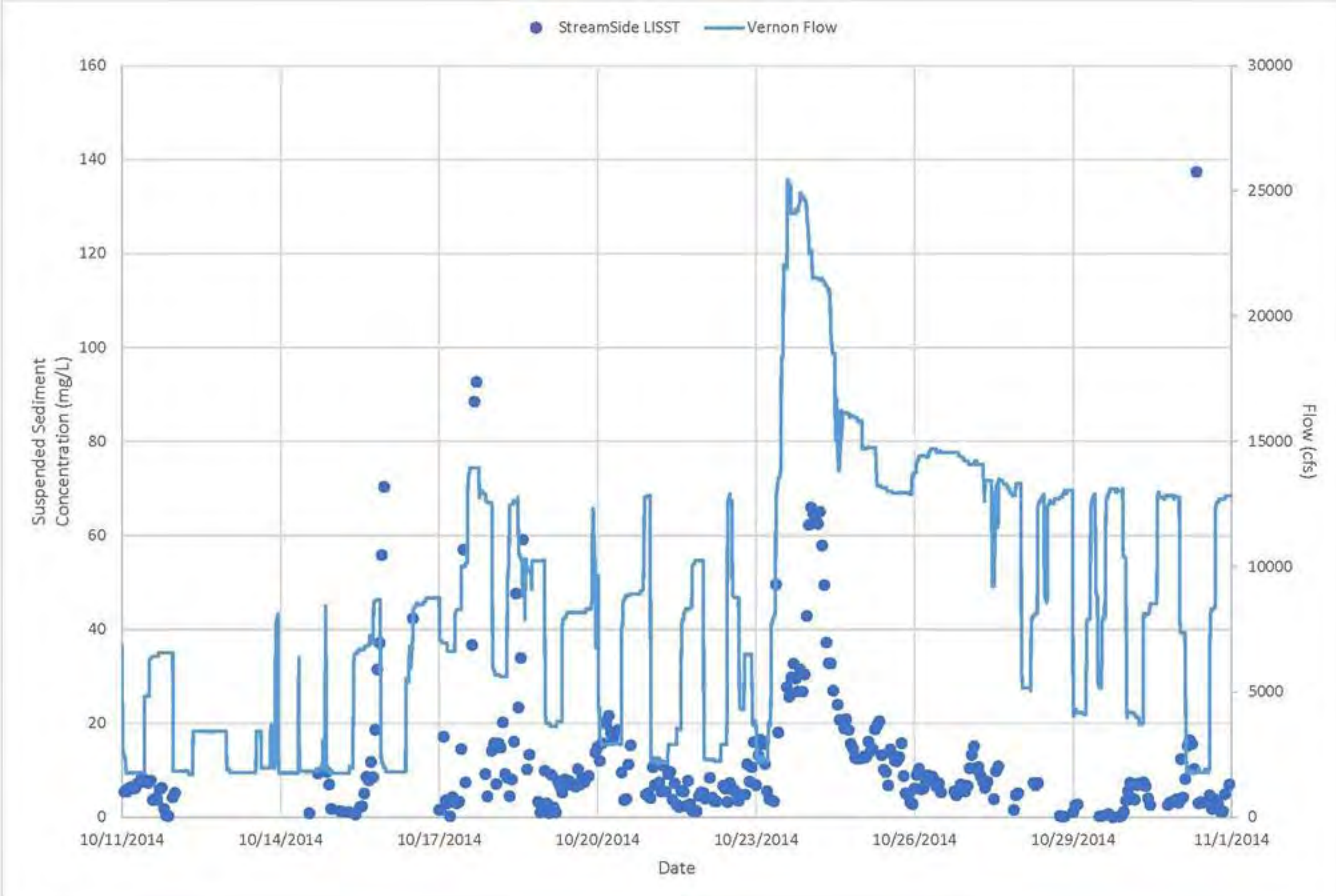

Figure 4.2.1-7 Typical Fall Period – SSC vs. Flow (StreamSide)

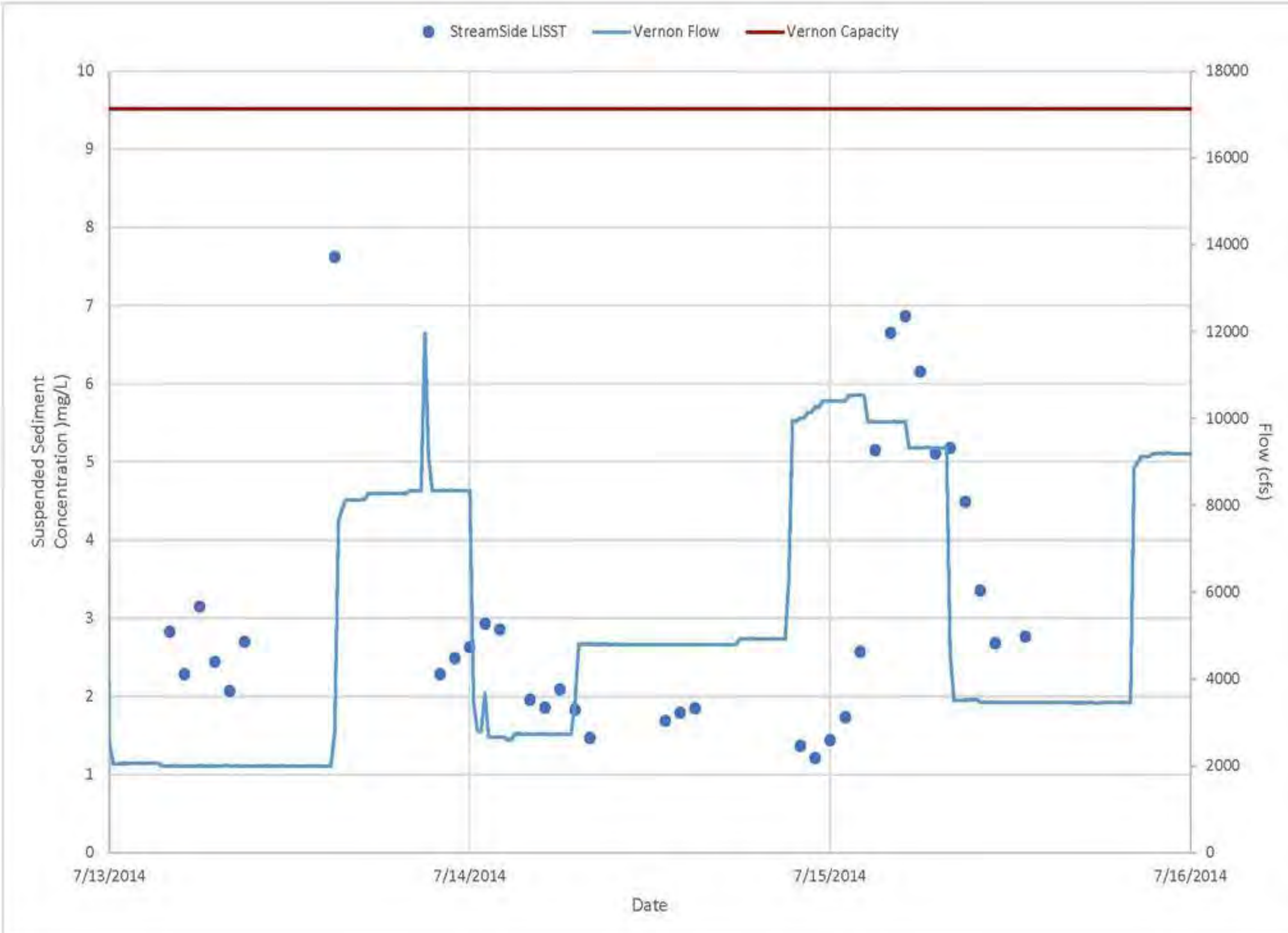

Figure 4.2.1-8 Turners Falls Impoundment SSC Values as Related to a Typical Vernon Peaking Sequence

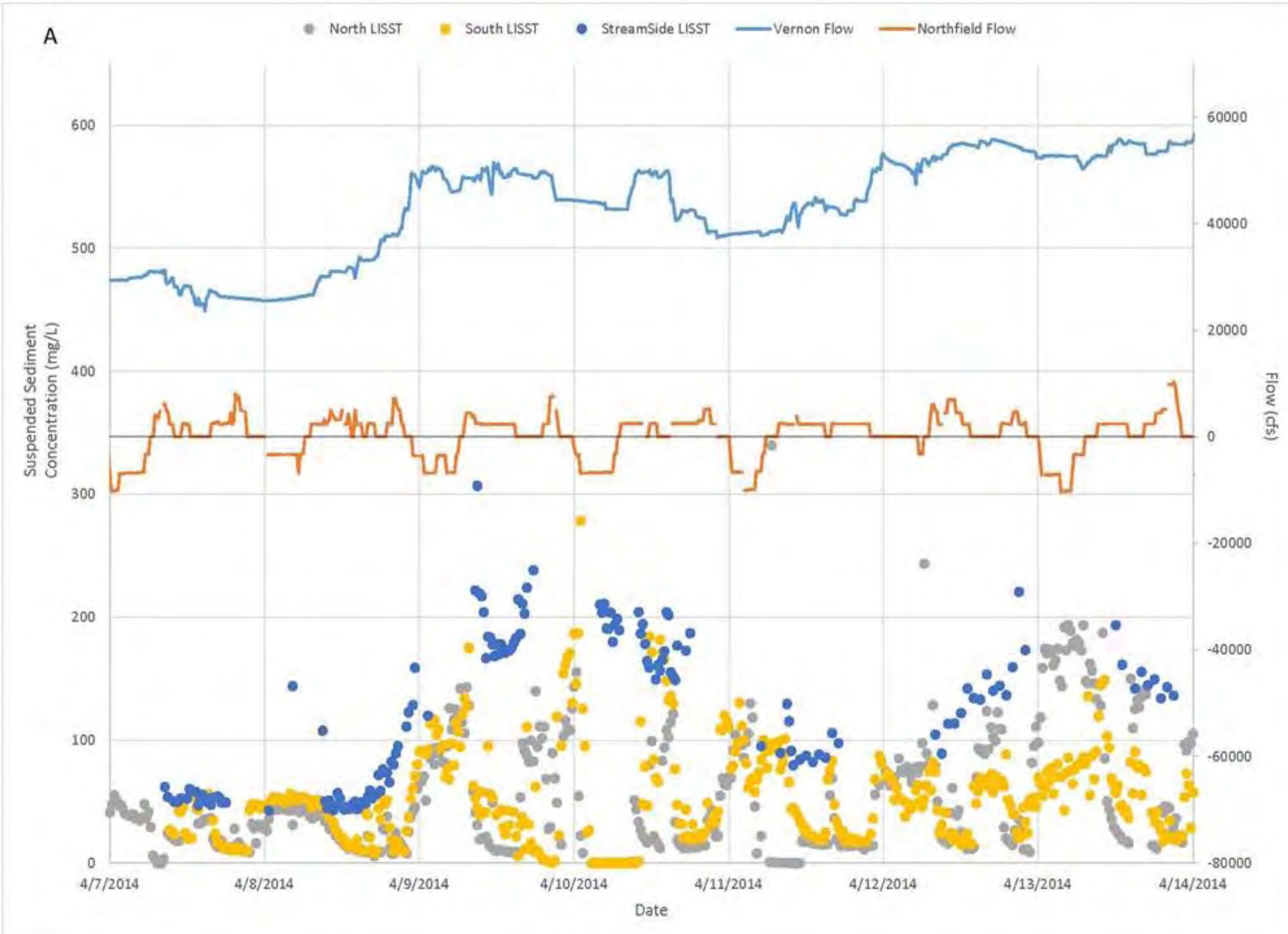

Figure 4.2.1-9 Northfield Mountain Tailrace High Flow Scenario (April 7-14, 2014)

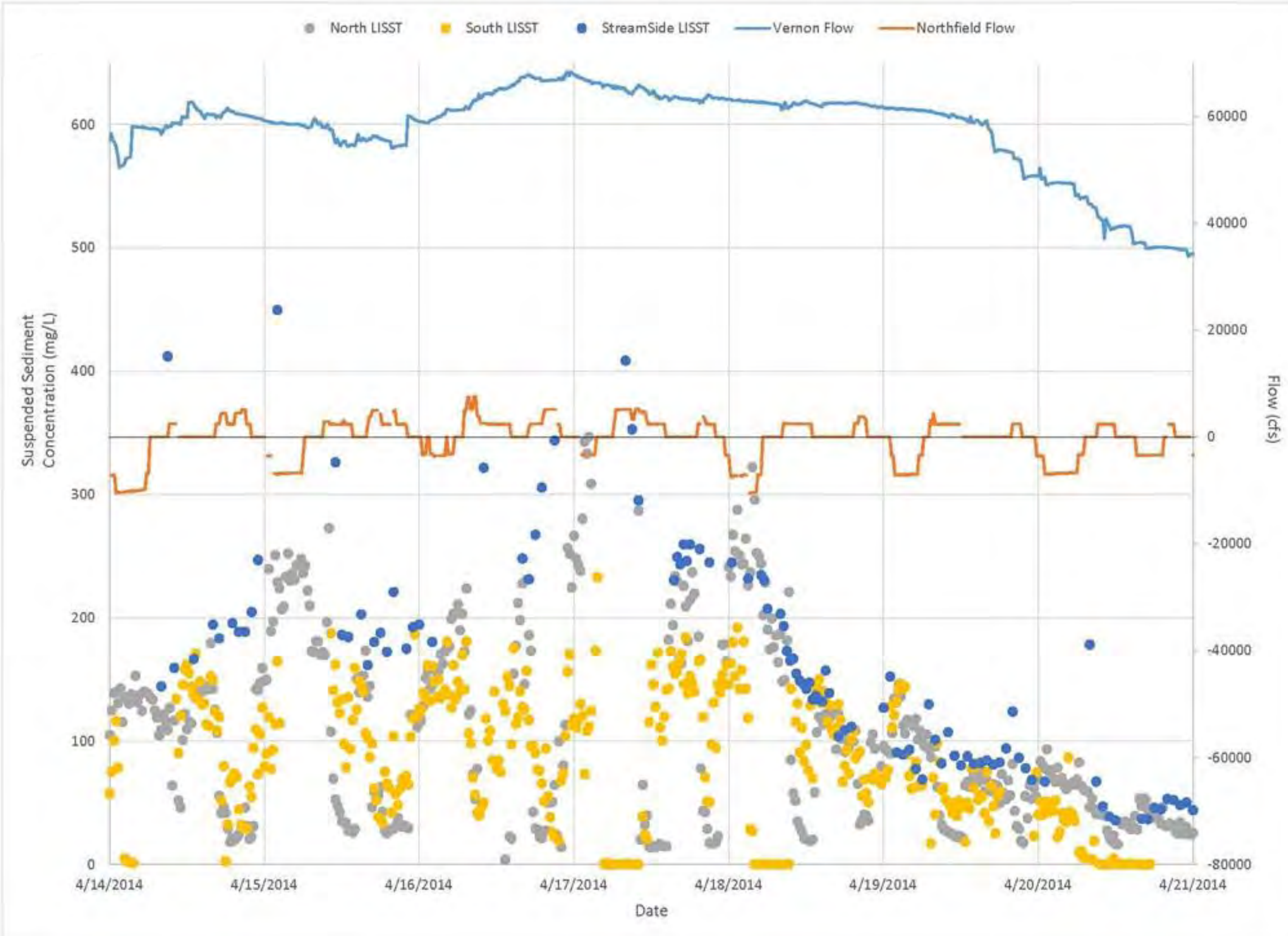

Figure 4.2.1-10 Northfield Mountain Tailrace High Flow Scenario (April 14-21, 2014)

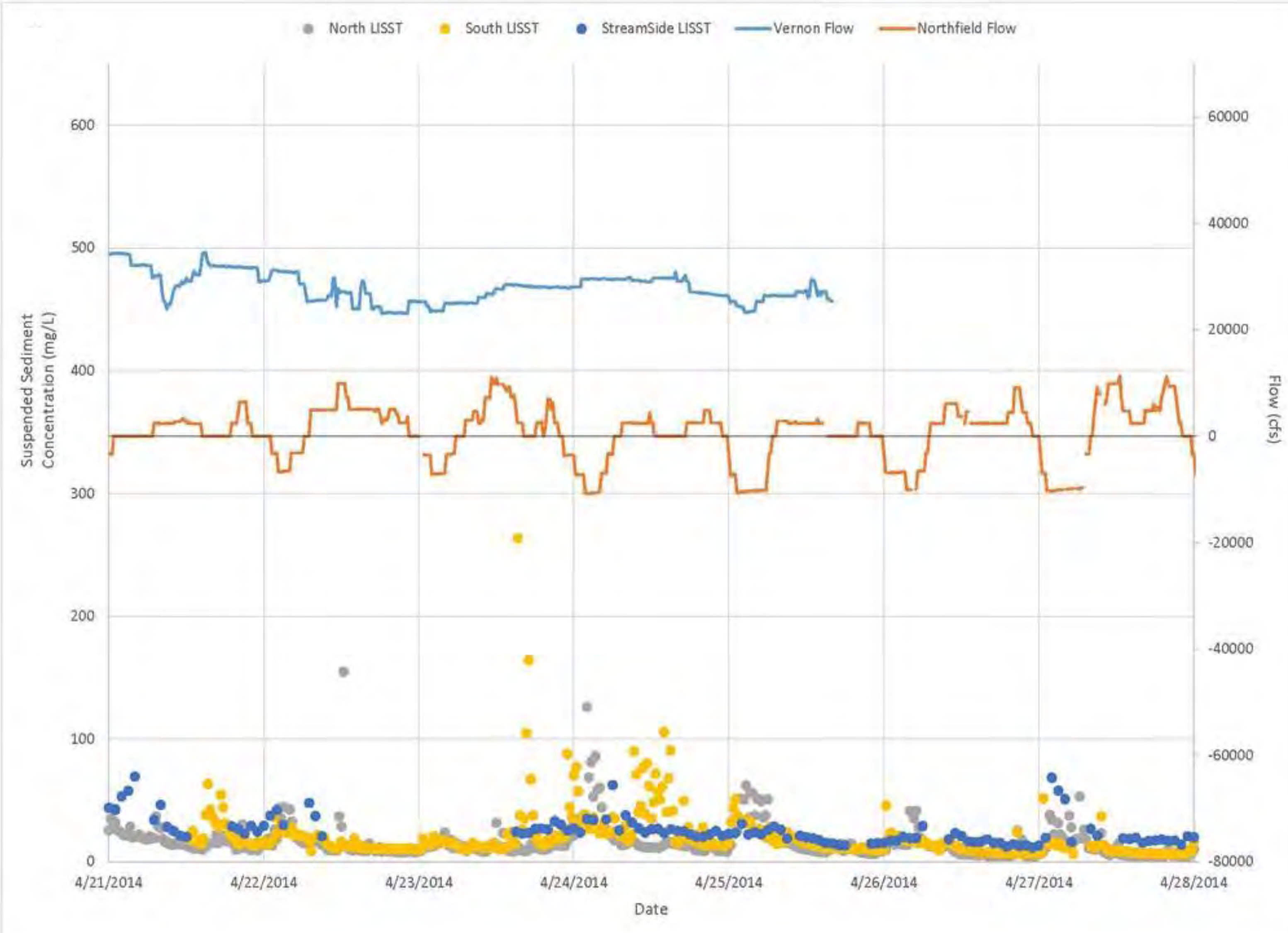

Figure 4.2.1-11 Northfield Mountain Tailrace Moderate Flow Scenario (April 21-28, 2014)

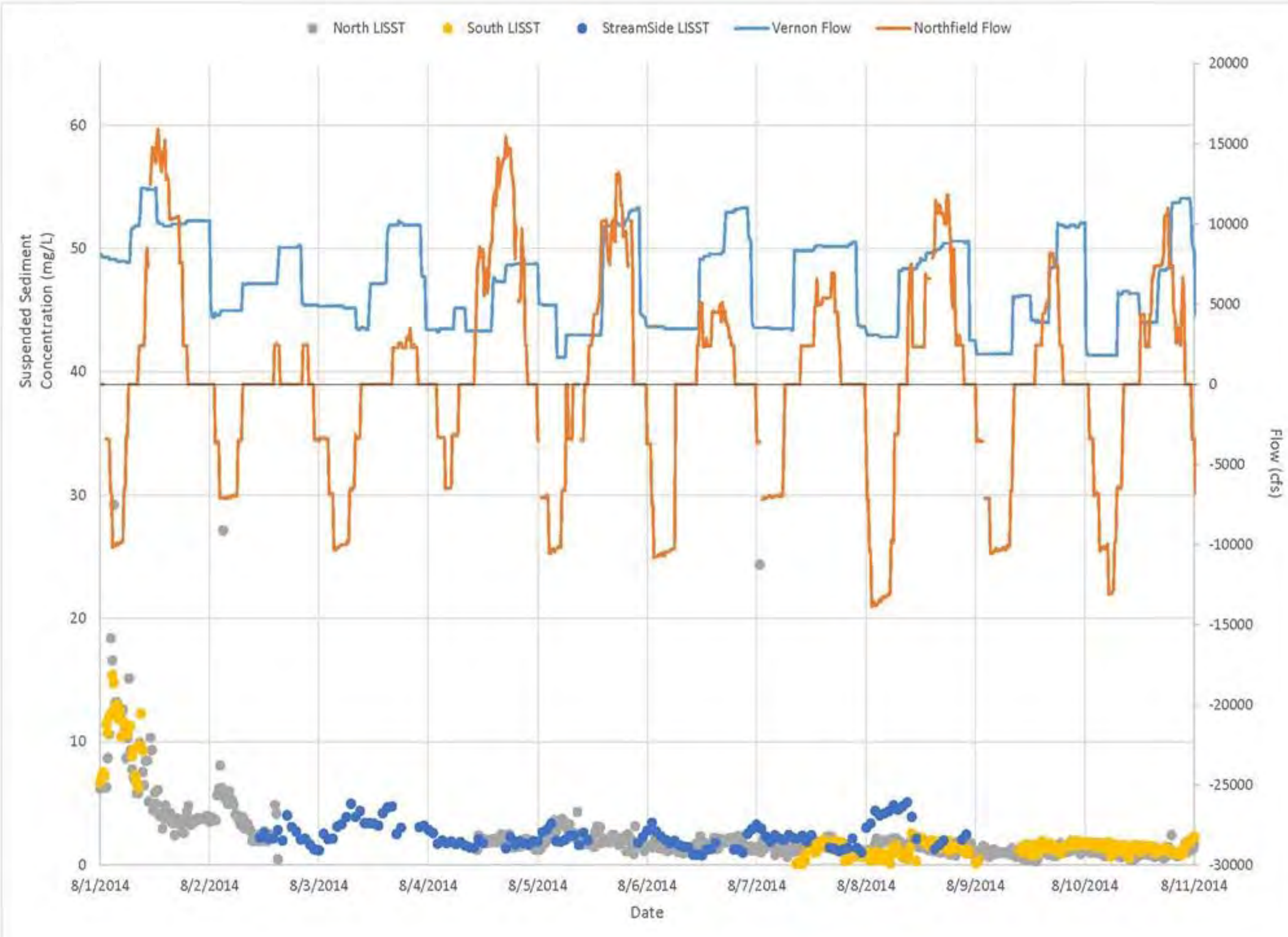

Figure 4.2.1-12 Northfield Mountain Tailrace Low Flow Scenario (August 1-11, 2014)

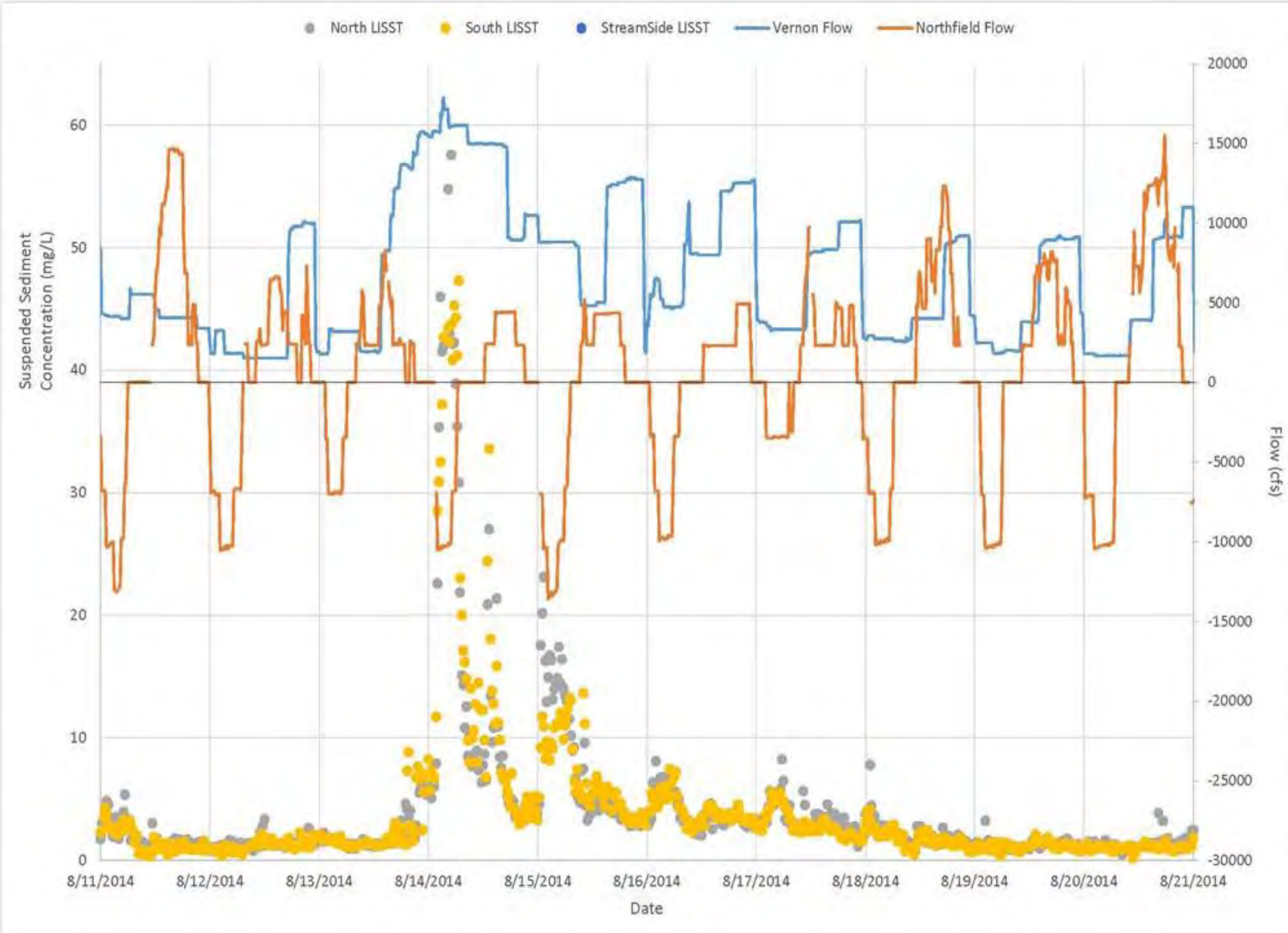

Figure 4.2.1-13 Northfield Mountain Tailrace Low Flow Scenario (August 11-21, 2014)

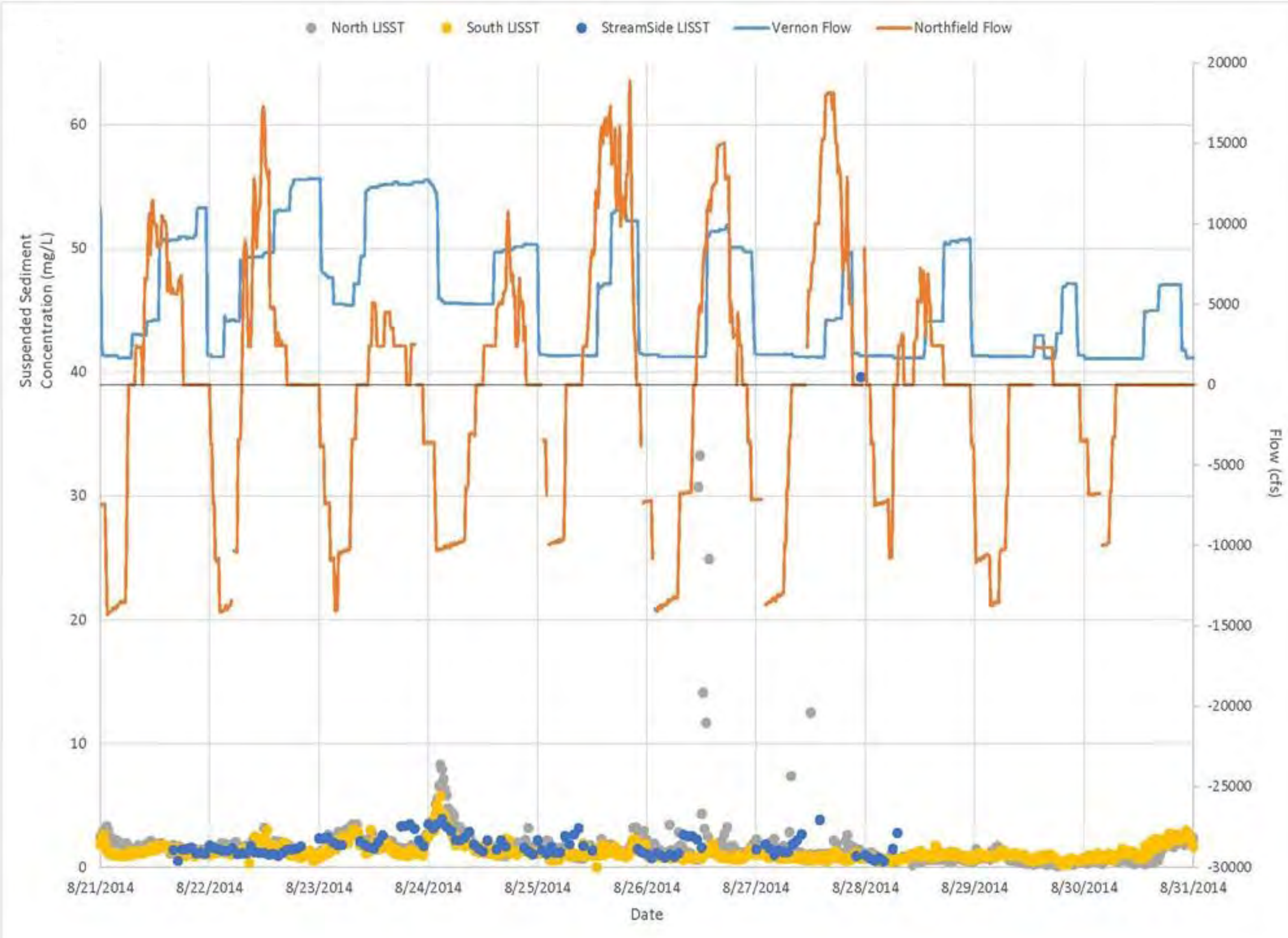

Figure 4.2.1-14 Northfield Mountain Tailrace Low Flow Scenario (August 21-31, 2014)

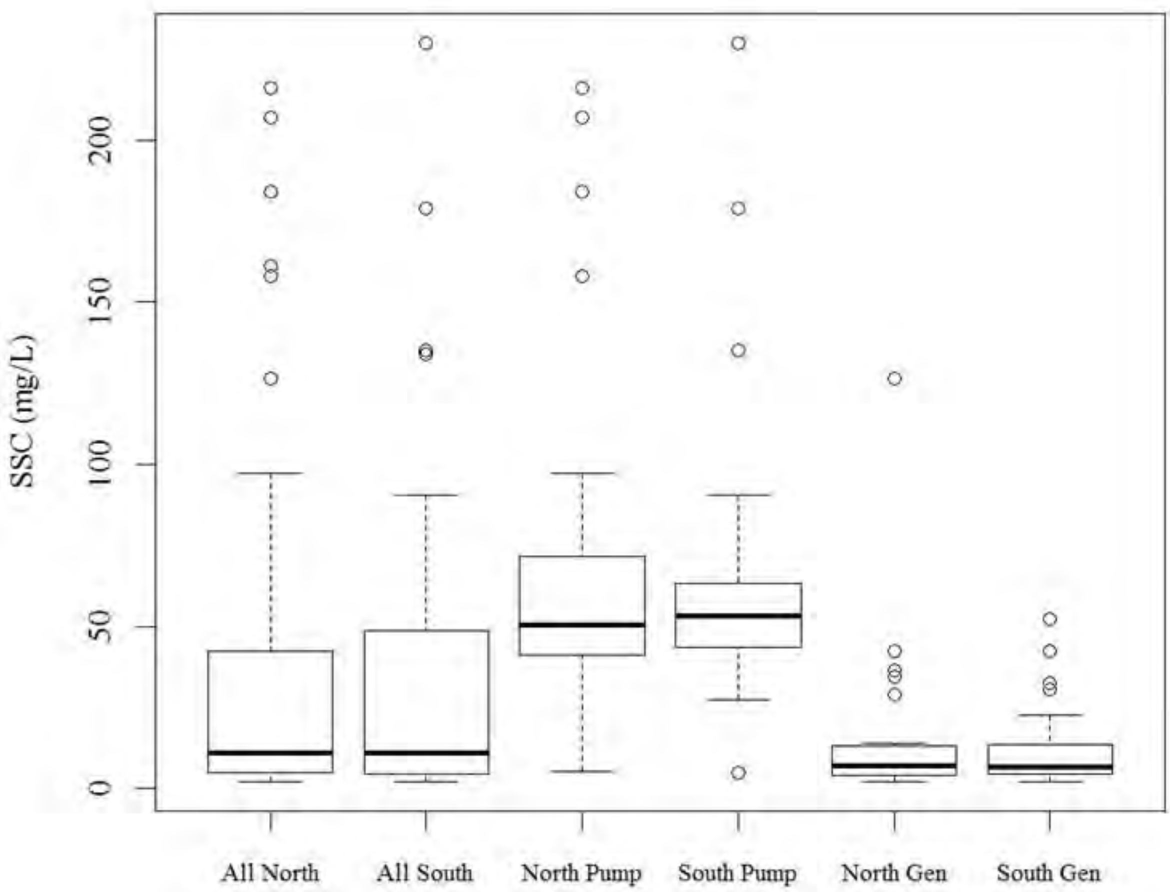

Figure 4.2.1-15 Paired Northfield Mountain Tailrace Grab Samples

4.2.2 Comparison of Cross-sectional Data - Rt. 10 Bridge and Northfield Mountain tailrace

In 2013, cross-sectional data were collected at the Rt. 10 Bridge and Northfield Mountain tailrace boat barrier buoy line over a range of flow and operating conditions via a LISST-100X. In 2015, supplemental cross-sectional grab sample data were collected at the Rt. 10 Bridge via a Kemmerer. Data collected during 2013 and 2015 followed the EWI method. The purpose of the cross-section data was to develop a better understanding of SSC dynamics across a cross-section and with depth and to determine if the StreamSide and HYDRO pump locations were representative of cross-section conditions. This section presents the results of the cross-section data collection efforts.

Rt. 10 Bridge Cross-section

LISST-100X data were collected across the Rt. 10 Bridge on eight separate occasions in 2013 over a range of flows (Table 4.2.2-1). The LISST-100X data were used to identify patterns in the variation of SSC across the cross-section and with depth. Review of this dataset found that changes in SSC across the river and with depth were only observed during the highest flow event measured (Vernon discharge 31,382 cfs on April 18, 2013). SSC values were highest on the left bank and near the bottom (Figure 4.2.2-1), though the range of measurements collected was only 5.4 µl/L. It was determined that the StreamSide pump was positioned in a location representative of the cross-section and that adjustments to the StreamSide data were not necessary. Appendix F contains various plots developed from the 2013 LISST-100X data.

Supplemental cross-section grab sample data were collected in 2015 on four separate occasions during the spring freshet (Table 4.2.2-2). Figure 4.2.2-2 depicts the hydrograph from this event as well as when grab samples were collected. Grab sampling events occurred during the rising limb, on either side of the peak, and across the falling limb. Grab samples were also collected from the edge-of-water in the vicinity of the StreamSide pump at the completion of the cross-section data collection to allow for direct comparison.

The results from the 2015 cross-section grab samples generally confirmed the findings of the LISST-100X data collection effort in 2013. SSC variation across the cross-section and with depth was not evident or was negligible during moderate flows (Figure 4.2.2-6). During higher flow, areas near the left bank exhibited slightly higher SSC values than the right bank, and SSC was often slightly higher with depth, particularly near the left bank (Figure 4.2.2-3 to 4.2.2-5). It should be noted that the cross-sectional surveys typically took approximately three hours to complete, which could also account for some of the variability. This may be particularly true of the April 14th and 17th sampling events, during which flow increased over the course of sampling.

Samples collected from the edge-of-water in the vicinity of the StreamSide pump were typically near or within the range of measurements from the cross-section. During the April 14th sampling event (Figure 4.2.2-3), the sample collected near the StreamSide (on the right bank) was comparable to the higher measurements observed from the cross-section near the left bank, but considerably higher than much of the remainder of the transect; this could be due to sample timing, given that flows and possibly SSC were increasing during this sampling event and the sample was collected near the StreamSide after the cross-sectional samples were collected. During the April 20th sampling event (Figure 4.2.2-5), SSC from the sample collected near the StreamSide was higher than expected based on the cross-sectional samples, though it was comparable to some of the higher measurements observed during cross-sectional sampling. The reason for this is unclear and could not be resolved in the absence of duplicate measurements, though potential explanations include sample timing, sample method, location, or laboratory sample issues. Samples collected near the StreamSide during the remaining two sampling events on April 17th and 28th (Figures 4.2.2-4 and 4.2.2-6) were comparable to the samples collected from the cross-section.

Northfield Mountain Tailrace Cross-section

LISST-100X data were collected on five occasions over a range of operating conditions across the Northfield Mountain tailrace boat barrier buoy line in 2013 (Table 4.2.2-3). Sediment concentrations did not change considerably by station or with depth, with measurements varying no more than 0.5 to 1.0 µl/L for the duration of the survey. Given these findings, it is likely that the pumps for the LISST HYDRO instruments are representative of the cross-section, and that a single instrument would suffice during the low river flow and SSC. Appendix F contains various plots developed from the 2013 LISST-100X data.

As previously reported, grab samples collected from near the surface at each bank did not differ from bank to bank under a range of flows and operational conditions, though it should be noted that tailrace sampling during higher river flows at different depths did not occur. FirstLight had proposed collecting supplemental grab sample data in 2015 at the Northfield Mountain tailrace cross-section during a moderate to high flow event (20,000-30,000 cfs); however, while these flow conditions did occur during the field season, sample collection did not occur due to safety concerns.

Table 4.2.2-1 Summary of LISST-100X Data Collected at the Rt. 10 Bridge (2013)

Date	Vernon Discharge (cfs)	Max SSC (µl/L)	Min SSC (µl/L)	Median SSC (µl/L)
4/18/2013	33,483	38.94	33.53	34.83
4/26/2013	15,980	10.54	10.26	10.42
5/2/2013	10,707	2.71	2.54	2.58
5/10/2013	10,070	4.11	3.73	3.97
10/3/2013	3,363	3.31	3.18	3.28
10/11/2013	5,450	5.40	4.92	5.02
10/16/2013	4,490	2.65	2.33	2.45
10/24/2013	4,278	3.94	3.73	3.84

Table 4.2.2-2 Summary of Rt. 10 Bridge Cross Section Grab Samples (2015)

Date	Vernon Discharge (cfs)	Max SSC (mg/L)	Min SSC (mg/L)	Median SSC (mg/L)	StreamSide SSC (mg/L)
4/14/2015	50,536 - 59,700	159	78.7	108	152
4/17/2015	47,970 - 52,591	106	80.3	89.3	82.1
4/20/2015	41,282 - 42,172	89.5	30.4	41.8	69.7
4/28/2015	19,112 - 20,437	13.5	6.1	11.5	12.5

Table 4.2.2-3 Summary of LISST-100X Data Collected at the Northfield Mountain Tailrace (2013)

Date	Scenario	Naturally Routed Flow (cfs)	Max SSC (µl/L)	Min SSC (µl/L)	Median SSC (µl/L)
10/10/2013	Idle	6,782	4.42	3.18	4.17
10/15/2013	1-Unit Gen	4,171	2.14	2.08	2.07
10/23/2013	2-Units Gen	4,640	2.90	2.28	2.62
10/26/2013	3-Units Gen	4,955	3.10	2.63	2.77
10/26/2013	2-Units Pump	4,955	3.10	2.25	2.45

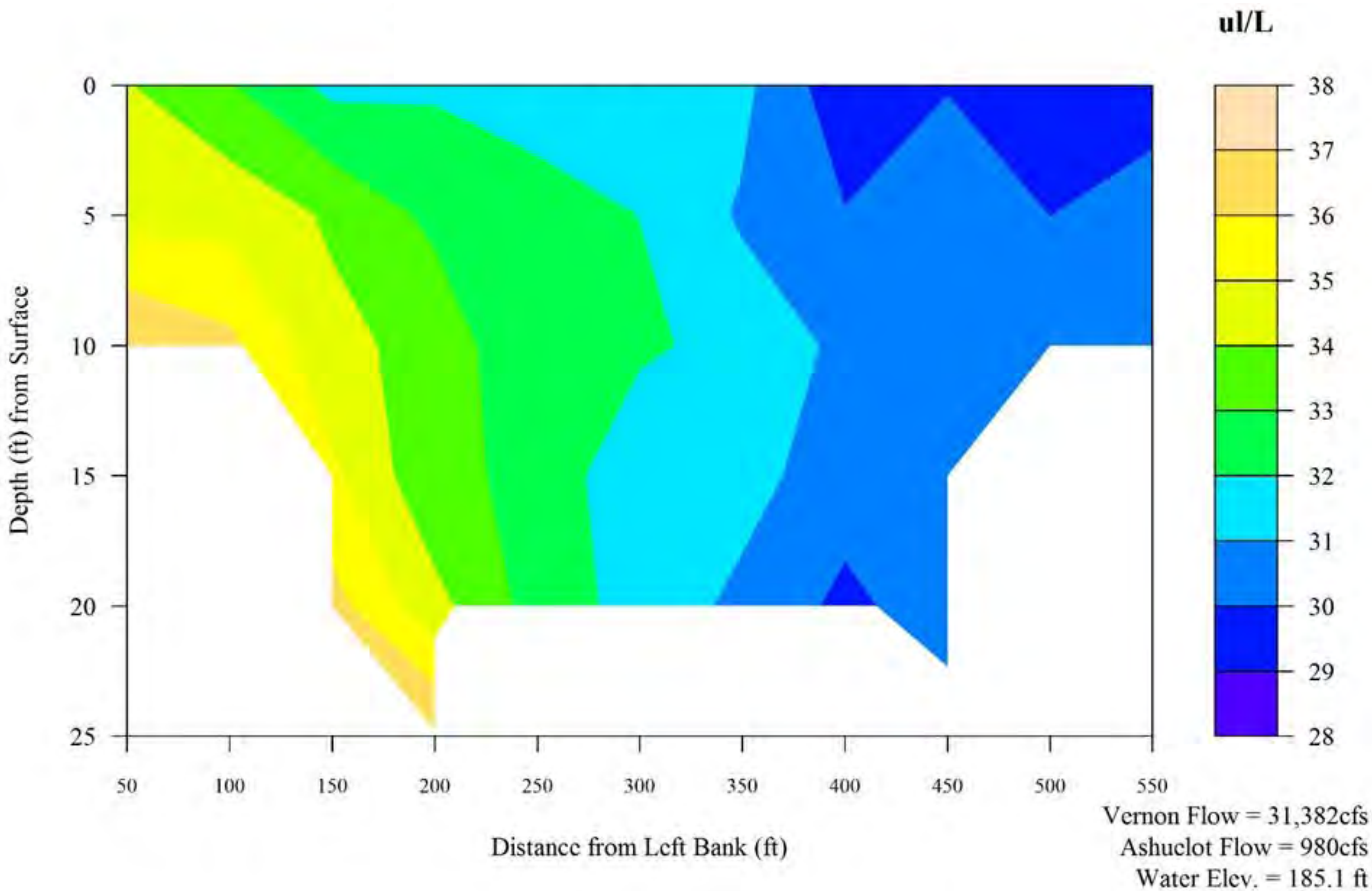

Figure 4.2.2-1 SSC Isopleth from Rt. 10 Bridge - April 18, 2013 (LISST-100X)

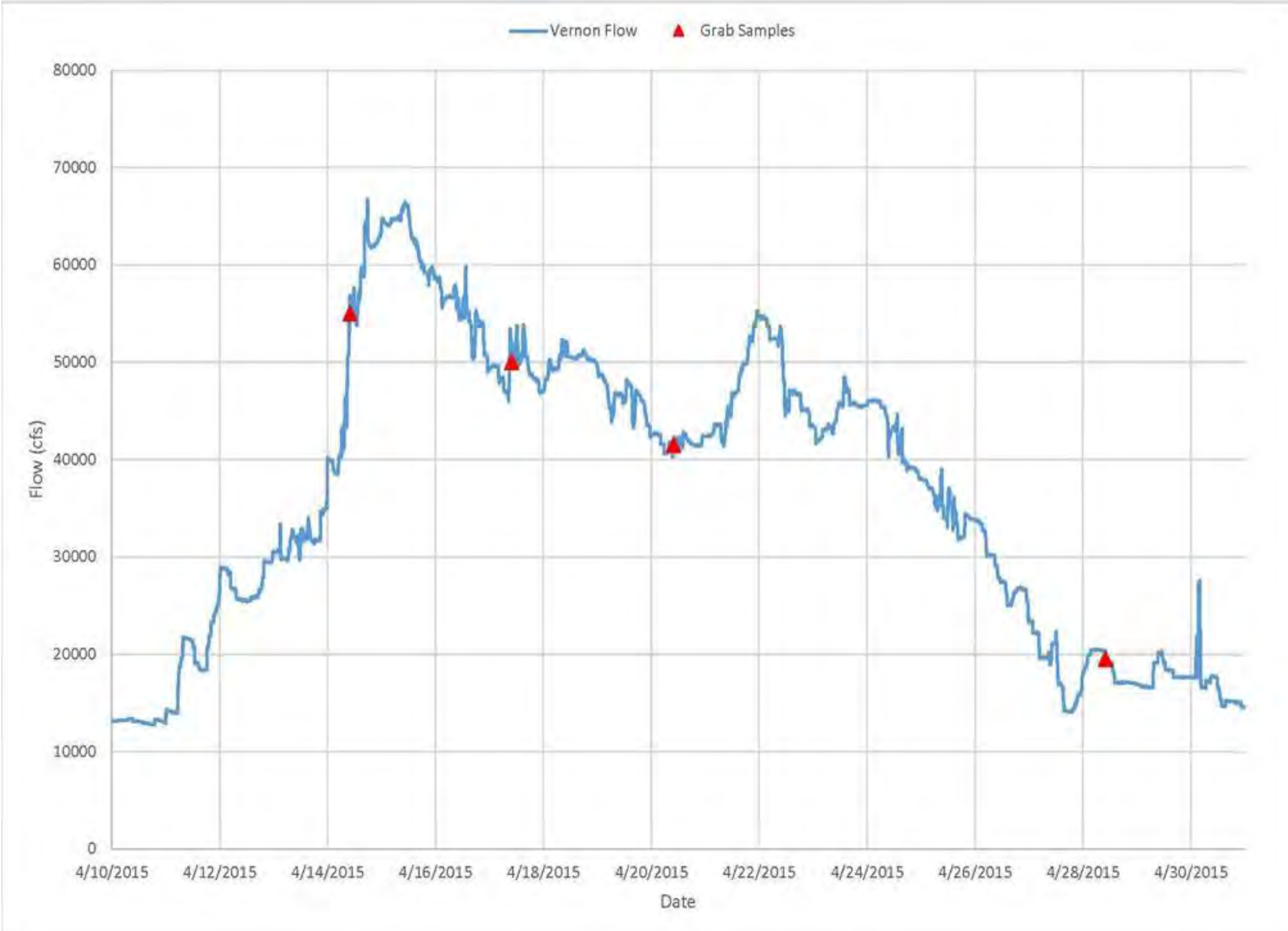

Figure 4.2.2-2 Turners Falls Impoundment Hydrograph - Rt. 10 Bridge Grab Sample Data Collection

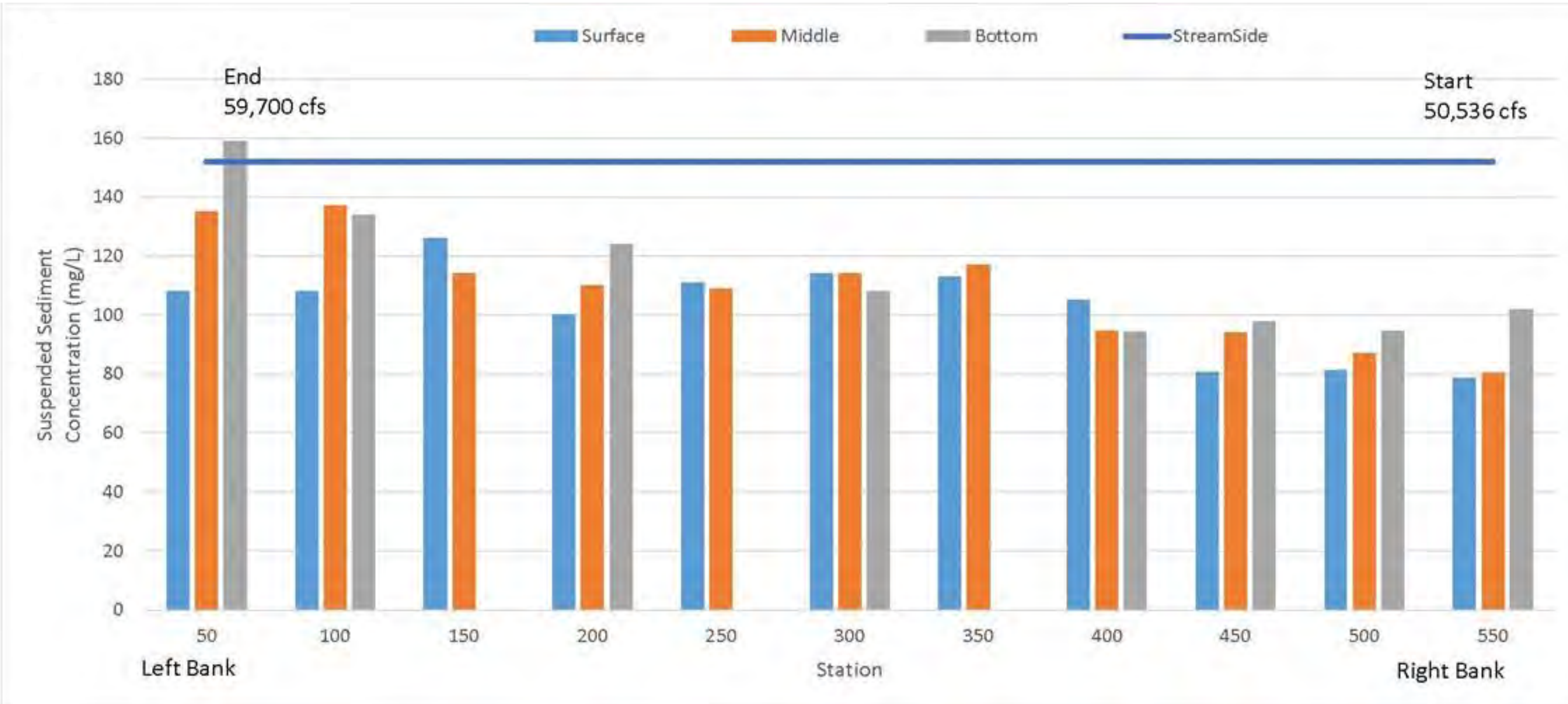

Figure 4.2.2-3 Rt. 10 Bridge Cross-section Grab Sample Data (April 14, 2015)

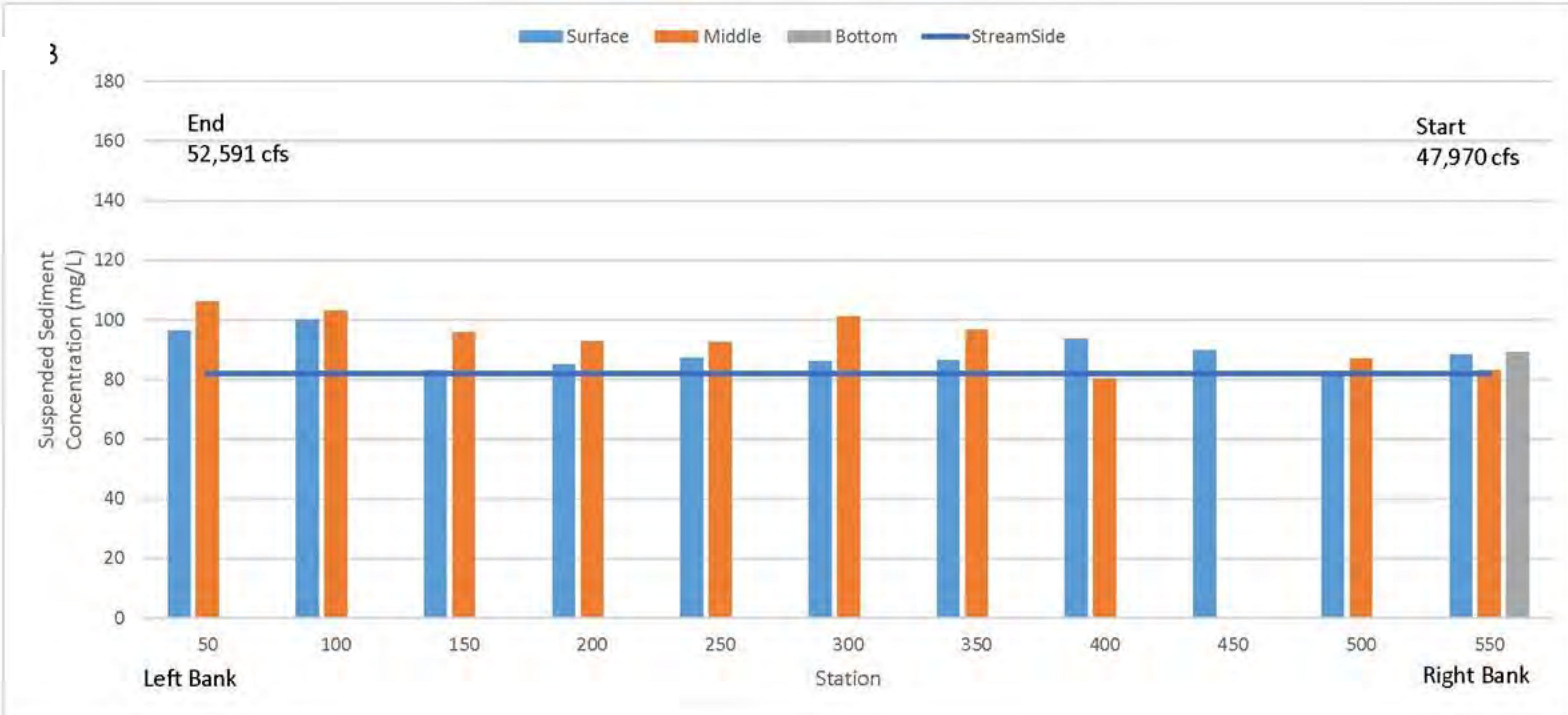

Figure 4.2.2-4 Rt. 10 Bridge Cross-section Grab Sample Data (April 17, 2015)[24]

[24] Bottom samples were not collected during this sampling event. The sounding weight used for sampling became detached from the Kemmerer at Station 0+550. Without the sounding weight, the Kemmerer could not reach the bottom due to the flow conditions; as such, bottom samples could not be collected.

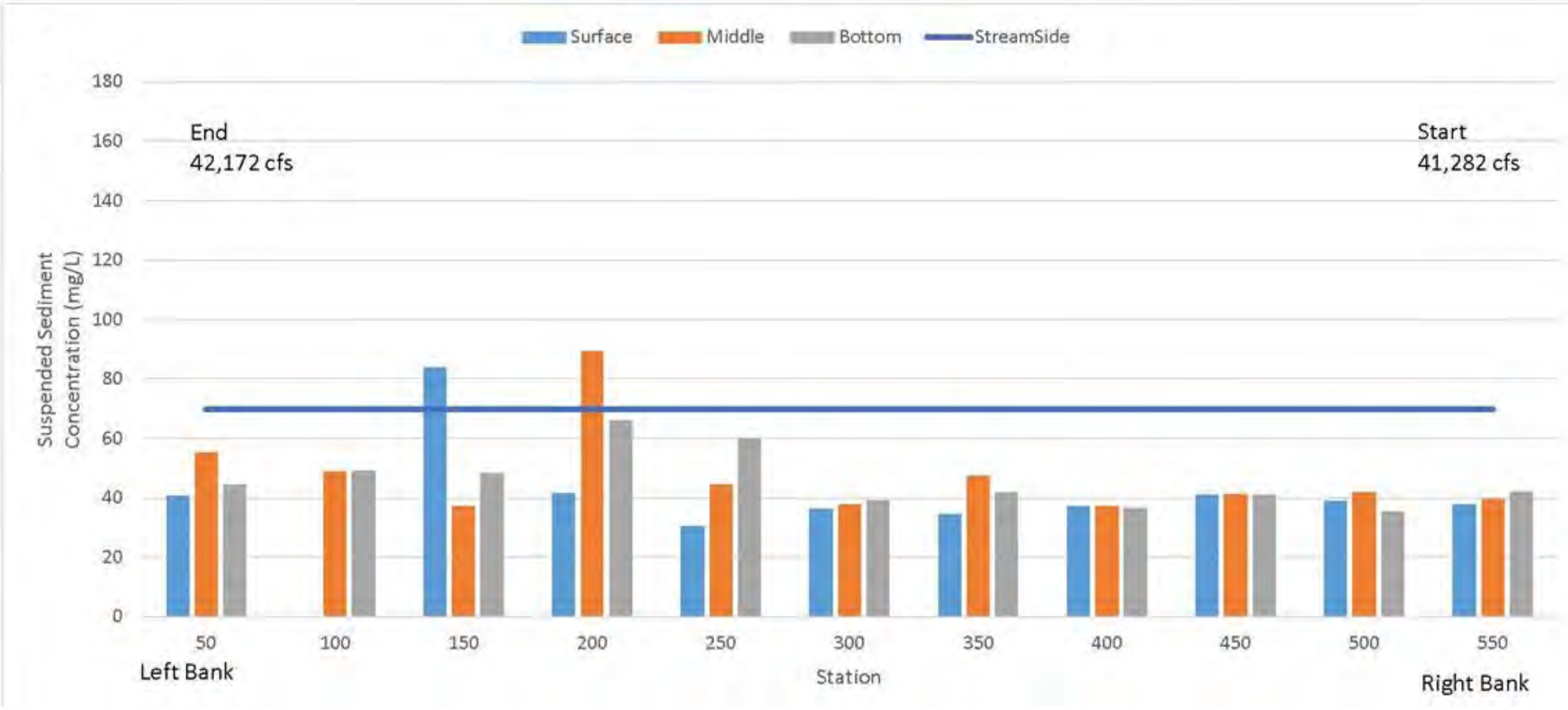

Figure 4.2.2-5 Rt. 10 Bridge Cross-section Grab Sample Data (April 20, 2015)

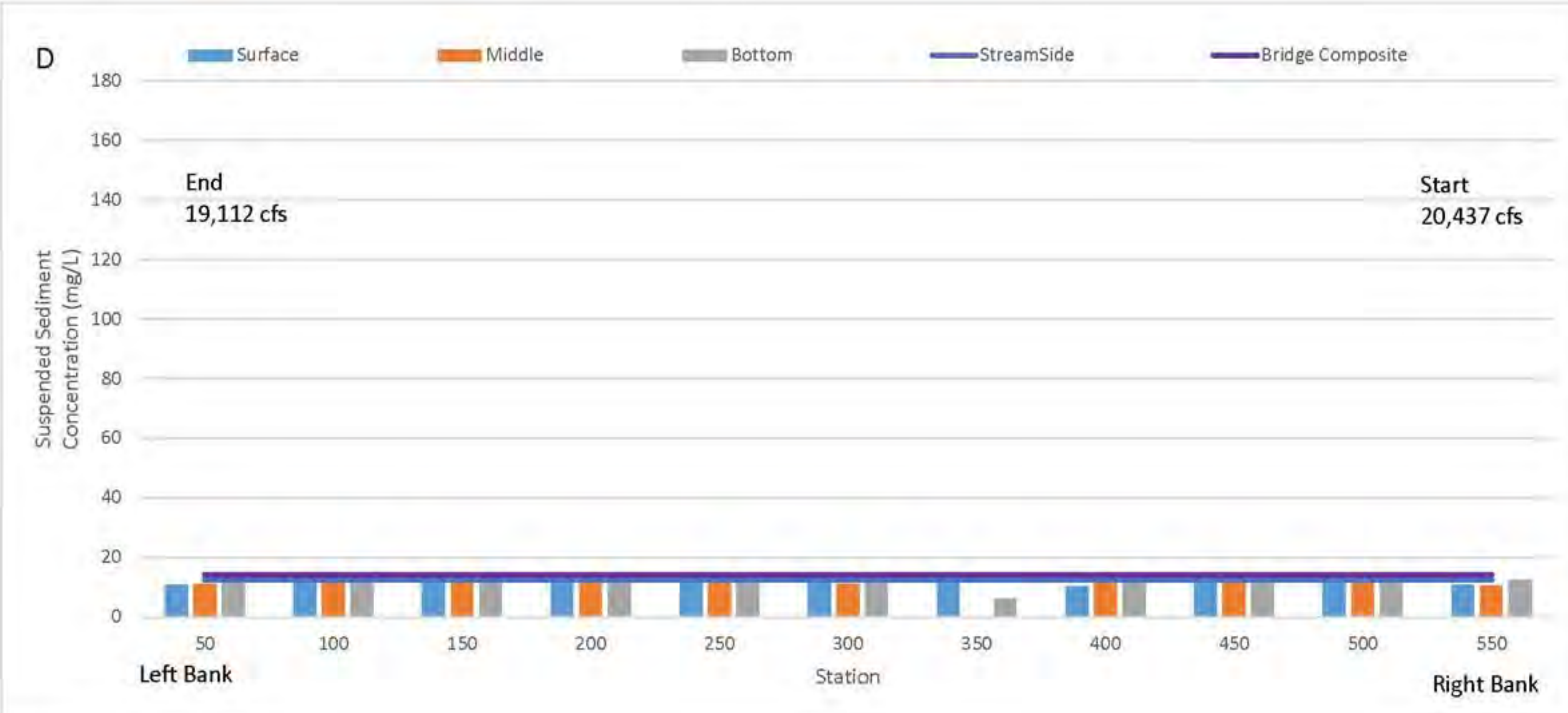

Figure 4.2.2-6 Rt. 10 Bridge Cross-section Grab Sample Data (April 28, 2015)

4.3 Modeling and Dredging Summary Discussion

This section presents a summary discussion pertaining to the results of the various modeling efforts conducted by Alden (discussed in Section 2.3) and the pilot dredge conducted in 2015 (discussed in Section 2.4). The results of these efforts, combined with the results of the bathymetric surveys and suspended sediment analyses previously discussed, were used to inform the proposed sediment management measures discussed in Section 5.

The results of the computational hydrodynamic sedimentation model of the Upper Reservoir found that the root cause of sedimentation in the Upper Reservoir likely begins with relatively high concentrations of entrained bed and suspended sediment loads from the Connecticut River being transported with process water during pumping phases. The water and sediment are transported at a high velocity through the conduit system to the Upper Reservoir. As the water and sediment combine with water already in the intake channel, the wider and deeper intake channel leads to a deceleration of the sediment rich pumped water and subsequent deposition of the sediment. Exit velocities are lower in the intake channel under generation than in the river intake and conduit system under pumping, meaning that much of the deposited sediment is not re-entrained during generation (Alden, 2014). These findings are consistent with the observations made from the bathymetric and suspended sediment data analyses.

Changes in operating procedures (i.e., lowering the Upper Reservoir drawdown) and/or physical modifications to the Upper Reservoir intake channel (i.e., narrowing its width) which were analyzed as part of the Upper Reservoir modeling were found to have minimal impact on reducing the amount of sediment entrained in the Upper Reservoir (Alden, 2014). Additionally, based on the current geometry of the Project works the modeling found that flushing deposited sediment back to the Connecticut River would result in that sediment being deposited at the tailrace tunnel exit for potential re-entrainment during subsequent pumping cycles. Based on these findings, and current layout of the intake channel, these potential sediment management measures were not considered for further evaluation at this time given their limited effectiveness.

The results of the CFD modeling of the tailrace area showed that since the river is perched 37 feet above the bottom of the tailrace tunnel exit structure/Upper Reservoir intake, any sediment in the Connecticut River has the potential to be mobilized to the Upper Reservoir under pumping. Operational conditions with 3 and 4 pumps operating were found to cause the majority of sediment uptake to the Upper Reservoir. The tailrace CFD model examined the effectiveness of constructing two different types of sediment exclusion structures to potentially reduce the amount of sediment entrained in the Project works during pumping cycles. Sediment exclusion structures which were examined included a shorter convex and longer concave sill built above the bed of the intake/tailwater channel and spanning the width of the tailrace. While the results of this modeling indicated that this potential management measure was more effective than the modeled Upper Reservoir alternatives, the sediment exclusion structures still were found to have limited effectiveness in reducing the amount of sediment entrained in the Project works during pumping (Appendix C).

The effectiveness of constructing a sediment exclusion structure at the tailrace was further evaluated through the development of a physical model developed by Alden. The physical model examined the effectiveness of (1) a 1,000 ft. long sediment exclusion structure with a 700 ft. long fixed crest overflow section, and (2) a 1,000 ft. long sediment exclusion structure with a 700 ft. long moveable crest overflow section. The potential sediment exclusions structure(s) would be located approximately where the original riverbank was prior to the construction of Northfield Mountain. The results of the physical model indicated that the fixed crest overflow alternative had a similar, limited effectiveness as observed from the results of the tailrace CFD model (Appendix C). The moveable crest overflow section was found to be slightly more effective than a fixed crest overflow section. Based on the findings of the tailrace CFD and physical models, constructing a sediment exclusion structure at the tailrace was found have low to moderate effectiveness.

As such, the sediment exclusion structure alternative is not being considered for further evaluation at this time.

In regard to the Upper Reservoir pilot dredge, from April 2015 to November 2015 approximately 46,000 cubic yards of sediment were successfully removed from within and immediately upstream of the Upper Reservoir intake channel by deep water hydraulic dredging. The availability of the Project for generation and pumping was not affected by the dredging operations. On average approximately 26 cubic yards of sediment per hour were removed from the Upper Reservoir while the dredge was actively operating. The hydraulic dredging operation was successful for removal of sediment from within and upstream of the Upper Reservoir intake channel without having any material sediment impacts to the Project Works or sediment discharges to the Connecticut River. Therefore, hydraulic dredging was found to be a viable sediment management measure.

5 PROPOSED SEDIMENT MANAGEMENT MEASURES

Over the past six years FirstLight has completed a number of field data collection, data analysis, and modeling efforts to better understand sediment dynamics in the Connecticut River and at the Northfield Mountain Project, including both the Upper Reservoir and tailrace areas. Based on the results of these efforts FirstLight proposes the following sediment management measures to minimize the entrainment of sediment into the Project works and Connecticut River during drawdowns or dewatering activities. The sediment management approach outlined below is an adaptive, multi-step approach which integrates the knowledge gained over the course of this study. Specific reasons for why certain alternatives are not being proposed were discussed in the previous section. The proposed measures outlined below encompass the most effective and successful management measures examined over the course of this study.

Based on the results of the Alden modeling, during normal Project operations (i.e., generation) material sediment releases are highly unlikely due to a combination of factors including the physical characteristics of the sediment, the velocity of the water, the configuration of the Upper Reservoir intake structure, and the water level of the Upper Reservoir. As such, the proposed management measures discussed below focus on minimizing the entrainment of sediment into the Project works and Connecticut River during dewatering activities.

During normal operating conditions FirstLight does not typically dewater the Upper Reservoir or Project works; however, there are still occasions where dewatering may need to occur (e.g., maintenance, emergencies, other unforeseen circumstances, etc.). In order to have the flexibility to dewater when needed and to minimize the risk of adverse environmental impacts when a dewatering occurs, FirstLight will employ a monitoring program to determine the amount of sediment that is present in the Upper Reservoir at a given time. The monitoring program will be based on bathymetric surveys of the Upper Reservoir and intake channel; surveys will be conducted at least every 2 years.

The results of the bathymetric surveys will be reviewed by FirstLight to determine: the estimated depth, location and shape of accumulated sediment as well as the estimated incremental amount of sediment which has accumulated between surveys. Based on FirstLight's review of the aforementioned accumulated sediment characteristics, excavation of the intake channel and/or other target areas will be planned and initiated as needed to minimize the potential for entrainment of sediment into the Project works and the Connecticut River during dewatering. Excavation of the accumulated sediment would occur via methods including, but not limited to, hydraulic dredging prior to dewatering or mechanical excavation after dewatering. The specific method will be developed based on the location and amount of sediment, the necessary time frame for removing the sediment, and then-available technologies and methods. FirstLight will notify MADEP, FERC, and USEPA in advance of any excavation activities. Following completion of excavation activities, a survey of the excavated area will be conducted in order to establish an updated baseline. The process of regular monitoring and periodic excavation will reduce the amount of accumulated sediment to levels where the risk of entraining significant amounts of sediment into the Project works and the Connecticut River is minimized.

In addition, and apart from periodic removals of sediment described in the preceding paragraph, FirstLight will develop protocols to be followed in the event of a dewatering in order to minimize the potential for the release of excess sediment to the Connecticut River. Protocols will be developed for two types of dewatering: (1) an emergency dewatering, and (2) a maintenance or other type of dewatering. FirstLight will provide the dewatering protocols to MADEP, USEPA, and FERC staff; these protocols may be updated periodically as needed to reflect changes in site conditions, new technologies, or otherwise. In the event that a dewatering does occur, FirstLight will visually monitor turbidity in the tailrace area throughout the dewatering for any noticeable increases.

In light of the viability of the physical removal of sediments from the Upper Reservoir and for the reasons discussed in the previous section, FirstLight is not proposing operational changes or physical modifications to either the Upper Reservoir intake channel or tailrace area as potential management measures at this time. In the future, FirstLight may explore other sediment management measures as technological advancements occur and the understanding of sediment dynamics at the Project continues to evolve. FirstLight will consult with MADEP, USEPA, and FERC staff in the event that future modifications are made to sediment management measures at the Project. The sediment management steps listed above are provided to satisfy the RSP, USEPA Administrative Consent Order, FERC, and MADEP requirements.

6 LITERATURE CITED

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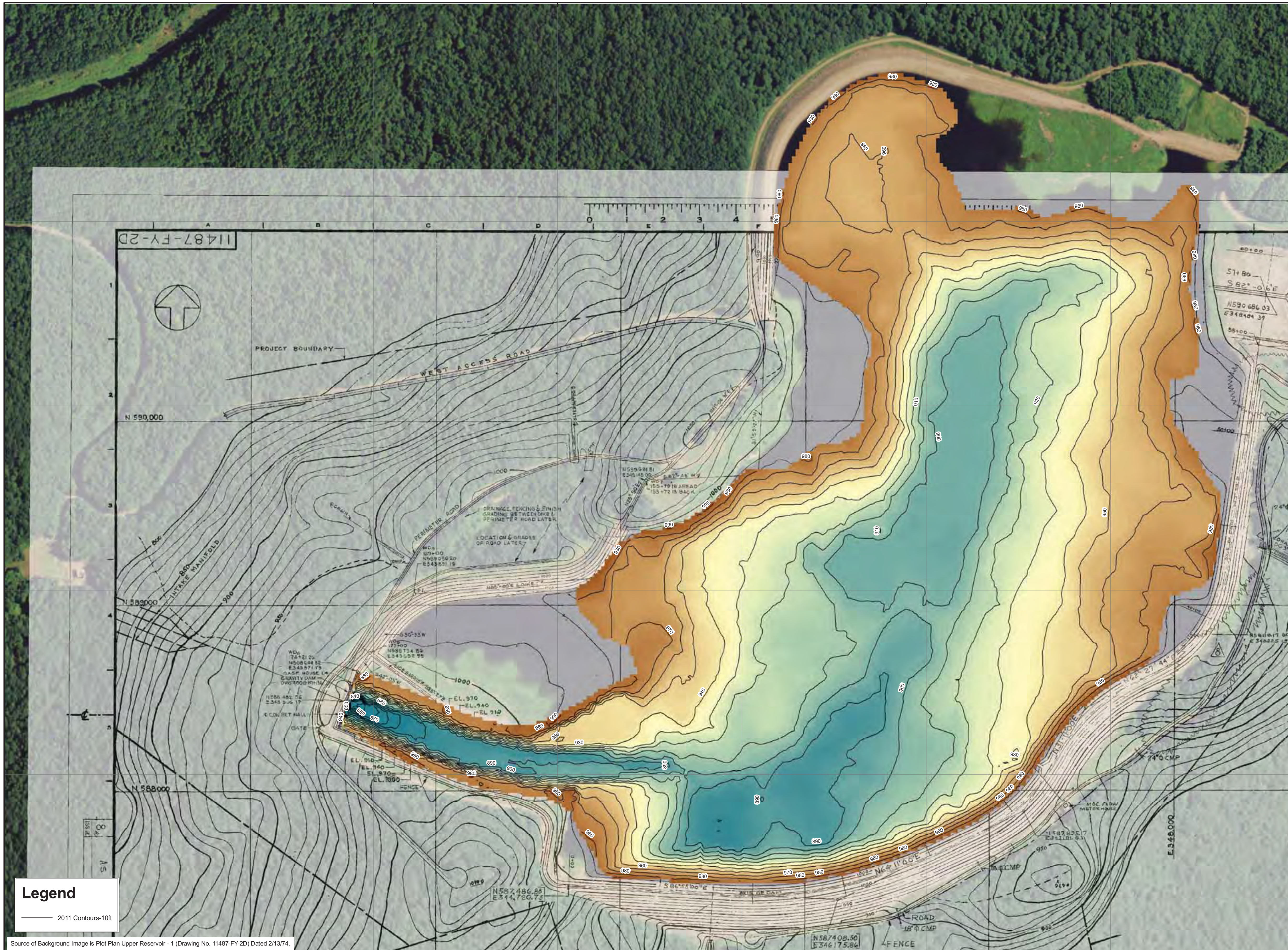
APPENDIX A – UPPER RESERVOIR BATHYMETRY SURVEY MAPS (2011-2013)

2011 UPPER RESERVOIR BATHYMETRY MAPS



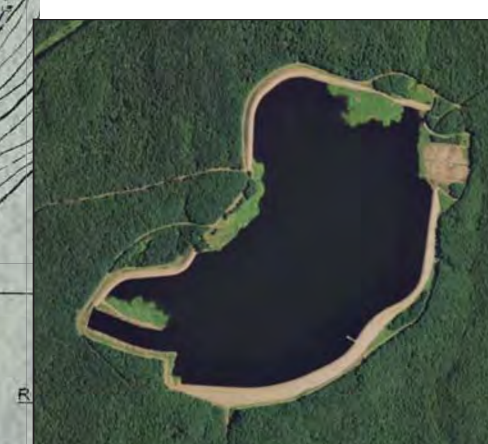
SEAVISION UNDERWATER SOLUTIONS

1. The hydrographic survey information depicted on this drawing represents a survey performed by SeaVision Underwater Solutions on November 5, 2011 and can only be considered to indicate the general condition existing at that time.

2. The hydrographic survey data was collected using a Trimble 5700 Differential Global Positioning System and a Knudsen 3212 (200 kHz) Echosounder. Horizontal and vertical positioning corrections were provided by using the KeyNet GPS Subscription Virtual Reference Station Real-Time Kinematic (RTK) GPS system. Bar check sound velocity calibrations were performed using an Innerspace 443a Digital Sound Velocity Profiler.

3. Horizontal positioning is expressed in feet and references the North American Datum of 1983, Massachusetts (Mainland) State Plane (Feet).

4. Elevations are expressed in feet (subscripts are tenths) and reference elevations relative to the Site Datum. Site Datum is assumed to have an elevation of +0.398 feet relative to the North American Vertical Datum of 1988 (NAVD 1988) based on a comparison of Site Benchmark CP-9 to observations made with a Trimble 4000 SSi and processed with the NGS OPUS system.



DESCRIPTION	DATE	BY	DESCRIPTION	DATE	BY

OCEAN AND COASTAL CONSULTANTS, INC.

Ocean and Coastal Consultants, Inc.
475 School Street, Unit 9
Marshfield, MA 02050
Tel: (508) 830-1110
Fax: (781) 834-4635

FirstLight Power Resources
GDF SUEZ

FirstLight Power
99 Millers Falls Road
Northfield, MA 01360

DESIGNED BY:	EDGO
DRAWN BY:	EDGO
CHECKED BY:	BRJO
	209080.3

NORTHFIELD STATION RESERVOIR, NORTHFIELD, MA
HYDROGRAPHIC SURVEY

SCALE	DATE	REVISION
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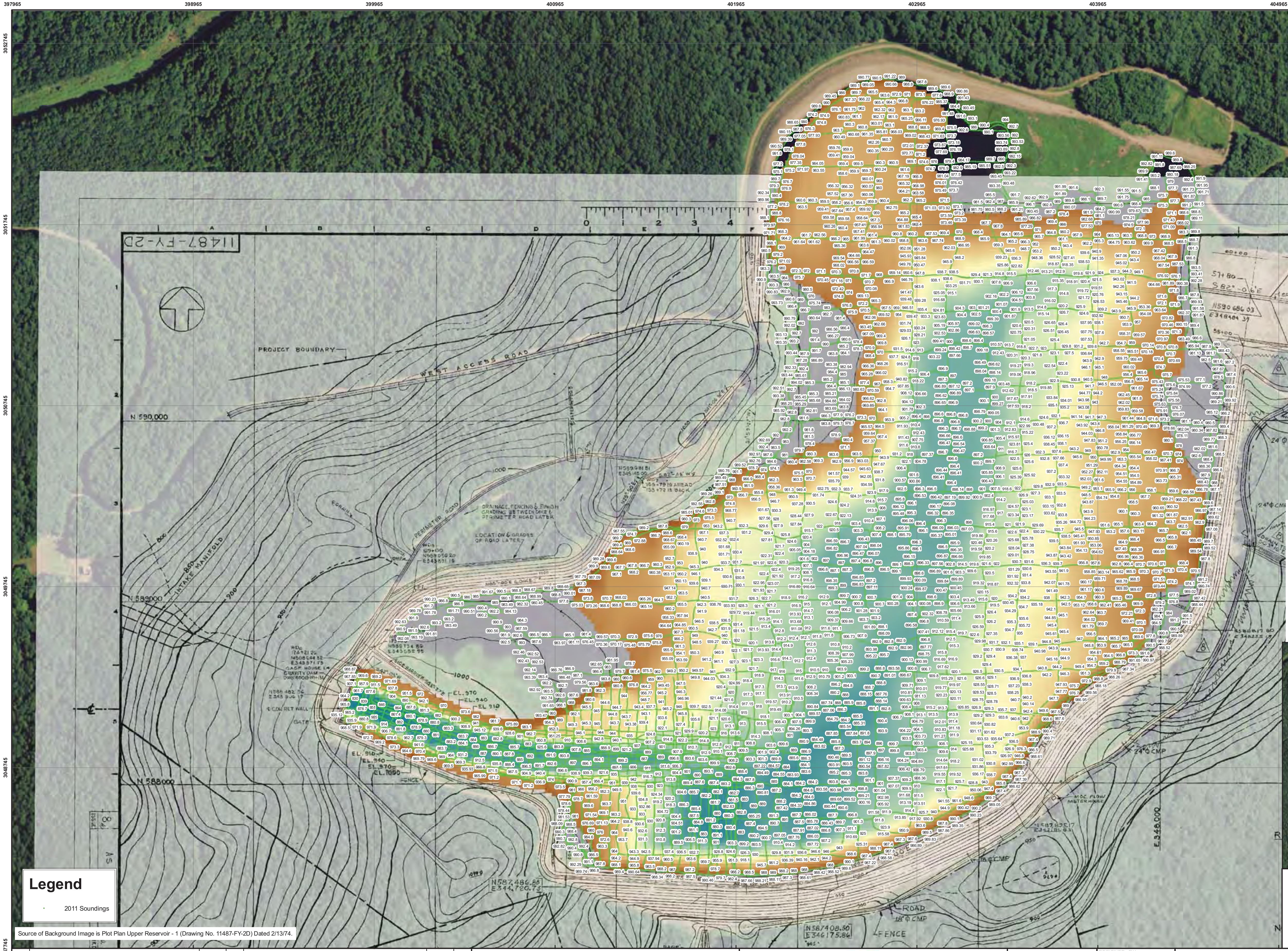
OVERALL SURVEY - CONTOUR PLAN

DRAWING NO. 1



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OCEAN AND COASTAL CONSULTANTS, INC.

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DESIGNED BY: EDGO	NORTHFIELD STATION RESERVOIR, NORTHFIELD, MA HYDROGRAPHIC SURVEY	SCALE 1:3000	REVISION 0
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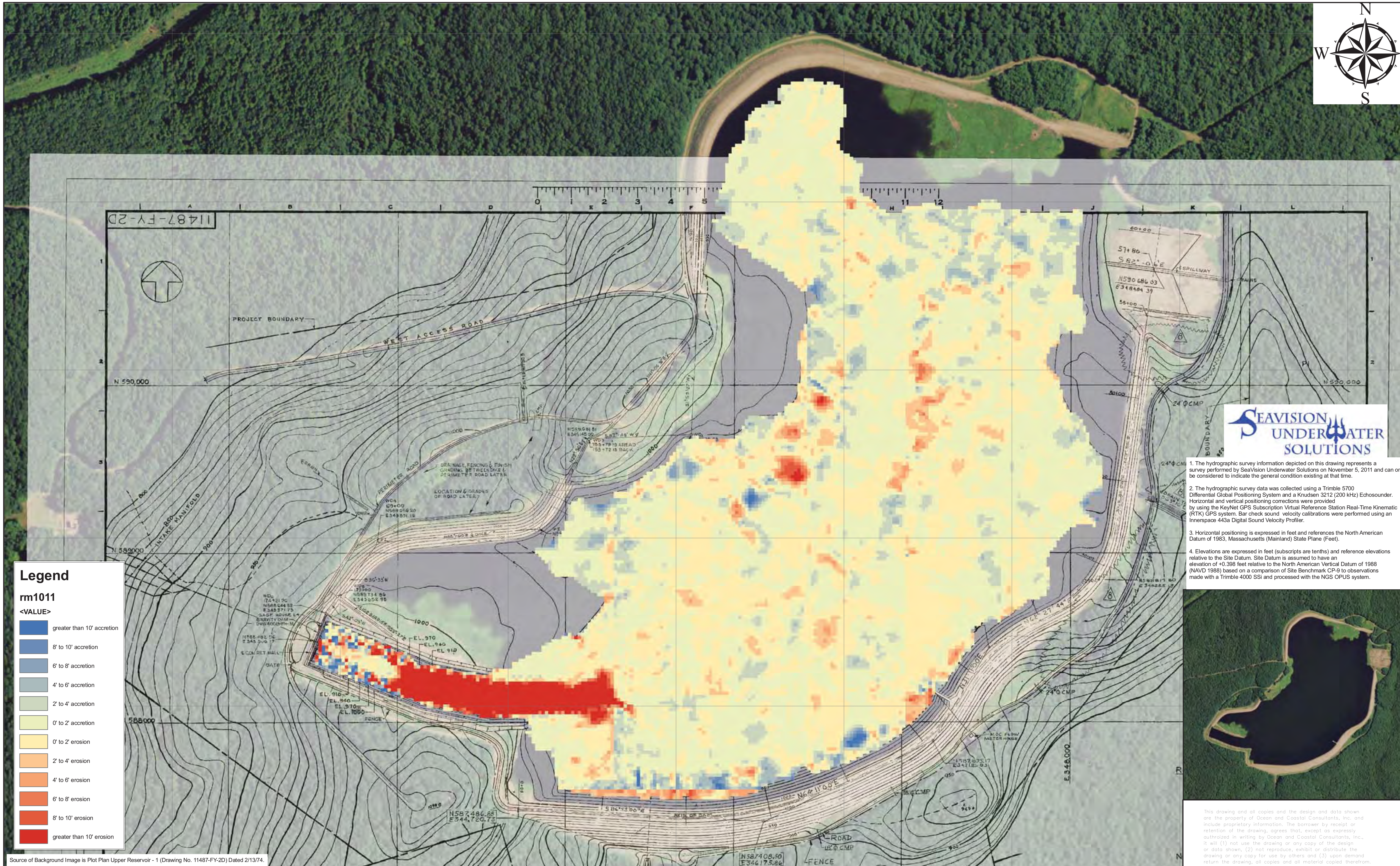

Source of Background Image is Plot Plan Upper Reservoir - 1 (Drawing No. 11487-FY-2D) Dated 2/13/74.

SEAVISION UNDERWATER SOLUTIONS

1. The hydrographic survey information depicted on this drawing represents a survey performed by SeaVision Underwater Solutions on November 5, 2011 and can only be considered to indicate the general condition existing at that time.

2. The hydrographic survey data was collected using a Trimble 5700 Differential Global Positioning System and a Knudsen 3212 (200 kHz) Echosounder. Horizontal and vertical positioning corrections were provided by using the KeyNet GPS Subscription Virtual Reference Station Real-Time Kinematic (RTK) GPS system. Bar check sound velocity calibrations were performed using an Innerspace 443a Digital Sound Velocity Profiler.

3. Horizontal positioning is expressed in feet and references the North American Datum of 1983, Massachusetts (Mainland) State Plane (Feet).

4. Elevations are expressed in feet (subscripts are tenths) and reference elevations relative to the Site Datum. Site Datum is assumed to have an elevation of +0.398 feet relative to the North American Vertical Datum of 1988 (NAVD 1988) based on a comparison of Site Benchmark CP-9 to observations made with a Trimble 4000 SSi and processed with the NGS OPUS system.

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DRAWN BY: EDGO		DATE 11/14/11	
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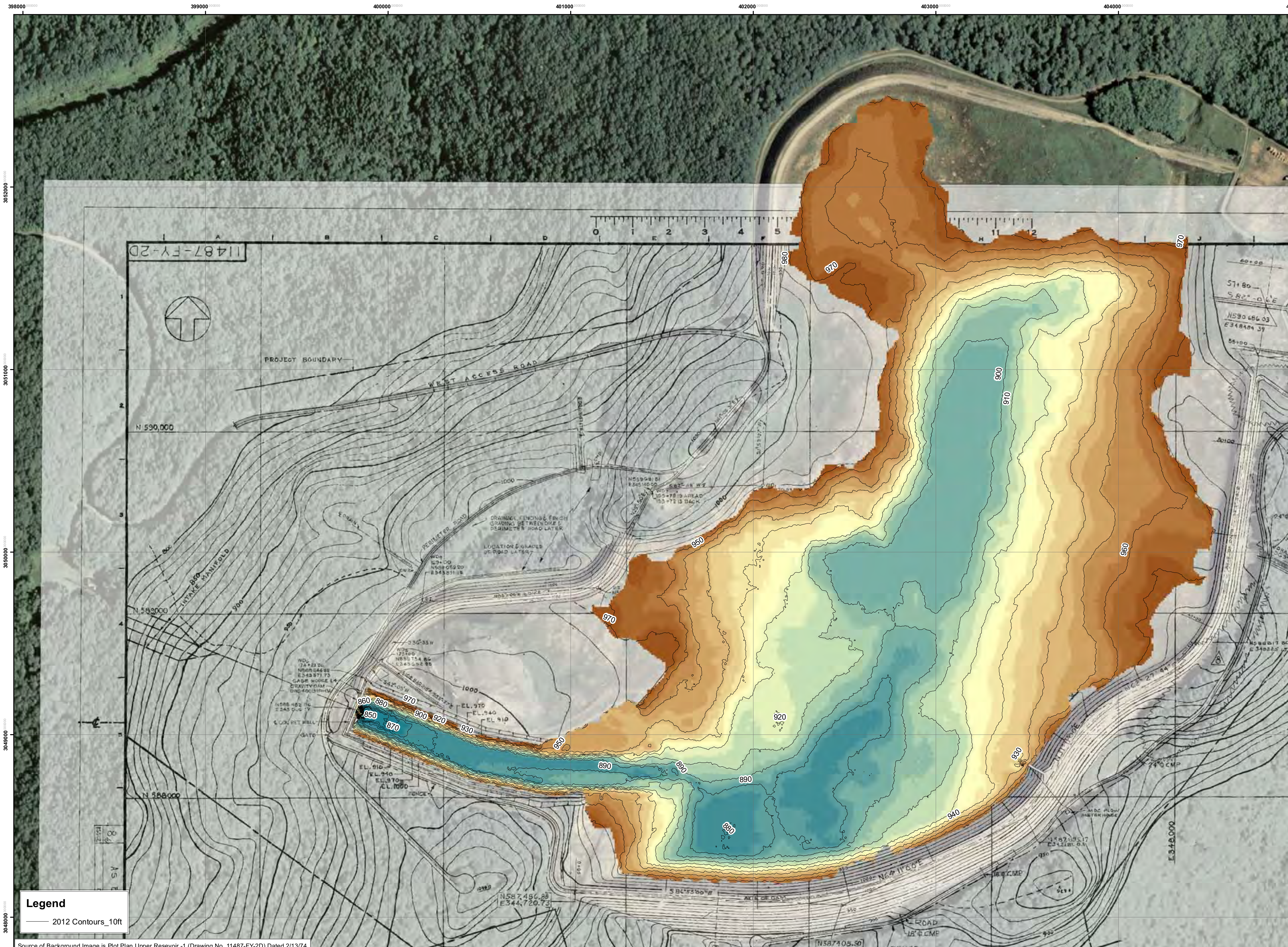
2012 UPPER RESERVOIR BATHYMETRY MAPS



Source of Background Image is Plot Plan Upper Resevoir -1 (Drawing No. 11487-FY-2D) Dated 2/13/74

SEAVISION UNDERWATER SOLUTIONS

1. The bathymetry depicted on these digital products represents the results of a survey performed by SeaVision Underwater Solutions, Inc. on September 29-30, 2012 and can only be considered to indicate the general conditions existing at that time.

2. The multibeam bathymetry data was collected using a HemisphereGPS R320 Differential Global Positioning System with Real-Time Kinematic corrections transmitted from the KeyNet GPS Virtual Reference Station Network. SeaVision utilized a Teledyne Odom ES3 260 kHz multibeam echosounder, a TSS DMS-05 Motion Reference Unit, and a ComNav G4 Heading Sensor to collect the data. For sound velocity corrections, we utilized a Valeport MiniSVS Sound Velocity Profiler to collect acoustic velocity data. All data was collected and integrated using the Hypack Hysweep Software package and post-processed to the project datums to account for water level and vessel motion.

3. Horizontal positioning is expressed in feet and references the North American Datum of 1983, Massachusetts-Mainland Zone State Plane (Feet). Vertical elevations are in feet and reference the site datum, equivalent to the National Geodetic Vertical Datum of 1929.

4. Water level observations were performed in real-time using the RTK-GPS Receiver, and checked against observations from the GDF-Suez/FirstLight Power control room at Northfield Mountain.

DESCRIPTION	DATE	BY	DESCRIPTION	DATE	BY

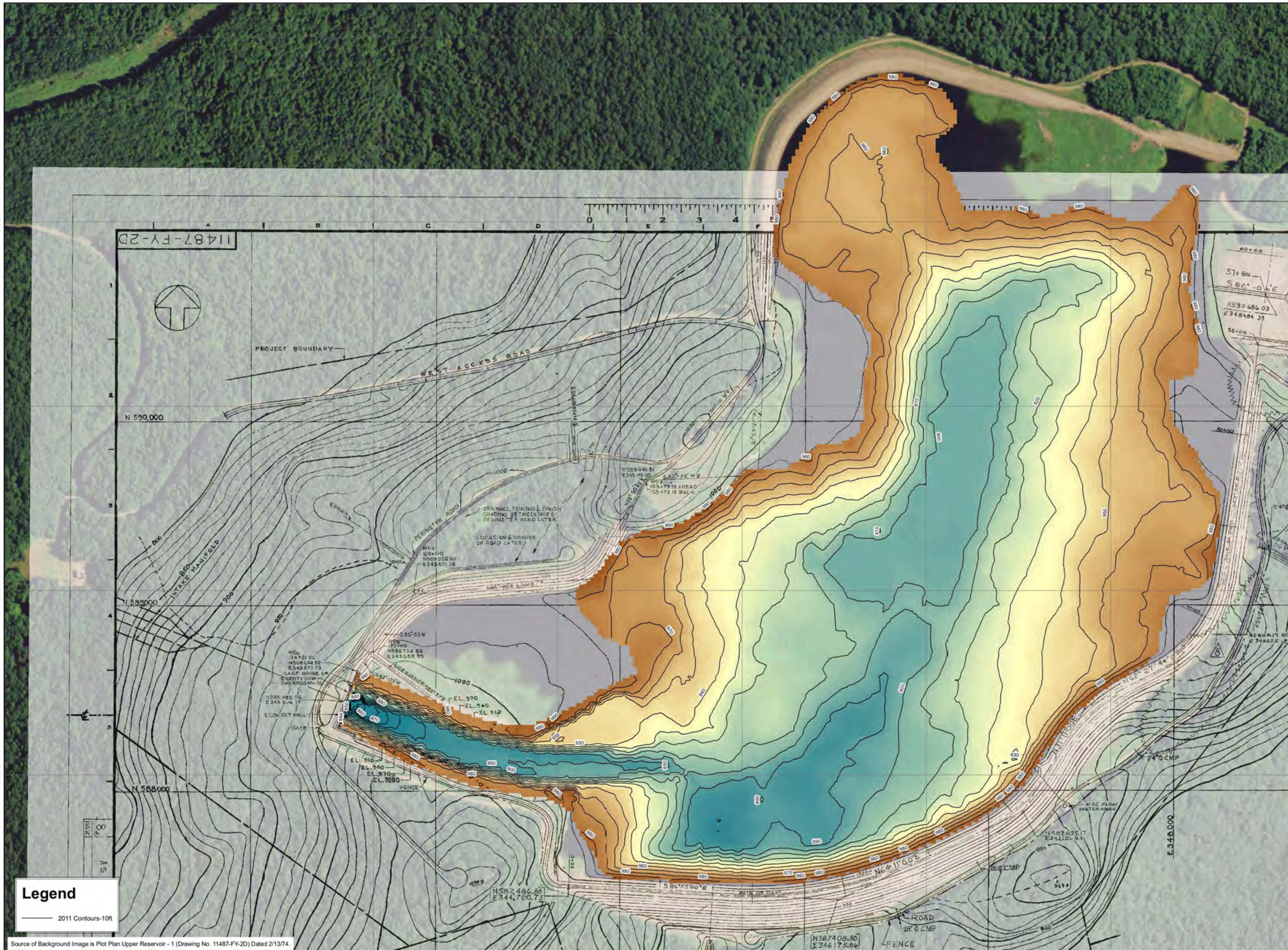
OCEAN AND COASTAL CONSULTANTS
a COWI company

Ocean and Coastal Consultants, Inc.
475 School Street, Unit 9
Marshfield, MA 02050
Tel: (508) 830-1110
Fax: (781) 834-4635

FirstLight Power Resources
GDF SUEZ

FirstLight Power
99 Millers Falls Road
Northfield, MA 01360

DESIGNED BY: RYAR	NORTHFIELD STATION RESERVOIR, NORTHFIELD, MA HYDROGRAPHIC SURVEY	SCALE 1:3,000	REVISION 0
DRAWN BY: RYAR		DATE 9-30-2012	
CHECKED BY: BRJO	**OVERALL SURVEY - 2012 CONTOUR PLAN**	DRAWING NO.	**1a**
209080.3			



SEAVISION UNDERWATER SOLUTIONS

1. The hydrographic survey information depicted on this drawing represents a survey performed by SeaVision Underwater Solutions on November 5, 2011 and can only be considered to indicate the general condition existing at that time.

2. The hydrographic survey data was collected using a Trimble 5700 Differential Global Positioning System and a Knudsen 3212 (200 kHz) Echosounder. Horizontal and vertical positioning corrections were provided by using the KeyNet GPS Subscription Virtual Reference Station Real-Time Kinematic (RTK) GPS system. Bar check sound velocity calibrations were performed using an Innerspace 443a Digital Sound Velocity Profiler.

3. Horizontal positioning is expressed in feet and references the North American Datum of 1983, Massachusetts (Mainland) State Plane (Feet).

4. Elevations are expressed in feet (subscripts are tenths) and reference elevations relative to the Site Datum. Site Datum is assumed to have an elevation of +0.398 feet relative to the North American Vertical Datum of 1988 (NAVD 1988) based on a comparison of Site Benchmark CP-9 to observations made with a Trimble 4000 SSi and processed with the NGS OPUS system.

OCEAN AND COASTAL CONSULTANTS, INC.

Ocean and Coastal Consultants, Inc.
475 School Street, Unit 9
Marshfield, MA 02050
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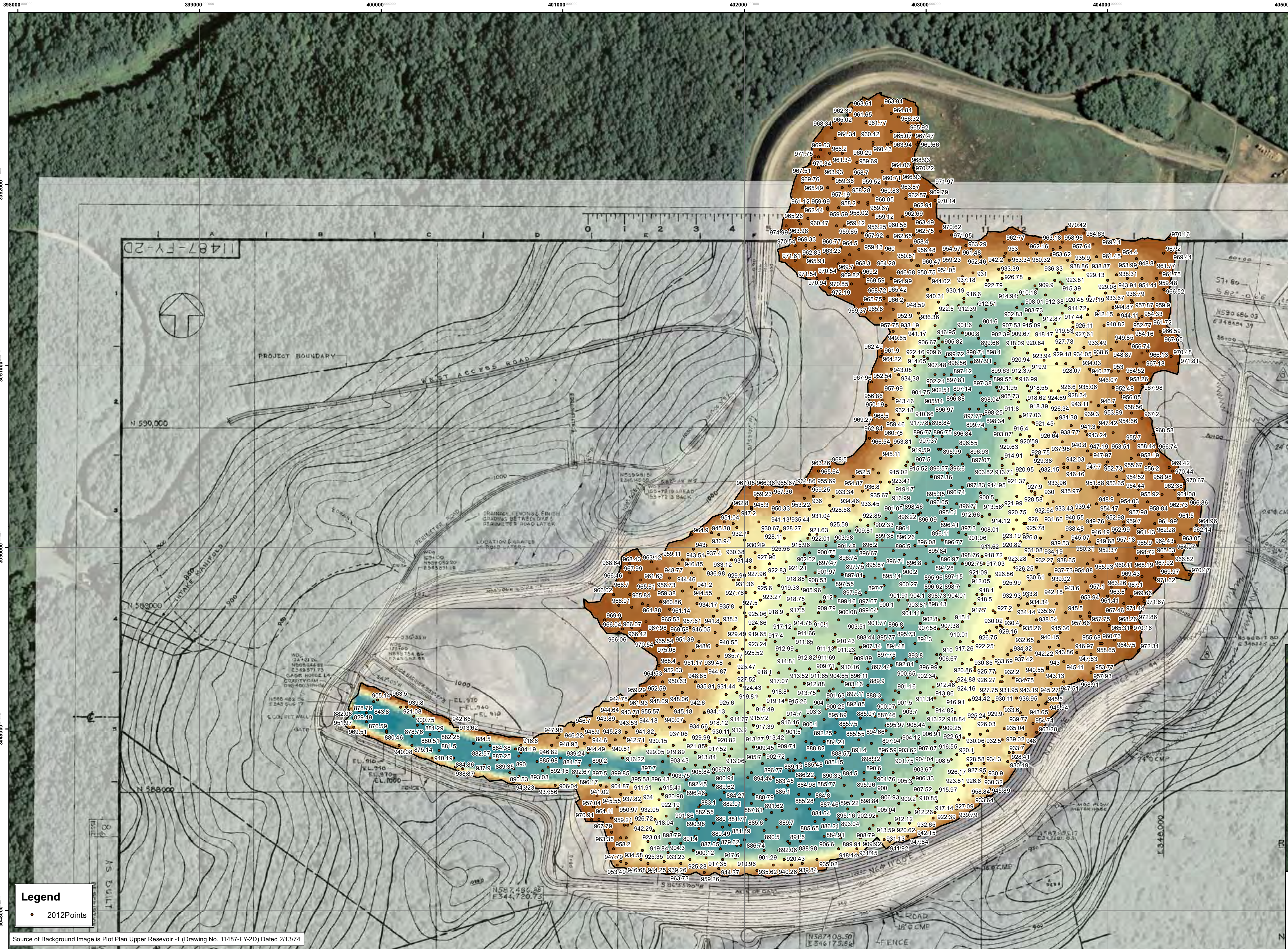
FirstLight Power Resources
GDF SUEZ

FirstLight Power
99 Millers Falls Road
Northfield, MA 01360

NORTHFIELD STATION RESERVOIR, NORTHFIELD, MA
HYDROGRAPHIC SURVEY

2011
OVERALL SURVEY - CONTOUR PLAN

1b



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4. Water level observations were performed in real-time using the RTK-GPS Receiver, and checked against observations from the GDF-Suez/FirstLight Power control room at Northfield Mountain.

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Ocean and Coastal Consultants, Inc.
475 School Street, Unit 9
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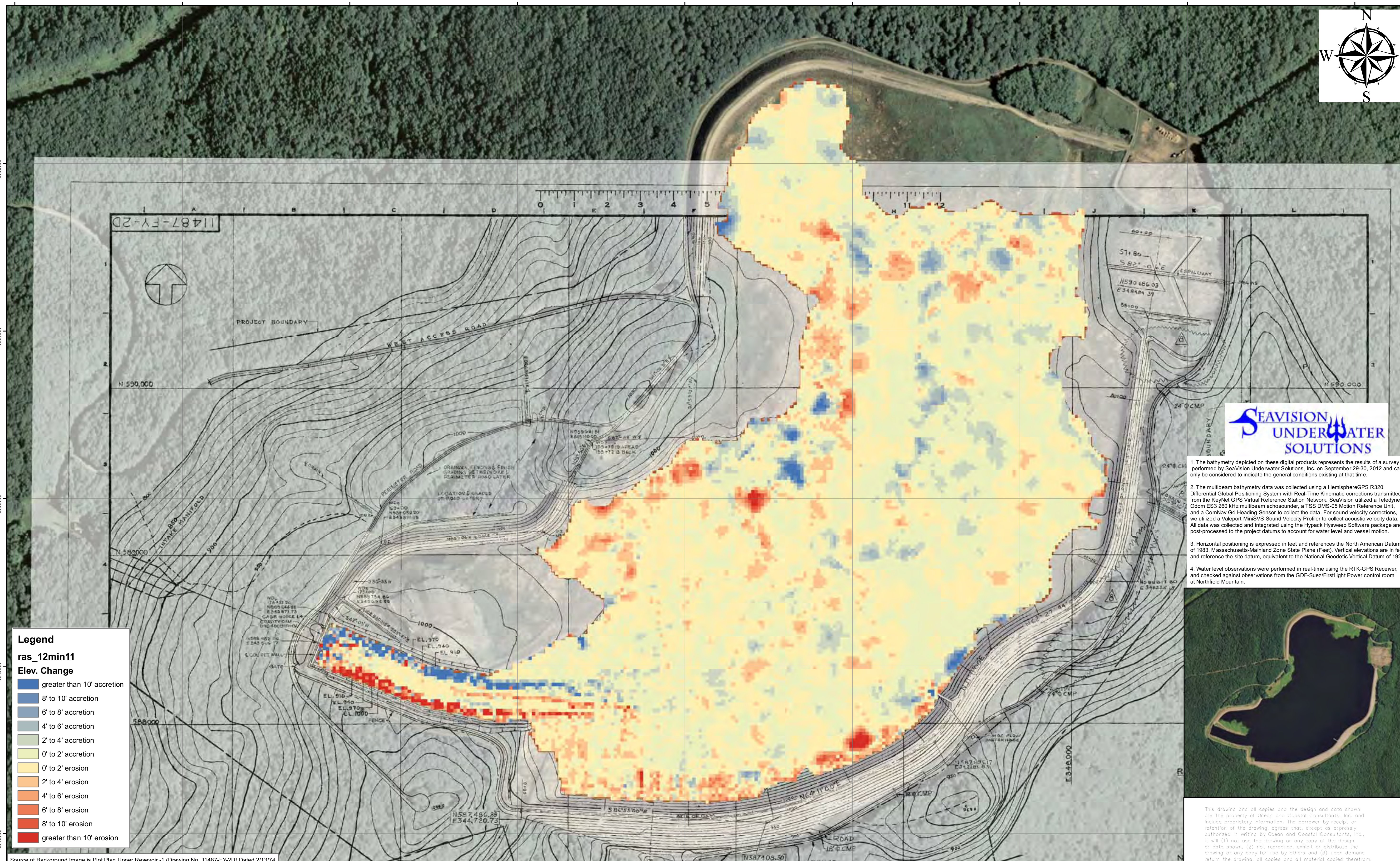
FirstLight Power Resources
GDF SUEZ

FirstLight Power
99 Millers Falls Road
Northfield, MA 01360

DESIGNED BY: RYAR	NORTHFIELD STATION RESERVOIR, NORTHFIELD, MA HYDROGRAPHIC SURVEY	SCALE 1:3,000	REVISION 0
DRAWN BY: RYAR		DATE 9-30-2012	
CHECKED BY: BRJO	OVERALL SURVEY - 2012 SOUNDING PLAN	DRAWING NO. 2	
209080.3			



SEAVISION UNDERWATER SOLUTIONS

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4. Water level observations were performed in real-time using the RTK-GPS Receiver, and checked against observations from the GDF-Suez/FirstLight Power control room at Northfield Mountain.

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Ocean and Coastal Consultants, Inc.
475 School Street, Unit 9
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FirstLight Power Resources
GDF SUEZ

FirstLight Power
99 Millers Falls Road
Northfield, MA 01360

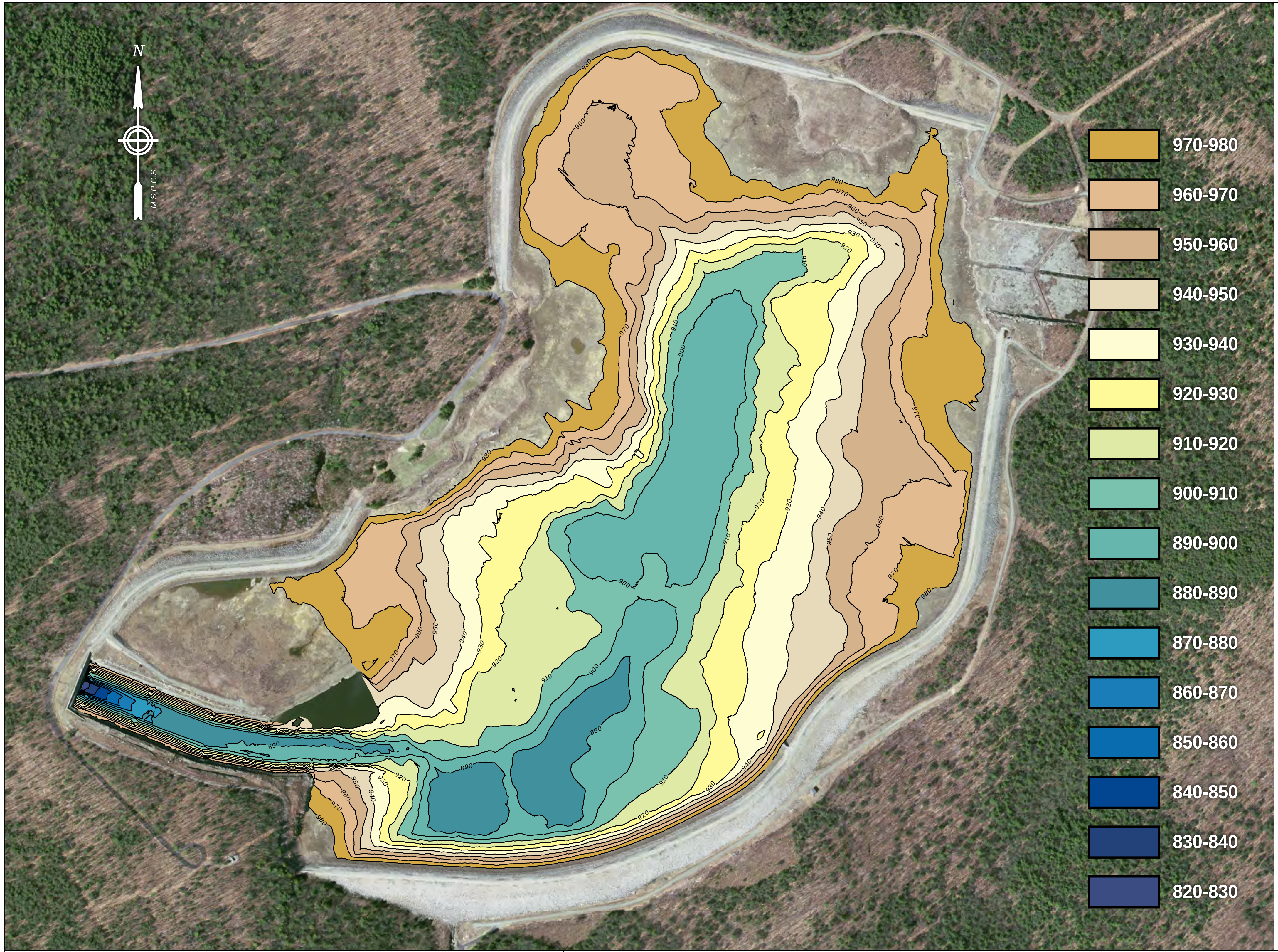
DESIGNED BY:	RYAR
DRAWN BY:	RYAR
CHECKED BY:	BRJO
	209080.3

NORTHFIELD STATION RESERVOIR, NORTHFIELD, MA
HYDROGRAPHIC SURVEY

OVERALL SURVEY - 2011-2012 ELEVATION CHANGE

SCALE	REVISION
1:3,000	0
DATE	
9-30-2012	
DRAWING NO.	
3	

2013 UPPER RESERVOIR BATHYMETRY MAPS



GENERAL NOTES:

1. CONTOURS AND ELEVATIONS PRESENTED ON THIS PLAN REPRESENT THE RESULTS OF A HYDROGRAPHIC SURVEY PERFORMED BY CHA CONSULTING, INC. ON OCTOBER 5 AND 6, 2013. REUSE OF THIS INFORMATION BY THE CLIENT OR OTHERS BEYOND THE SPECIFIC SCOPE OF WORK FOR WHICH IT WAS ACQUIRED SHALL BE AT THE SOLE RISK OF THE USER AND WITHOUT LIABILITY TO CHA CONSULTING, INC.

2. THE GRID COORDINATES ARE BASED ON THE MASSACHUSETTS STATE PLANE COORDINATE SYSTEM, ZONE 2001 (M.S.P.C.S.) AND ARE EXPRESSED IN US SURVEY FEET.

3. ELEVATIONS ON THIS PLAN ARE EXPRESSED IN FEET AND ARE REFERENCED TO THE NORTHFIELD MOUNTAIN PUMPED STORAGE FACILITY (NMPSF) SITE VERTICAL DATUM. PER THE BID SPECIFICATIONS DOCUMENT, DATED APRIL 4, 2013, THE LOCAL SITE DATUM IS CALCULATED TO BE "+0.398 FEET TO THE NORTH AMERICAN VERTICAL DATUM OF 1988 (NAVD 88)". TO CORRELATE ELEVATIONS BETWEEN DATUMS, THE FOLLOWING FORMULA SHOULD BE APPLIED:

$$EL_{NMPSF} = EL_{NAVD88} + 0.398 \text{ FT}$$

4. THE VERTICAL BENCHMARK HELD FOR THIS SURVEY IS A LEAD PLUG AND TACK LOCATED ON THE NORTH WEST CORNER OF THE CONCRETE MDC INTAKE STRUCTURE AND IS KNOWN AS CP-9 (EL=1009.94 FT. (NMPSF)).

101 Accord Park Drive
Norwell, MA 02061
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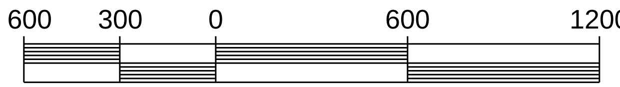


PREPARED FOR:

FIRST LIGHT POWER RESOURCES/GDF SUEZ
99 MILLERS FALLS ROAD
NORTHFIELD, MA 01360

TITLE:

2013 HYDROGRAPHIC SURVEY - CONTOUR PLAN
NORTHFIELD MOUNTAIN UPPER RESERVOIR
NORTHFIELD, MA 01360

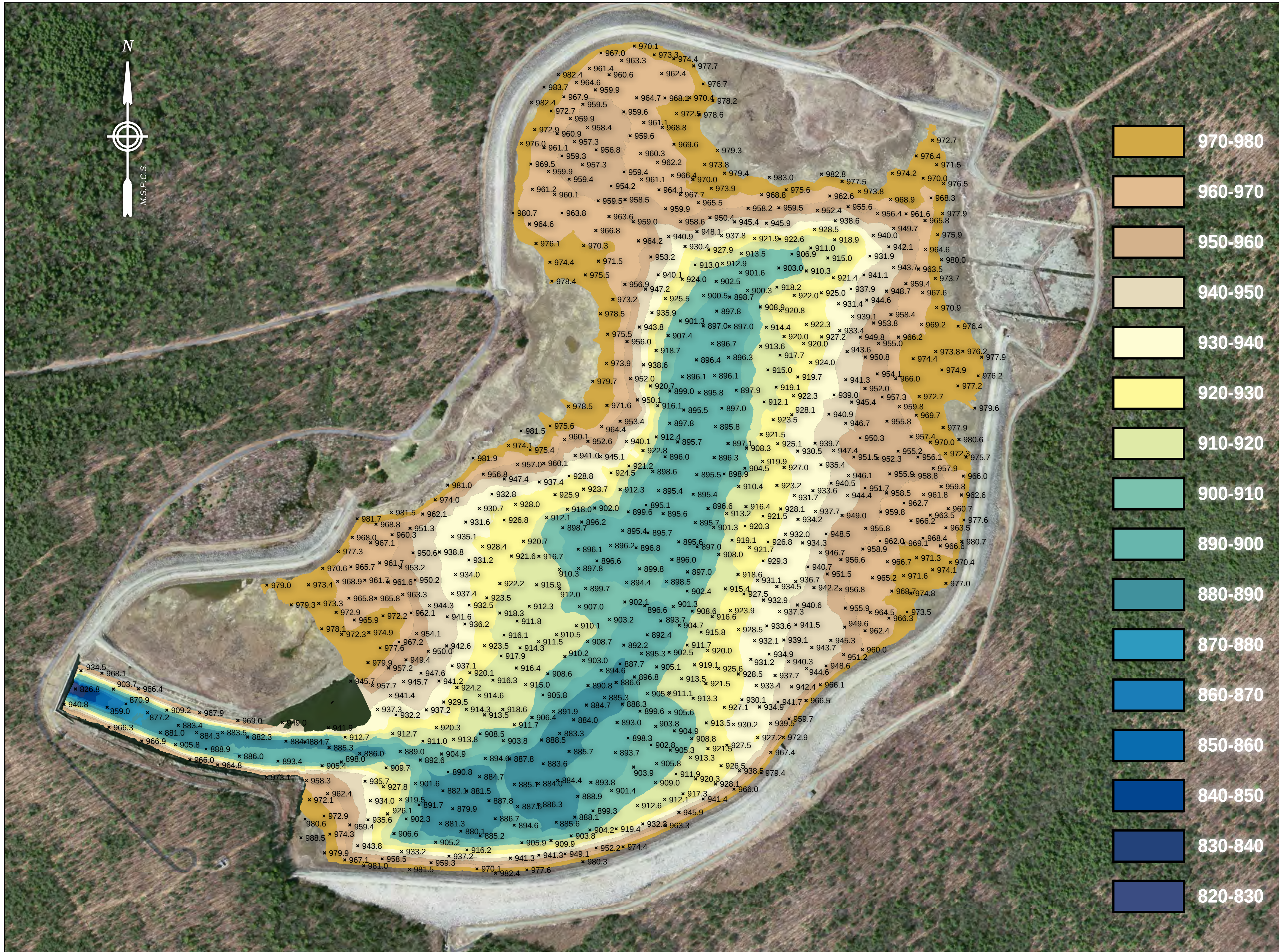
DATE: OCTOBER 31, 2013

SCALE: 1"=600'

DRAWN: AMC CHECK: EJP

DWG NAME: 26727 Upper Reservoir Hydro 2013

Fig-3



GENERAL NOTES:

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CHA
101 Accord Park Drive
Norwell, MA 02061
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600 300 0 600 1200

PREPARED FOR:

FIRST LIGHT POWER RESOURCES/GDF SUEZ
99 MILLERS FALLS ROAD
NORTHFIELD, MA 01360

TITLE:

2013 HYDROGRAPHIC SURVEY - SOUNDING PLAN
NORTHFIELD MOUNTAIN UPPER RESERVOIR
NORTHFIELD, MA 01360

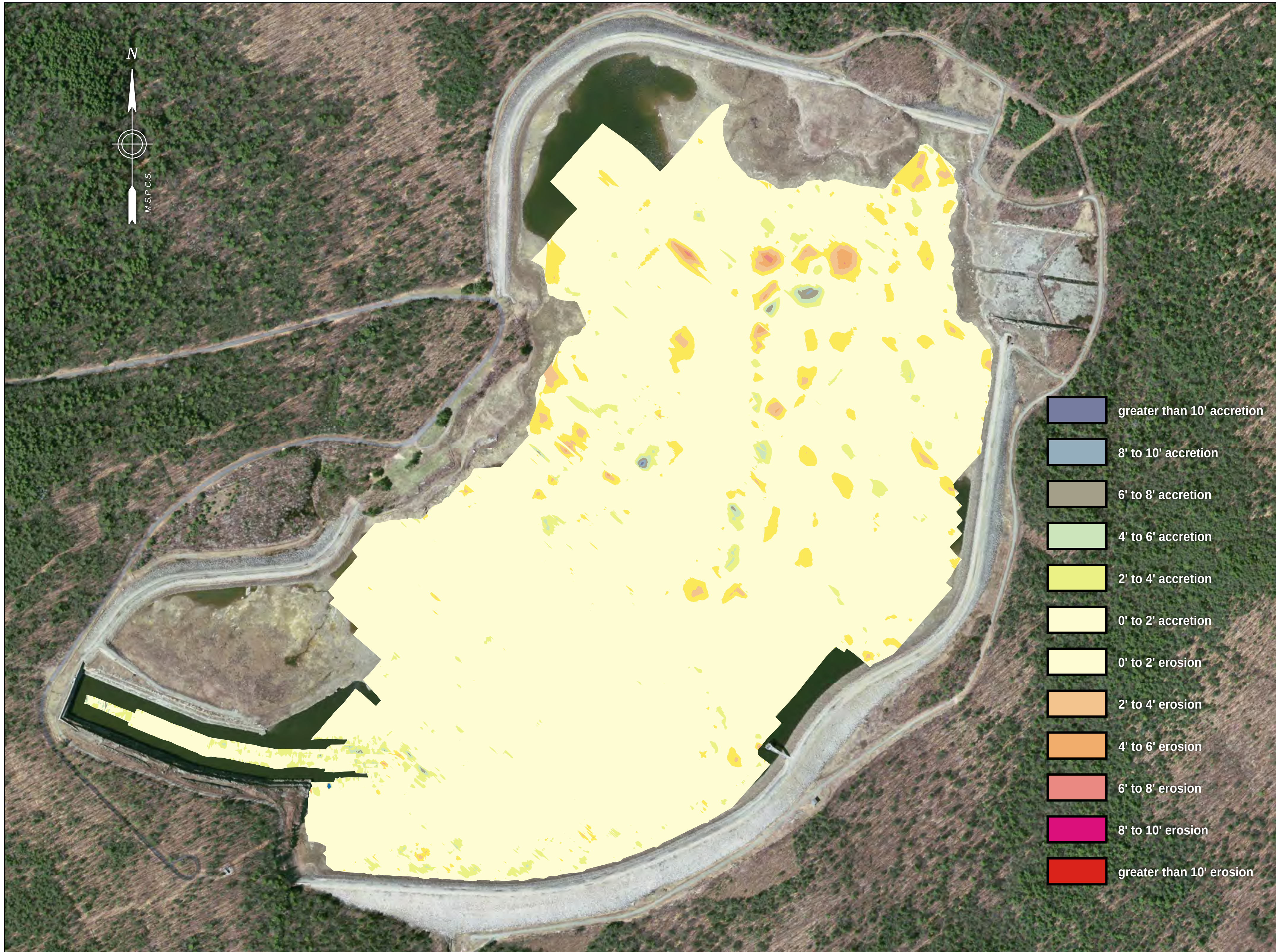
DATE: OCTOBER 31, 2013

SCALE: 1"=600'

DRAWN: AMC CHECK: EJP

DWG NAME: 26727 Upper Reservoir Hydro 2013

Fig-4



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600 300 0 600 1200

PREPARED FOR:

FIRST LIGHT POWER RESOURCES/GDF SUEZ
99 MILLERS FALLS ROAD
NORTHFIELD, MA 01360

TITLE:

2013 HYDROGRAPHIC SURVEY - ELEVATION CHANGE PLAN
2013 SURVEY vs. 2012 SURVEY
NORTHFIELD MOUNTAIN UPPER RESERVOIR
NORTHFIELD, MA 01360

DATE: OCTOBER 31, 2013

SCALE: 1"=600'

DRAWN: AMC CHECK: EJP

DWG NAME: 26727 Upper Reservoir Hydro 2013

Fig-5

APPENDIX B – SUMMARY OF 2015 CORRESPONDENCE & MANUFACTURER CERTIFICATION LETTER

2015 Correspondence Summary

Author	Distributed To	Date	Description
FirstLight	FERC	February 24, 2015	Pilot Dredge Filing
USEPA	FirstLight	March 9, 2015	Review and Comments on Northfield Mountain Pumped Storage Project Sediment Management Plan 2014 Summary of Annual Monitoring
FirstLight	USEPA	March 31, 2015	FirstLight Response to EPA Comments on 2014 Summary of Annual Monitoring
FirstLight	FERC, USEPA, MADEP	June 24, 2015	Northfield Mountain Pumped Storage Project Sediment Management Plan-Suspended Sediment Monitoring Equipment Status Update
FirstLight	FERC, USEPA, MADEP, Stakeholders	September 14, 2015	Status update and available results report filed with the 2015 Updated Study Report
N/A	N/A	September 30, 2015	FirstLight hosted Day 2 of the Updated Study Report meeting at which time the report filed on September 14, 2015 was presented to Stakeholders.
FirstLight	FERC, USEPA, MADEP	December 1, 2015	Annual summary of monitoring report (i.e. updated September 14, 2015 report)

Sequoia Scientific, Inc.
2700 Richards Road, Suite 107
Bellevue WA 98005 USA
425.641.0944 (T); 425.643.0595 (F)
www.SequoiaSci.com ; info@SequoiaSci.com

Thursday, November 14, 2013

Brian Sousa
FirstLight Power Resources - GDF Suez NA
Northfield Mountain Pump Storage Project - Turners Falls Project
99 Millers Falls Road
Northfield, MA 01360
Tel: (413) 659-4412

Dear Brian,

On October 9th and 10th I visited First Light's two LISST-Hydro instruments installed near the Northfield Mountain Pump Storage Project. The purpose of the visit was to review the installation and offer any suggestions for changes. The details of notes and resulting action items from my visit are documented in the "Chuck Pottsmith Site Visit Recap – 10-2103" document created by Tim Sullivan.

Both the North and South LISST-Hydro installations are well executed. The enclosure for the instruments is more than adequate, the battery and solar power chargers are well done, the clean water tank is large and has the necessary filters, and the pump is correctly mounted and its cable and hose is well protected. The installations are well within the requirements needed for proper operation of the LISST-Hydros.

During the same visit the installation of the LISST-StreamSide was also reviewed. It was also found to have an adequate enclosure, battery power and solar charging is adequate. Clean water tank is acceptable. The installation of the LISST-StreamSide is within the requirements needed for proper operation.

Please let me know if you have any additional questions. I can be reached by email at cpottsmith@sequoiasci.com or by phone at 425-641-0944 ext 107.

Sincerely,

Chuck Pottsmith

Chuck Pottsmith
VP , Sales and Market Development

APPENDIX C – ALDEN REPORTS

ALDEN

Solving flow problems since 1894

Engineering Studies of Sediment Uptake at the Northfield Mountain Connecticut River Intake/Tailwater

Alden Report Number:

1145QNORTH2-FINAL

Submitted to:

FirstLight Power Resources/GDF Suez N.A.
Northfield Mountain/Turners Falls Projects

September 12, 2016

ALDEN RESEARCH LABORATORY, INC.

ALDEN Research Laboratory, Inc.
30 Shrewsbury Street, Holden, Massachusetts 01520-1843

508-829-6000/phone • 508-829-5939/fax
info@aldenlab.com • www.aldenlab.com

EXECUTIVE SUMMARY

The Northfield Mountain Pumped-Storage Hydroelectric Project, located in the Towns of Erving and Northfield, Massachusetts, has a history of sedimentation accumulation issues. Entrained sand and fine sediment material from the Connecticut River is transported to the Upper Reservoir during operational pumping phases. The accumulation of sediment in the Northfield Mountain Upper Reservoir requires periodic maintenance. A detailed 3-Dimensinoal Computational Fluid Dynamics (3-D CFD) model of the Connecticut River Intake/Tailwater was developed to better understand the mobilization of Connecticut River sediment. The CFD model results can provide decision support regarding possible changes to the intake/tailwater configuration. Any modifications to the Intake/tailwater area would be designed to limit sediment conveyance from the Connecticut River to the Upper Reservoir.

After the hydraulic response of the existing conditions CFD model was validated with field observations from the April through July, 2014 river surveys, a series of three CFD sediment simulations were used to compute sediment uptake under the existing intake configuration, and to quantify the effectiveness of a convex sediment exclusion structure located outside of the boat exclusion as well as a longer concave sediment exclusion structure.

The effectiveness of the sediment exclusion structures was evaluated using the sediment transport capacity results of the CFD models. Structural alternatives can reduce annual sedimentation and uptake to the Upper Reservoir by approximately 10% to 20%.

The sedimentation model results indicated that much of the sediment mobilized to the Upper Reservoir occurs during periods of high sediment concentration in the Connecticut River. In addition model results show that operational strategies at the Northfield Mountain Pumped-Storage Hydroelectric Project could reduce sediment pumped to the upper reservoir.

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SEDIMENTATION STUDIES AT THE CONECTICUT RIVER INTAKE/TAILWATER

1.0 INTRODUCTION

Alden Research Laboratory, Inc. (Alden) has been retained by FirstLight Power Resources (FirstLight) to provide 3-dimensional (3-D) Computational Fluid Dynamic (CFD) hydraulic and sedimentation modeling of the Northfield Mountain Connecticut River Intake/Tailwater.

The Northfield Mountain Pumped-Storage Hydroelectric Project is located on the Connecticut River, near Turners Falls, Massachusetts. The project location is shown in Figure 1. Figure 2 shows a more detailed aerial view of the pumped storage intake/tailwater on the Connecticut River.

In 2013, Alden conducted 2-dimensional (2-D) sedimentation modeling of the Northfield Mountain Upper Reservoir to understand the process of sediment deposition upon discharge into the Reservoir. The 2013 modeling study concluded that sedimentation in the Northfield Mountain Upper Reservoir is due to relatively high concentrations of entrained sediment from the Connecticut River being conveyed to the Reservoir along with process water under pumping phases (Reference 1, Alden).

The present study of the Connecticut River Intake/Tailwater investigated the mechanism of sediment entrainment and mobilization within the River and developed exclusion strategies at the confluence of the Connecticut River and the Intake/Tailwater.

A detailed 3-dimensional model of the Connecticut River extending 500 feet upstream and downstream from the Northfield Mountain Pumped-Storage Intake/Tailwater (including the intake/tailwater area) was developed, validated, and used to simulate sediment mobilization under a range of Connecticut River discharge, Turners Falls Impoundment level, and operational pumping schemes (1, 2, 3, or 4 pumps moving water to the Upper Reservoir).

Figure 1: Northfield Mountain Reservoir Location Map

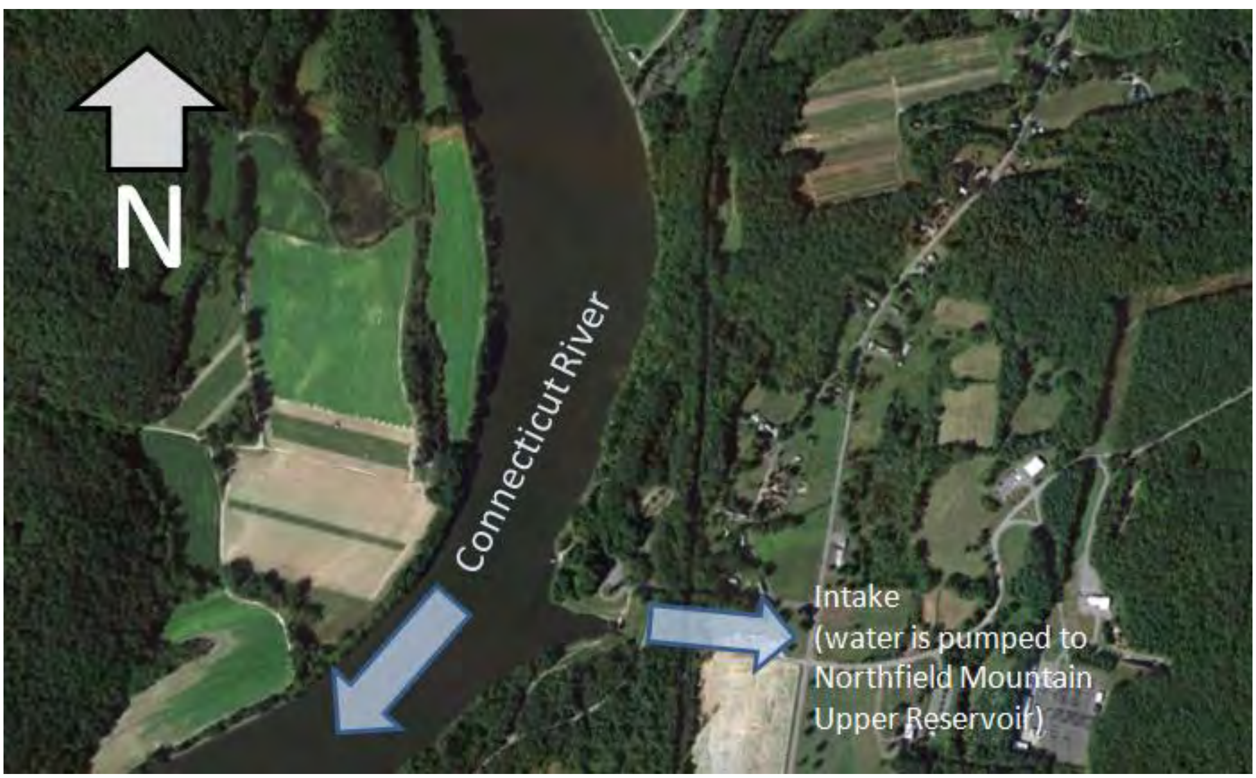

Figure 2: Overview of Connecticut River Intake/Tailwater

2.0 PROJECT OBJECTIVES

The ultimate objective of this sedimentation study was to determine if physical modifications to the intake/tailwater could help to reduce future sediment accumulation in the Upper Reservoir. Structural modifications were designed to exclude a portion of Connecticut River bed and suspended sediment from entering the intake/tailwater.

The specific objectives of the Connecticut River Intake/Tailwater study are as follows:

- Create a 3-D CFD model to simulate flow-fields in the vicinity of the Northfield Mountain Project Connecticut River Intake/Tailwater under a range of river and impoundment conditions during representative pumping cycles.

- Determine sediment mobilization potential at the intake/tailwater for a range of hydraulic model boundary conditions (river discharge, impoundment level, and pumping rate).

- Develop means and methods to decrease entrainment/uptake of mobilized sediment at the Connecticut River Intake/tailwater.

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3.0 MODELING APPROACH, METHODOLOGY, AND INPUT

3.1 Computational Model Selection

A variety of physical and numerical modeling approaches were considered to study the sedimentation trends and to evaluate alternatives intended to minimize uptake at the Connecticut River Intake/Tailwater.

Scaled physical models have a long history of application in river sedimentation problems. Physical models can have significant scaling limitations when used to evaluate temporal sediment conveyance, and are especially sensitive to fine sediment. Typically the model sediment cannot be reduced in size by the same ratio as the model scale. For direct scaling, sediment particles in a 1:50 scale model would be 50 times finer in the model than the measured Observed sandy material deposited in the Upper Reservoir ranges from 0.05 to 0.15 millimeters in size. Physical model sediment in the 0.001 to 0.003 millimeter size range (0.05 to 0.15 divided by 50) is very fine silt and clay, both of which are cohesive materials having significantly different sediment transport characteristics (entrainment and conveyance) than sand. The use of plastic surrogate sediment material to avoid cohesive problems, when scaled to account for buoyancy effects leads to additional transport and conveyance issues. Small scale physical models typically lack the necessary turbulence to cause sufficient movement of sediment in suspension; they tend to under predict sediment transport and are generally unable to provide reliable quantitative results.

Alden maintains a comprehensive library of 1-, 2-, and 3-dimensional Computational Fluid Dynamics (CFD) software and has current project experience using many different codes. Several available CFD models could be used to simulate sediment transport trends and compute uptake volume from the intake/tailwater. Generally, these models can be classified as 1-, 2-, and 3-dimensional computational models. A 1-dimensional model incorporates a cross sectional approach through a river reach and is useful for predicting gross changes in riverbed geometry. Two-dimensional hydraulic models are able to discretize a domain into computational cells in the X and Y dimensions. This type of model allows computation of the depth averaged flow field with longitudinal and lateral components and would be adequate to resolve the cross channel flow component of the intake/tailwater.

An important shortcoming of 1-D and 2-D models is that neither of these approaches can quantify the vertical movement of sediment in the Z dimension. Since the proposed intake/tailwater modifications include vertical flow restrictions (sediment retaining sills or exclusion structures), a 3-dimensional sediment transport models is necessary for this application. Three-dimensional models have cells in the vertical (or Z) direction and are able to develop a vertical velocity profile and predict variations in sediment concentration with depth. Typically a 3-D model is used for projects where quantification of the vertical velocity profile and/or sediment concentration profile is important.

Alden primarily uses FLUENT (by ANSYS), Star-CCM and FLOW-3D (by Flow Science) for 3-D CFD models. The fluid solvers of the three models are similar in that all solve non-linear 3-dimensional Reynolds Averaged Navier-Stokes (RANS) equations, but they use various models for the creation, transport and dissipation of turbulent kinetic energy. FLOW-3D uses a Cartesian mesh while FLUENT and Star-CCM use a more computationally intensive body-fitted computational grid. Implementation of the governing equations in FLOW-3D differs from that in Star-CCM and Fluent, making the models well suited to different types of flow problems. Generally, FLOW-3D tends to be the best software for modeling large riparian domains and Star-CCM and FLUUENT tend to be more suitable for detailed modeling of closed conduit problems.

FLOW-3D uses the Volume-of Fluid (VOF) method to track fluid-solid and fluid-sediment interfaces, and incorporates the Fractional Area/Volume Obstacle Representation (FAVOR) method (Reference 2, Hirt and Sicilian) to represent solid objects and complex boundaries like the riverbed, the Connecticut River Intake/Tailwater, and any potential sediment exclusion measures. FLOW-3D is well suited for problems involving a deformed free surface (water surface in an open channel or riverine flow problem) and is very efficient at time dependant solutions. FLOW-3D is typically faster to setup than Fluent or Star-CCM and changes in model geometry (i.e. exclusion measures) are more readily implemented. Additionally FLOW-3D incorporates a sediment transport module for modeling sedimentation patterns.

Due to streamlined model setup, quicker representation of physical measures to exclude sediment, higher computational efficiency, and available sediment transport module, Alden selected FLOW-3D as the most suitable software to simulate the flow-field and to evaluate sedimentation trends of the Northfield Mountain Connecticut River Intake/Tailwater.

3.2 Sedimentation Modeling with FLOW-3D

Sediment transport is modeled in FLOW-3D by enabling the sediment transport module. This module estimates the motion of particles by accounting for erosion, entrainment, advection, and sediment deposition. Sediment exists in one of three states within the model: transported as suspended sediment or as bedload, or stationary as packed sediment (making up the river bed). Bedload, which typically consists of larger-sized particles, is transported along the bed due to bed shear caused by water movement.

Suspended and bedload sediment are transported cell to cell within the model based on the physics of the flow-field. Local advection, drag, and settling of particles are computed using the momentum equation and solved for each sub-category of sediment species. In this case, coarser bed material and finer suspended material were considered. Suspended sediment transport is computed using the governing fluid flow equations including an adjustment to local fluid density due to spatially varied sediment concentration.

Re-suspension of sediment from the packed sediment is evaluated with the Mastbergen and Van den Berg model which calculates a local Shields parameter at the channel bed (sediment-water interface). The Shields parameter determines a sediment particle's incipient motion and entrainment potential.

Bedload transport is evaluated with the Meyer, Peter and Muller (MPM) model, where the volumetric bedload transport rate, q is determined by:

$$q = \Phi\left[g\left(\frac{\rho_s - \rho}{\rho}\right)d_s^3\right]^{1/2}$$

Equation (1)
[ref 3]

In Equation 1, g is the acceleration due to gravity, ρ_s is the sediment density, ρ is the fluid density, d_s is the diameter of the sediment species, and where Φ is the dimensionless bed-load transport rate (Equation 2).

$$\Phi = \beta(\Theta - \Theta''_{crit})^{1.5}$$ Equation (2)
[ref 3]

In Equation 2, β is a constant, Θ is the Shields parameter, and Θ''_{crit} is the modified critical Shields parameter.

A coupled CFD sedimentation model computes the transport of sediment within complicated river forms like bends and tributaries (similar to the intake/tailwater area) and around complex, three-dimensional structures such as dikes and sills. This modeling approach is ideal for evaluating alternative designs to mitigate sediment uptake to the Upper Reservoir.

3.3 Model Geometry: Domain, Bathymetry, and Model Grid

A 3-D model domain was selected to allow for the development of river flow patterns through the region upstream from the intake/tailwater and to eliminate boundary effects on flow near the intake/tailwater. Figure 3 shows the large domain model (brown dashed rectangle) which extends about 2,700 feet upstream and 1,400 feet downstream from the intake/tailwater. The large domain model is defined by a 4,060 by 2,300 foot rectangle and contains 233,450 cells. The large domain model cells are 20 feet long by 20 feet wide horizontally and 10 feet high in the vertical dimension. Figure 4 shows the large domain model mesh. A smaller higher resolution model was developed (the blue rectangle in Figure 3) within the large domain model. The high resolution model is used to provide more detailed results near the intake/tailwater. The high resolution model extends about 500 feet upstream and downstream from the intake/tailwater and is 1,410 feet wide by 1,050 feet long. This model is made up of 296,100 cells 10 feet wide by 10 feet long by 5 feet high. Figure 5 illustrates the mesh density and resolution of the high resolution model. The high resolution model uses flow field results from the large domain model to define the flow field at its boundaries.

The 3-D model geometry is based on the 2014 bathymetric survey of the Connecticut River and Northfield Mountain Intake/Tailwater (Reference 4, Gomez and Sullivan). The bathymetric survey was not detailed in the area of the intake structure due to limited safe access. Missing portions of the bathymetric survey in the boat exclusion zone (near the Tailrace Tunnel Exit) were enhanced with information from the Tailrace Tunnel Exit Structure & Portal and Tailrace Excavation Plans (References 5 and 6, Stone & Webster). Figures 6 and 7 show the intake/tailwater details from the tailrace structure and excavation plans. Dimensions taken from these plans were used to generate the 3-D model bedform in this area.

Figure 8 shows the contour lines generated from the bathymetric survey and plans. The Connecticut River bathymetry shown in Figure 8 was imported to define the riverbed and intake/tailwater area throughout the model domain. Figure 9 is a rendering of the bedform within the high resolution FLOW-3D model.

Figure 3: Model Domain

Figure 4: Large Domain Model Grid Resolution

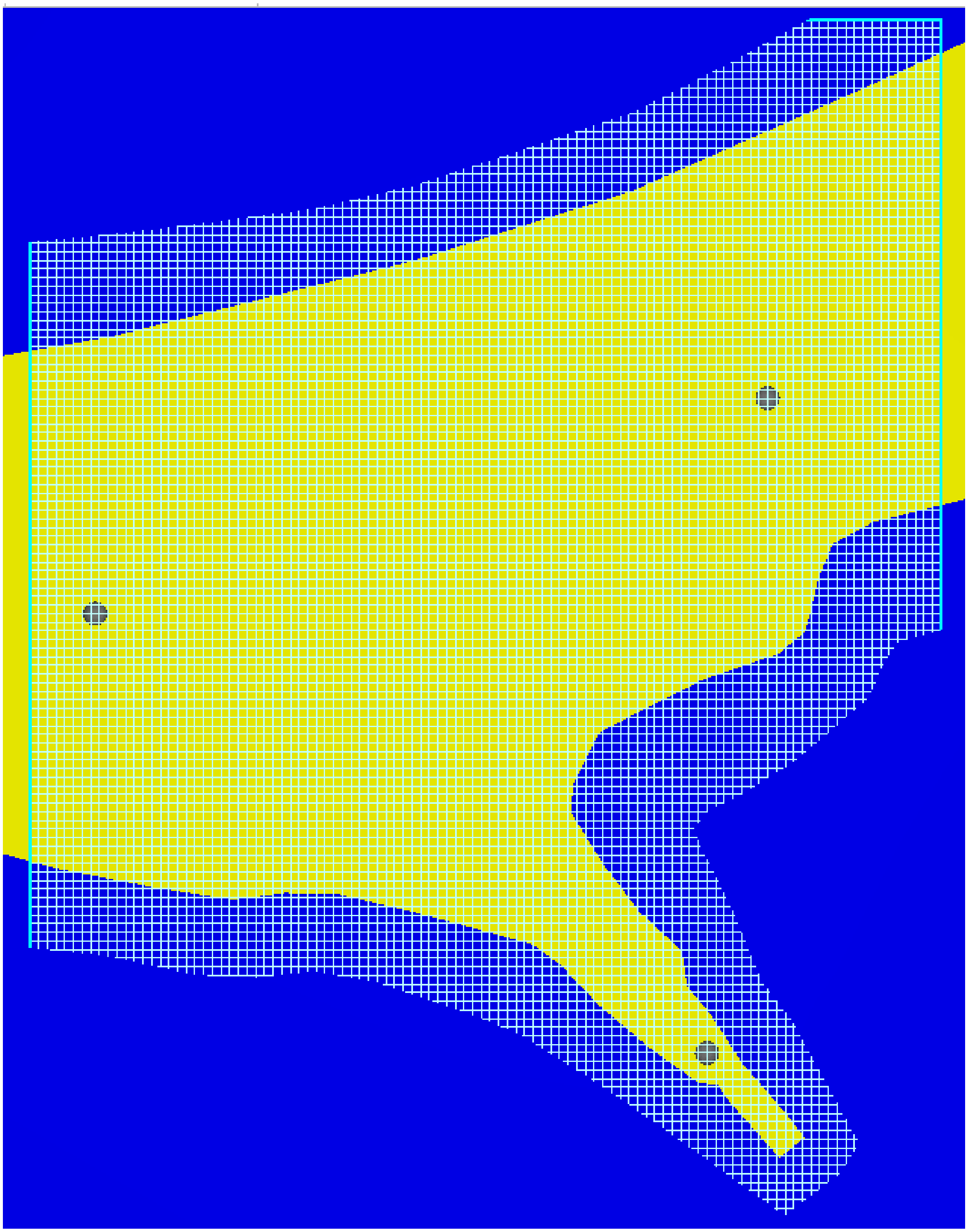

Figure 5: Detailed Small Domain Model Grid Resolution

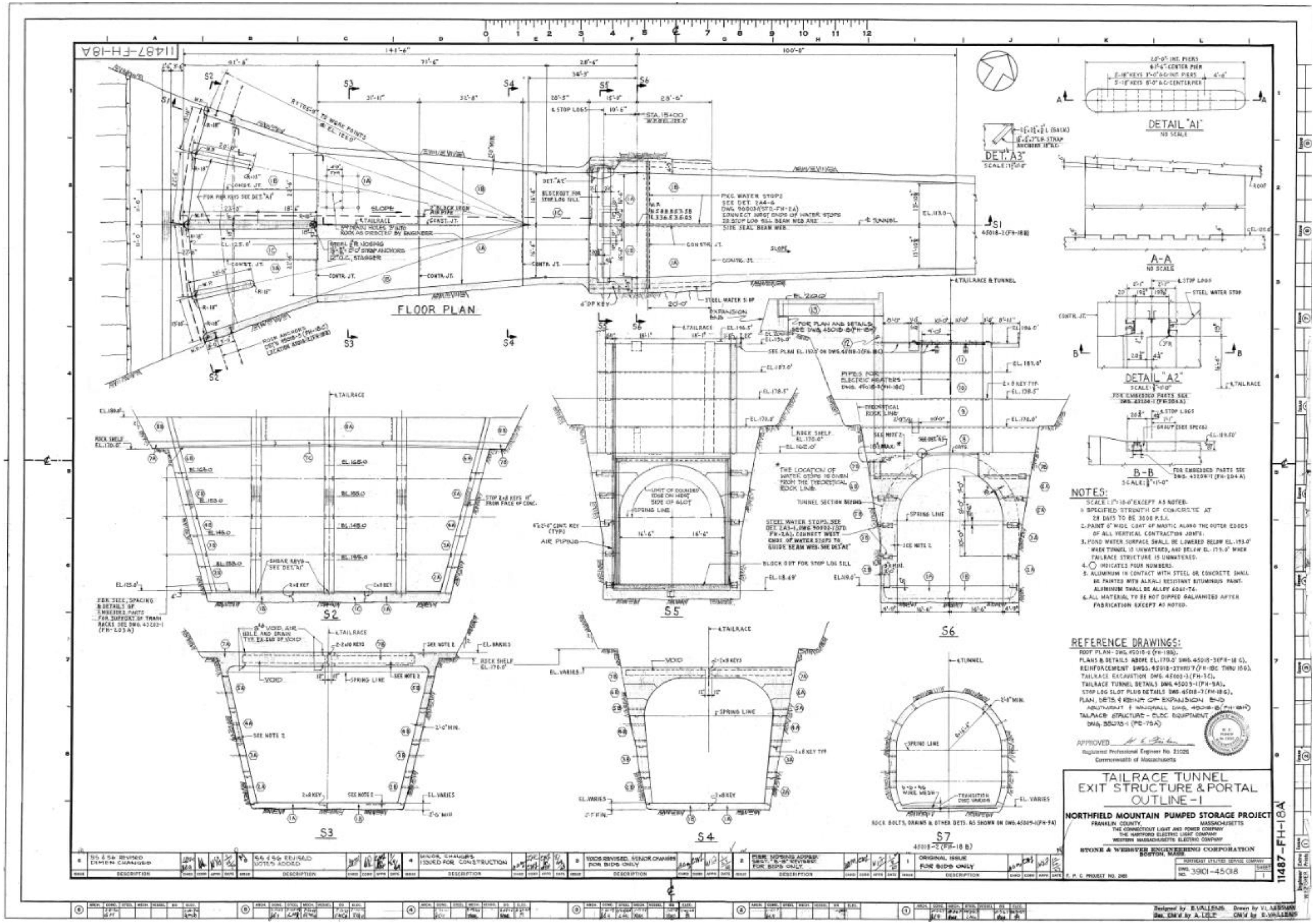

Figure 6: Tailrace Tunnel Exit Structure Plans (Reference 5)

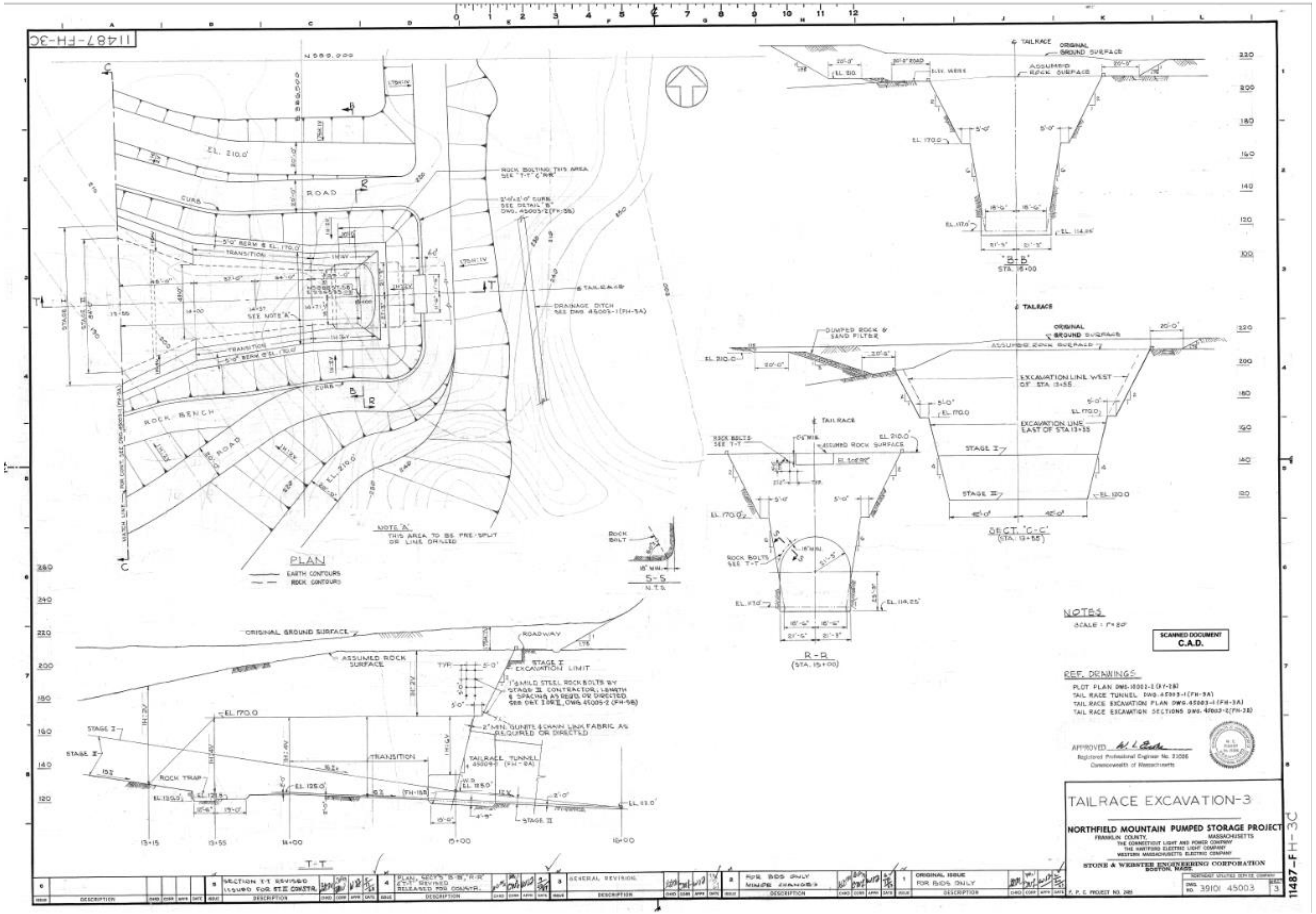

Figure 7: Tailrace Excavation Plans (Reference 6)

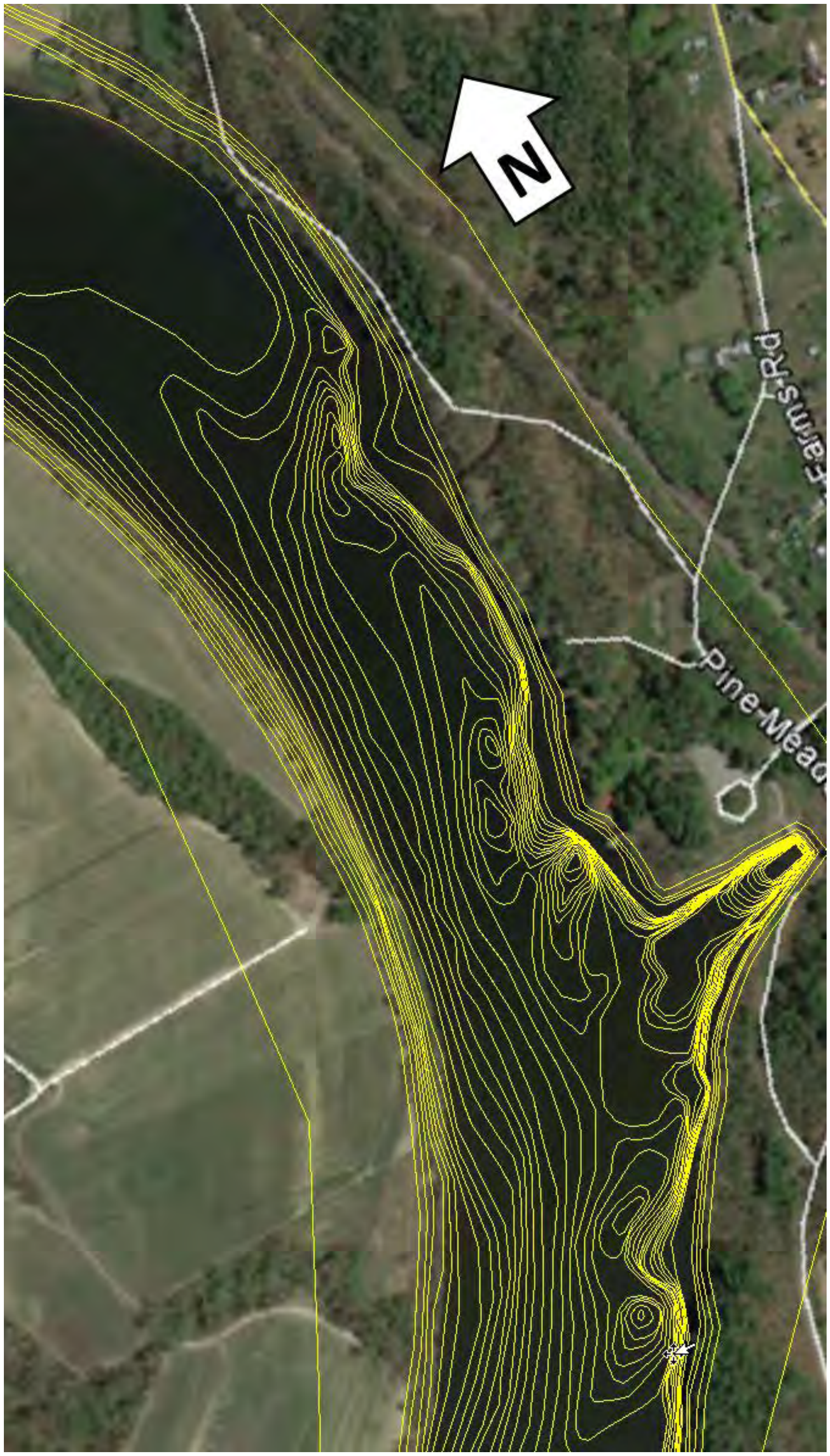

Figure 8: Bathymetic Survey Contours

(Adjusted with Tailrace Tunnel and Excavation Plans)

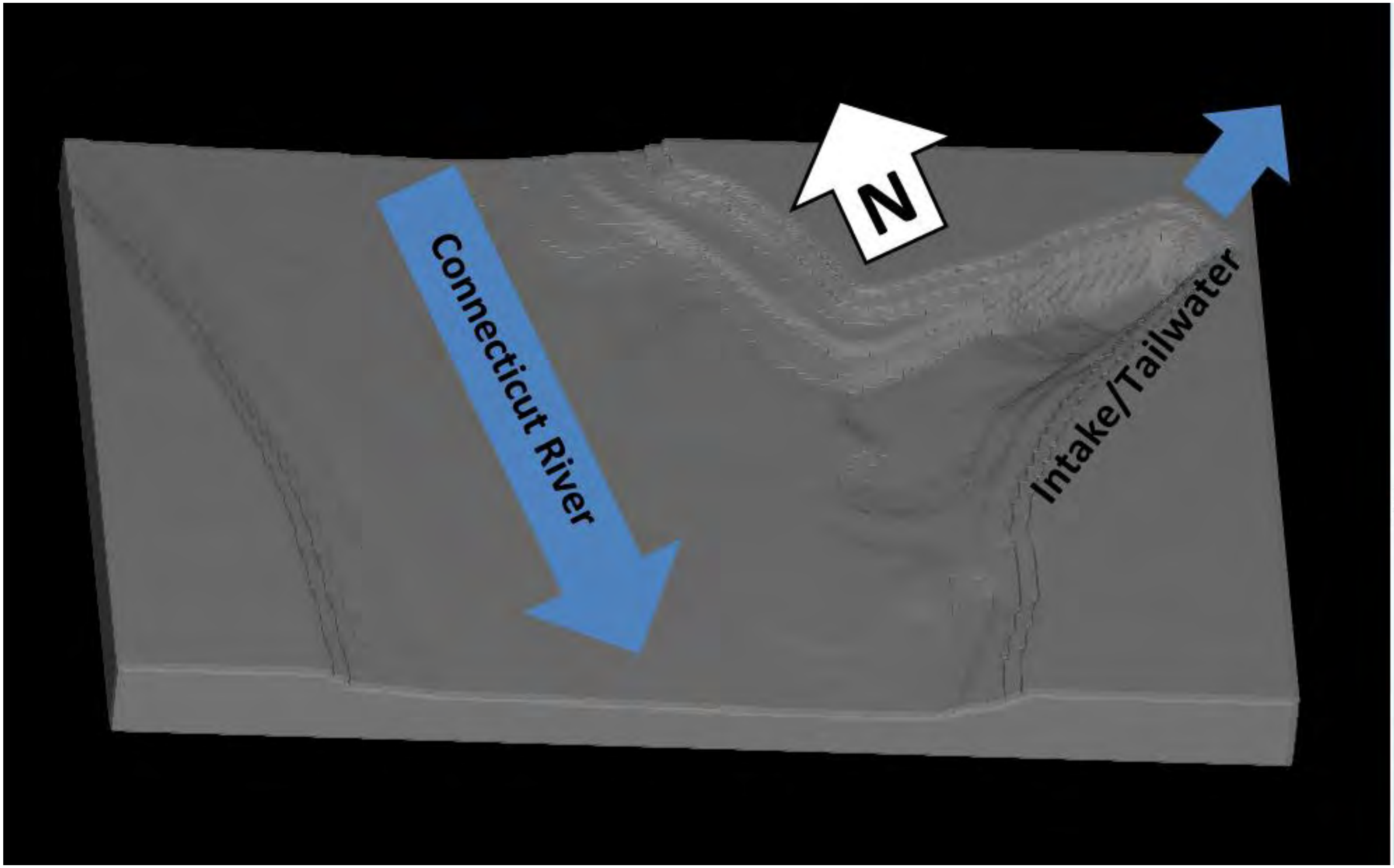

Figure 9: Small Domain Model Bedform

3.4 Model Input: Hydraulic Boundary Conditions

In addition to the bathymetric survey based model geometry/bathymetry, several other key inputs describe boundary conditions for the hydraulic model. The northern/upstream/inflow model boundary is defined by the volume of Connecticut River inflow. The southern/downstream/outflow end of the model is a regulated by a water surface elevation boundary which corresponds to the Turners Falls Impoundment level. The intake/tailwater boundary condition is based on Northfield Mountain Pumped-Storage Hydroelectric Project pumping operations (one to four pumps move water out of this boundary during normal operations). The sedimentation model requires an incoming sediment concentration at the upstream model boundary as well as additional parameters which define sediment characteristics in the riverbed and their entrainment potential (Section 3.5 describes the sediment input characterization).

The 3-D modeling was executed with twenty representative boundary condition combinations (summarized in Section 3.6). This set of boundary conditions was considered to represent a full range of river and operational conditions and was selected based on 10 years of environmental and operational records. Annual sediment mobilization from the Connecticut River to the Upper Reservoir was computed by aggregating the annual sediment transport capacity (tons per day times days per condition) of each the twenty model runs.

3.4.1 Upstream Boundary – Inflow

The upstream inflow boundary was defined to represent a typical range of flows in the Connecticut River which deliver sediment to the intake/tailwater area. A ten year period of Connecticut River flow records (Reference 7, Gomez and Sullivan) is shown in Figure 10. Peak flows in the Connecticut River during this period reached almost 80,000 cfs but most of the time the river flows at much lower levels. The average discharge for this period is just over 13,000 cfs.

A flow duration curve of the Reference 7 discharge data is shown in Figure 11. The flow duration curve is useful in determining representative Connecticut River discharges for the sedimentation modeling. High discharge levels in the River are likely to correlate with times of high sediment concentration in the river. Periods when the Connecticut River flow exceeded 50,000 cfs are relatively uncommon and of short duration. Over this period of record, the

Connecticut River flow was greater than 50,000 cfs for about 3% of the hourly discharge measurements. Connecticut River flow exceeded 30,000 cfs only 10% of the time.

It is interesting to note that most of the time when Connecticut River flow exceeded 30,000 cfs was between March and May (springtime freshets). Figure 12 shows the monthly association of high Connecticut River flow periods.

Five Connecticut River discharge ranges were selected to represent a typical annual range of flows for the sedimentation modeling. Flows higher than 50,000 cfs were dismissed because they happen so infrequently, and flows less than 5,000 cfs were left out because they are also infrequent and are expected to deliver lower amounts of sediment to the intake/tailwater area. Table 1 shows the five representative upstream/inflow model boundary discharges.

Table 1: Representative Connecticut River Discharge Range for Sedimentation Modeling

Case	Connecticut River Flow (cfs)	2000-2010 Annual Exceedence
A	50,000	3%
B	35,000	8%
C	25,000	14%
D	15,000	30%
E	5,000	75%

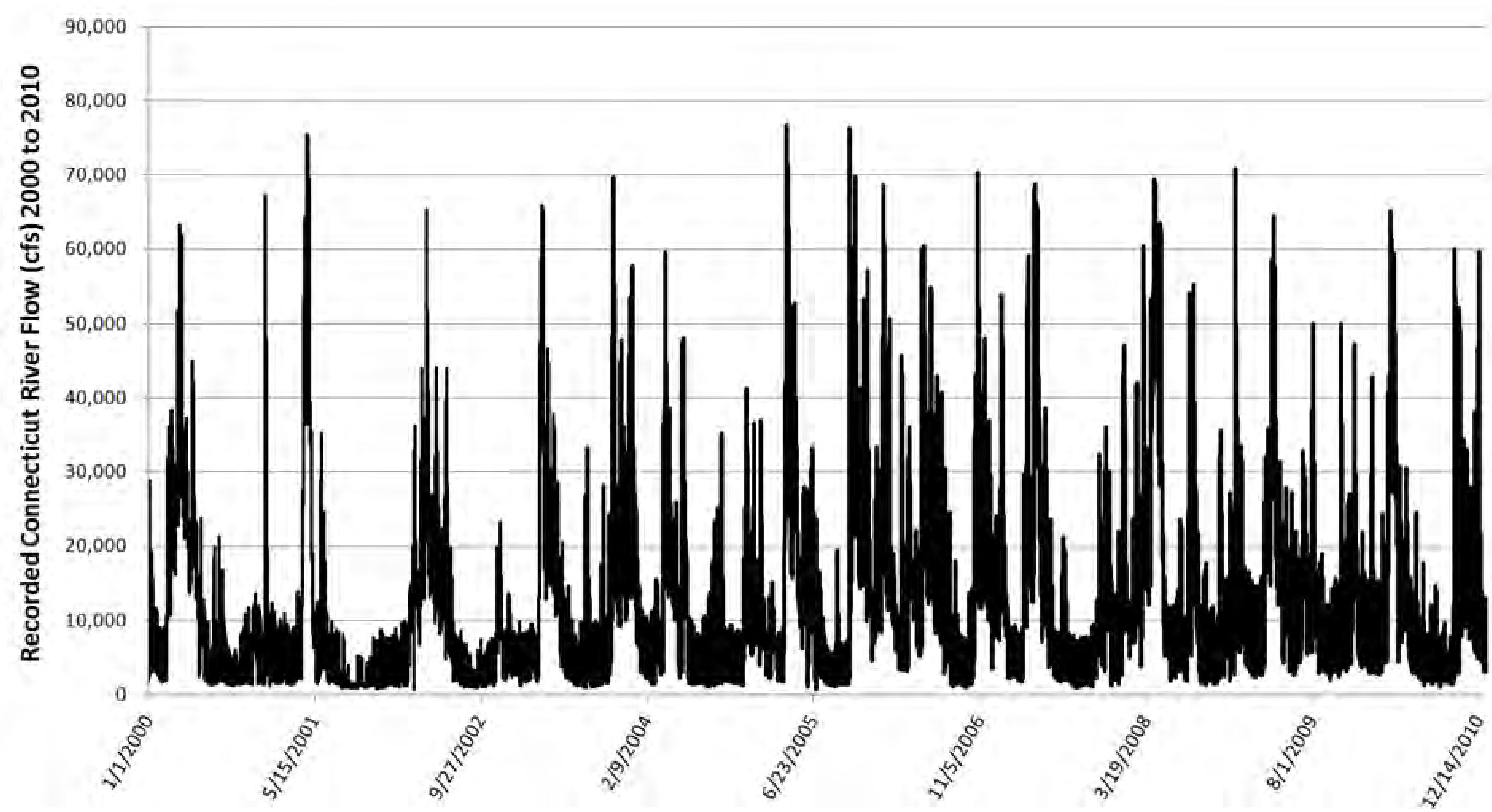

Figure 10. Connecticut River Discharge at Intake/Tailwater (2000 – 2010)

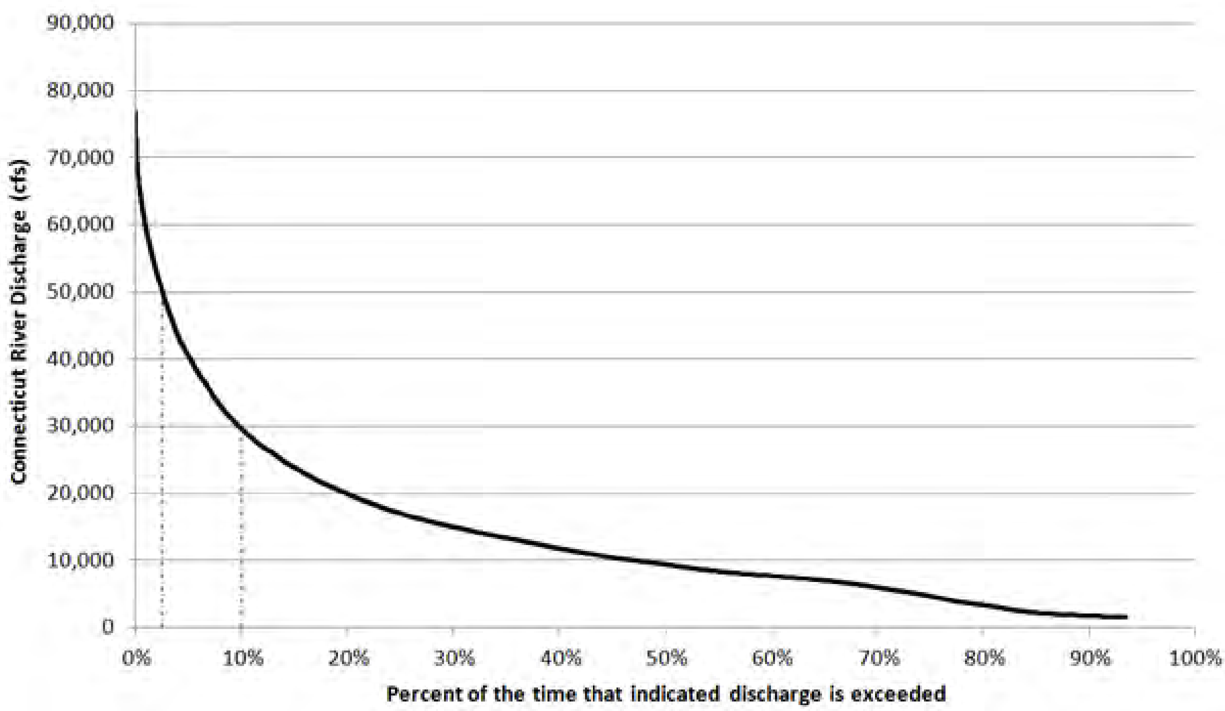

Figure 11: Connecticut River Flow Duration Curve (2000 – 2010)

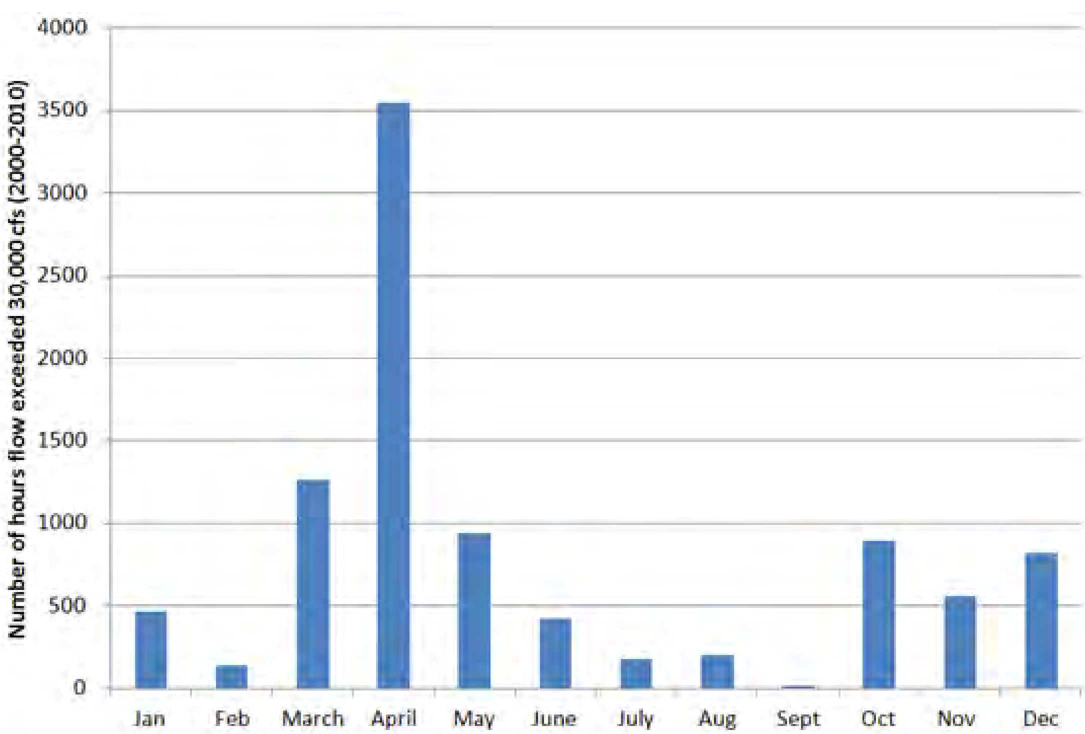

Figure 12: Monthly Occurrence of Connecticut River Flow > 30,000 cfs (2000 – 2010)

3.4.2 Downstream Boundary –Water Surface Level

The downstream sedimentation model boundary is defined as the Turners Falls Impoundment water surface level. Figure 13 shows the Turners Falls Impoundment level exceedence curve (Figure 4.3.1.3-7 of Reference 10, First Light/GDF Suez). The red line in Figure 13 is the annual exceedence curve for the Turners Falls Impoundment water surface level at the Northfield Mountain Pumping Project Intake/Tailwater. Based on the 2000 to 2009 hourly record analyzed in the Pre-Application Document (PAD), the impoundment level is higher than 185 feet 10% of the time, and lower than 181.4 feet 10% of the time. This means that the impoundment level near the intake/tailwater is between 181.4 and 185 feet 80% of the year, so the 3-D model was run with downstream boundary conditions inside this range of typical operations.

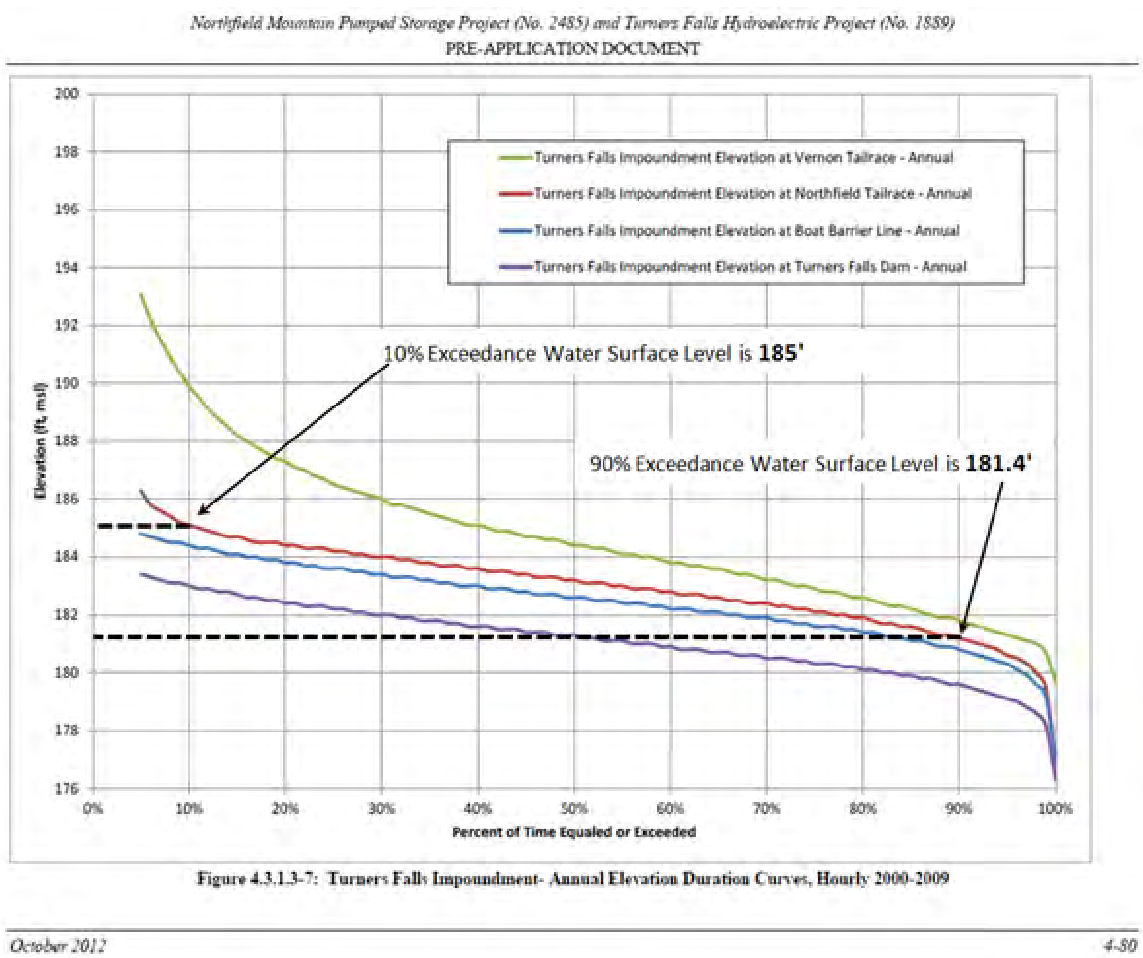

Figure 13: Turners Falls Impoundment Annual Water Surface Level Exceedence Curve (Reference 10)

Further investigation of the data provided in References 7 and 8 (2000 to 2010 hourly measured River discharge, Turners Falls Impoundment level and outflow, and Pumping and Generating data, Gomez and Sullivan) revealed that the Turners Falls Impoundment level is largely dependent on Connecticut River discharge (Figure 14).

The downstream boundary condition for each of the discharge levels in Table 1 was selected based on the relationship in Figure 14. The 50,000 cfs Connecticut River discharge case was limited to 185 feet to keep that boundary condition within the 10% Exceedence level computed in the PAD study. Table 2 shows the downstream water surface level boundary conditions for the modeling cases.

Turners Falls Dam outflow was considered as an additional possible downstream boundary condition. Hourly Connecticut River discharge data is plotted against Turners Falls Dam outflow (from References 7 and 8, Gomez and Sullivan) in Figure 15. While there is some variation due to other operational management, is a one-to-one relationship between Connecticut River discharge and Turners Falls Dam outflow is evident. Considering the response in Figure 15, and the historic relationship between Connecticut River flow and the Turners Falls Impoundment level (in Figure 14), the impoundment level was determined to be a better downstream boundary condition.

Table 2: Downstream Boundary Conditions for Sedimentation Modeling Cases

Case	Connecticut River Flow (cfs)	Turners Falls Tailwater Level (ft)
A	50,000	185
B	35,000	184.6
C	25,000	183.5
D	15,000	182.6
E	5,000	182.2

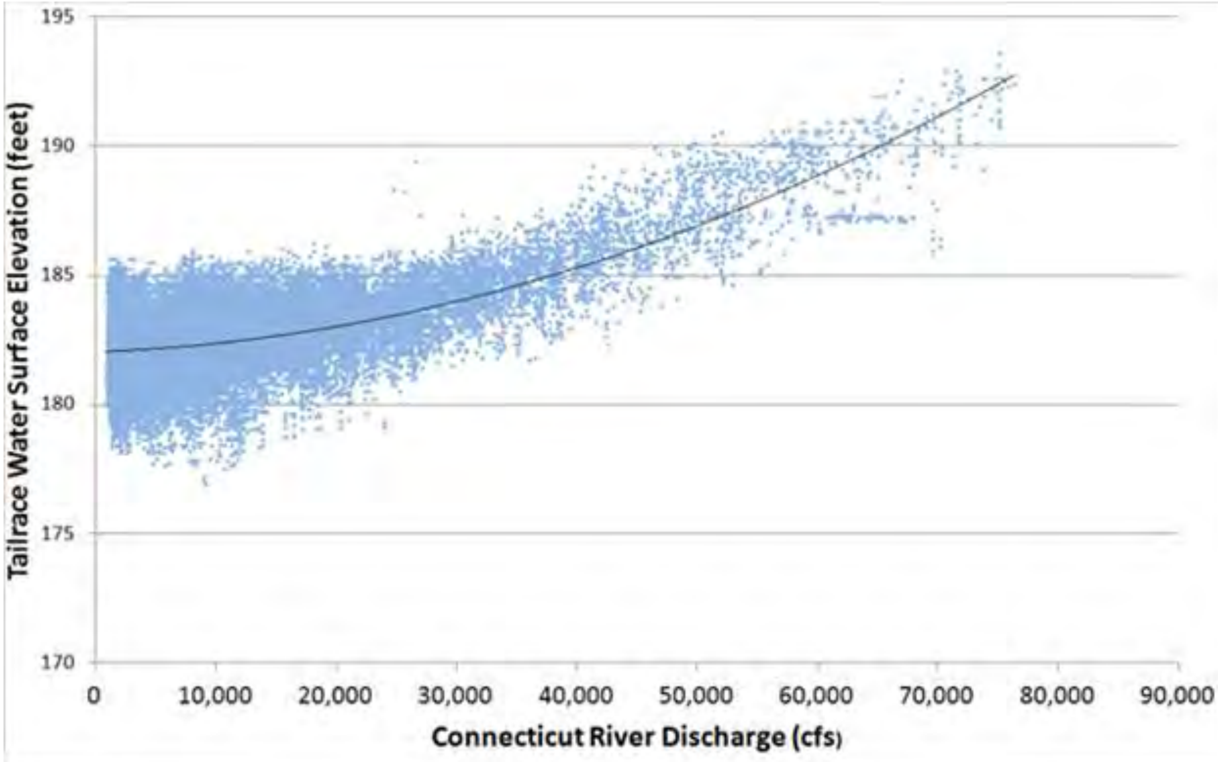

Figure 14: Intake/Tailwater Water Surface vs Connecticut River Flow

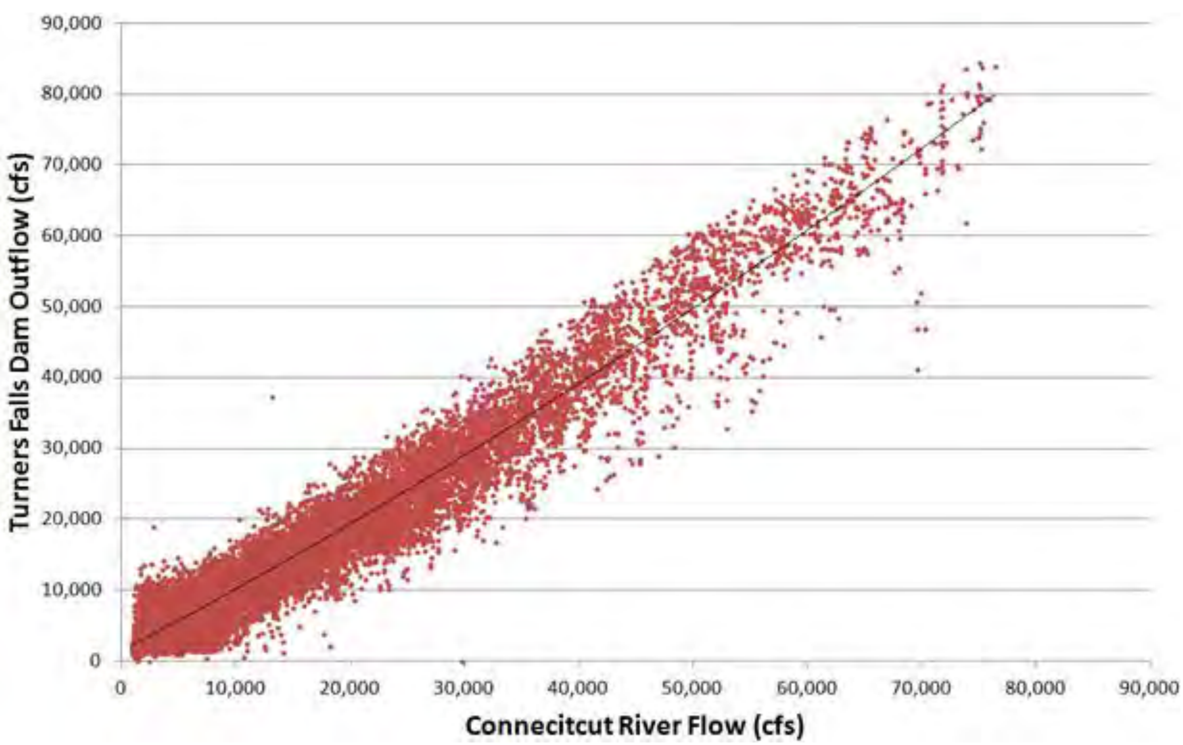

Figure 15: Turners Falls Dam Outflow vs Connecticut River Flow

3.4.3 Intake/Tailwater Boundary – Outflow to Northfield Mountain Upper Reservoir

The intake/tailwater boundary is a volume flow rate sink in the 3-D model. A mass sink element was created in the shape of the Tailrace Tunnel Exit Structure and Portal. A series of four outflows were assigned to this element to represent a typical range of operational pumping.

From the Project Facilities chapter of the Pre-Application Document (Section 3.2.2 of Reference 10, First Light/GDF Suez), the powerhouse pumps are capable of a maximum pumping rate of 15,200 cfs or 3,800 cfs per pump (multiplied by four pumps).

The following breakdown of pumping in terms of percent of time during a normal year when a given combination of pumps were used was developed from the Northfield Pumping Flow Duration Curve in Figure 16 (Reference 10, Gomez and Sullivan):

1	Pump	0 up to 3,800 cfs	**9%** of Annual Flow Duration Curve
2	Pumps	3,800 to 7,600 cfs	**10%** of Annual Flow Duration Curve
3	Pumps	7,600 to 11,400 cfs	**10%** of Annual Flow Duration Curve
4	Pumps	11,400 to 15,200 cfs	**6%** of Annual Flow Duration Curve

Application of the Megawatt to cubic foot per second pumping conversion (Equation 3 and Figure 17) to the recorded hourly pumping data in Reference 8 (Gomez and Sullivan) lead to the development of Figure 18.

Pumping (in cfs) = 13.28 x MW + 5.7649 Equation (3)
[ref 9]

Looking at the operational records from Reference 8 in Figure 18, there is a significant amount of variation in the pumping rate for all of the pumping configurations (1 Pump, 2 Pumps, 3 Pumps, or 4 Pumps operating) over the ten year hourly record. It seems reasonable to group hours of volume pumped into four classes as divided by the dashed horizontal lines in Figure 18. The thick horizontal populations of blue points (at about 3,600 cfs, 6,200 cfs, 9,800 cfs, and 13,200 cfs) indicates a given pump combination being run at full volume. Lighter density zones of blue points above each dense region represent times when a new pump is being added to the maxed out previous pump configuration. The pumping rate may then be increased to the limit of the new pump added combination. The typical pumping rate breakdown was computed by dividing the 33,645 total recorded hours of pumping from Reference 8 into four groups. The hourly pumping rates for each of the groups were averaged to provide a representative typical pumping rate for each pumping configuration. The pumping rates used for the modeling are presented in Table 3.

Table 3: Pump Rate Average Discharge and Percent of Record 2000 to 2010

Pumps	hrs at Pump Configuration	Average Pump Rate (cfs)	Percent of Pumping Time
4	6,008	12,348	18%
3	10,825	8,585	32%
2	5,085	5,252	15%
1	11,727	1,278	35%

(from Reference 8)

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Northfield Mountain Pumped Storage Project (No. 2485) and Turners Falls Hydroelectric Project (No. 1889)
PRE-APPLICATION DOCUMENT

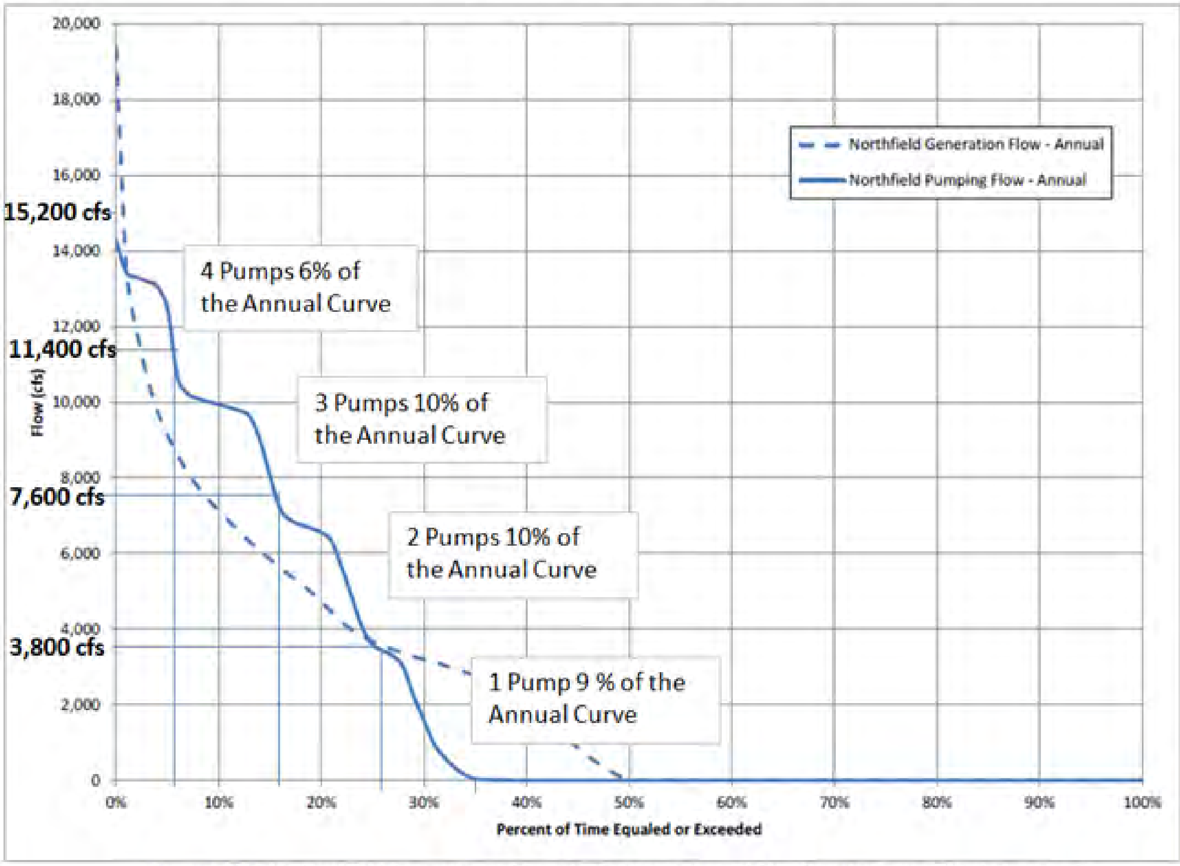

Figure 4.3.1.3-35: Northfield Generation and Pumping Discharge- Annual Flow Duration Curve, Hourly 2000-2009

October 2012 *4-108*

Figure 16: Attributed Northfield Pumping Flow Duration Curve

(original figure from Reference 10)

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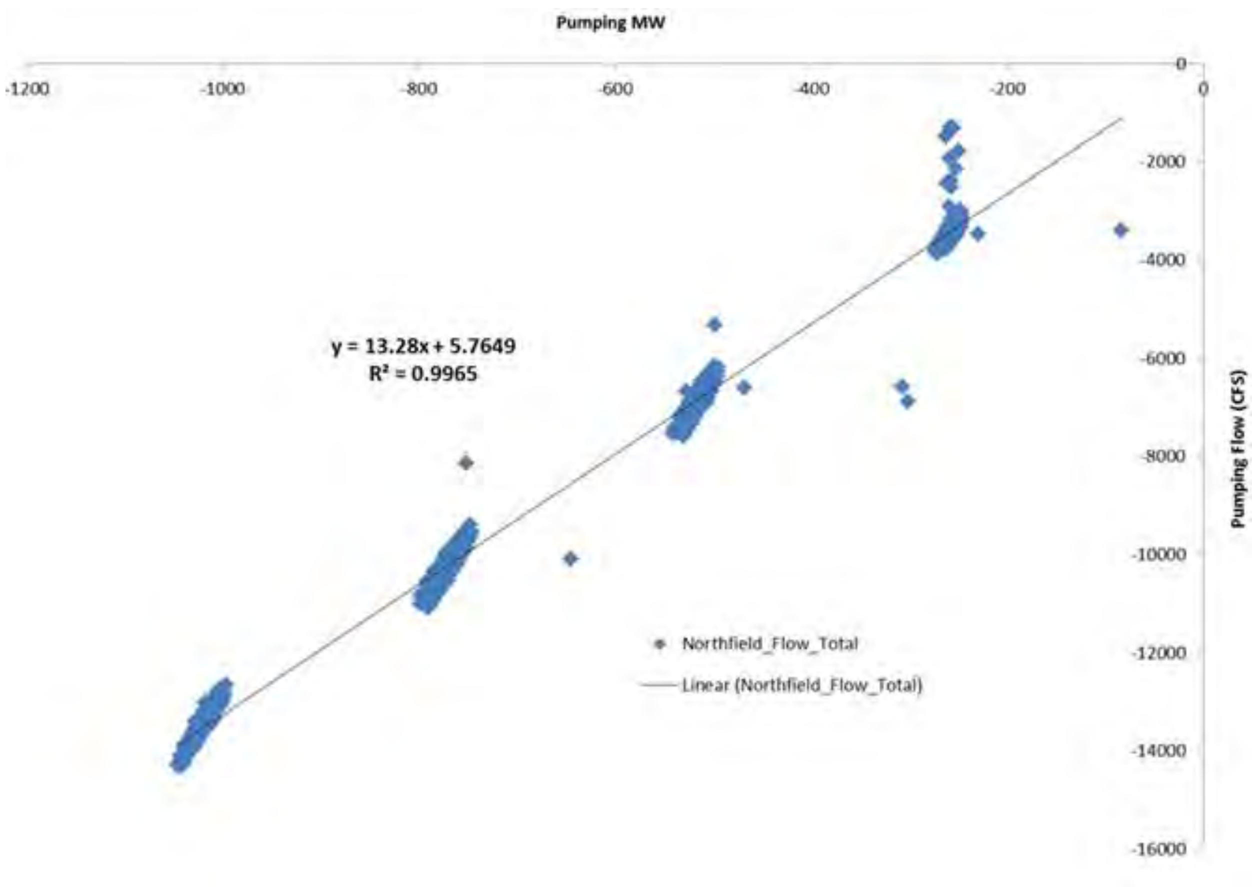

Figure 17: Pumping: Transformation from MW (recorded) to Cubic Feet per Second (from Reference 9)

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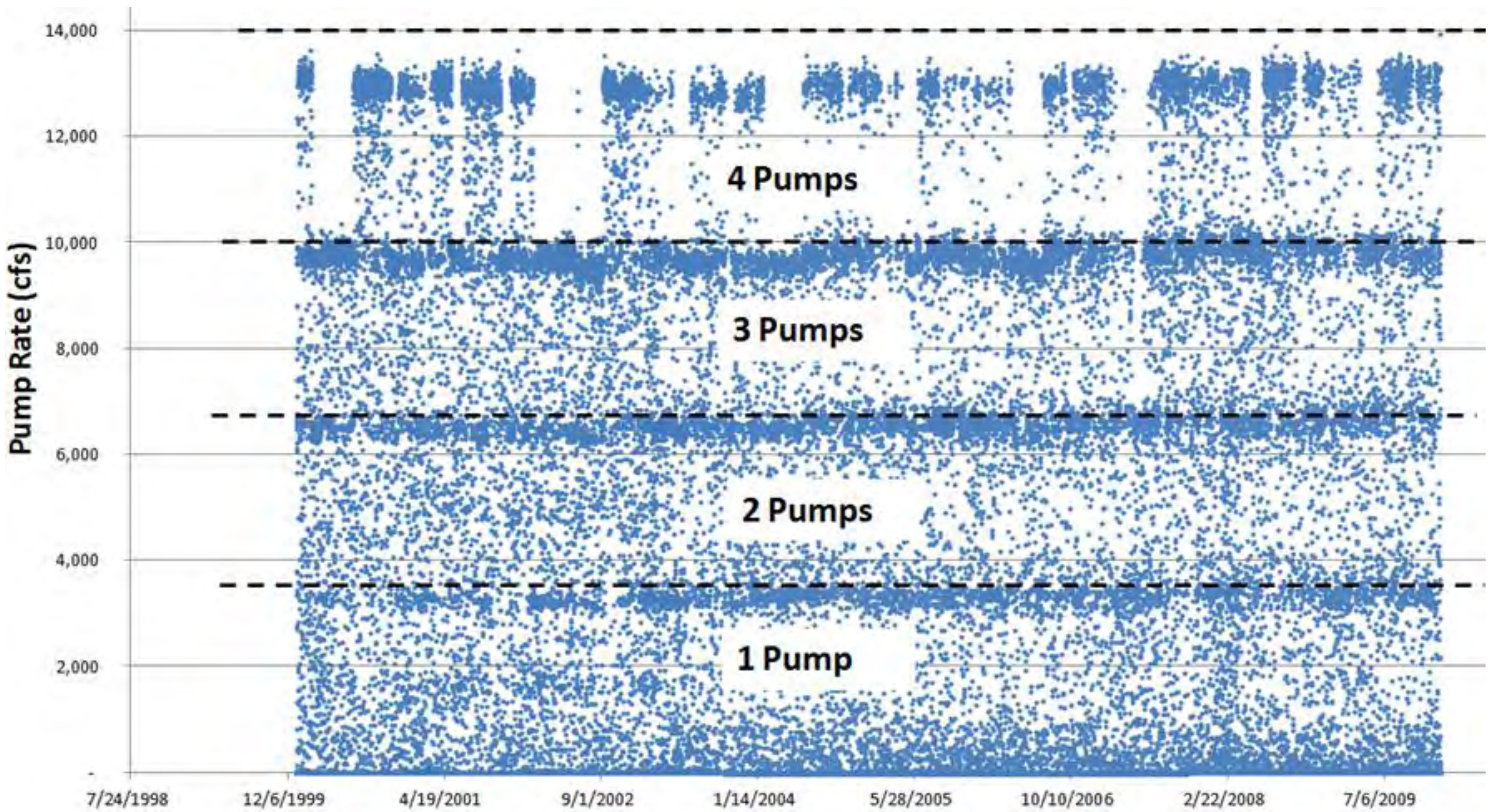

Figure 18: Hourly Recorded Pumping Rates 2000 – 2010 (from ref. 8)

3.5 Sediment Model Input

3.5.1 Available Sediment Data

The available sediment information was integrated into the sedimentation model:

- Measured suspended sediment concentration in the Connecticut River,
- Measured sediment size in the Upper Reservoir,
- Observed depositional volume trends in the Upper Reservoir

Suspended sediment concentration in the Connecticut River was plotted against Connecticut River discharge in Figure 19 (from Reference 1, Alden). At times, notably at about 37,000 and about 62,000 cfs, measured suspended sediment concentration varied with respect to discharge. However, sediment concentration typically increases with discharge as shown by the function represented by the red trendline. This function was used to assign sediment concentration to the modeled Connecticut River inflows shown as shown in Table 4.

Table 4: Sediment Concentration at Modeled Discharges

Connecticut River Flow (cfs)	River Sediment Concentration (ppm)
50,000	175
35,000	64
25,000	26
15,000	8
5,000	3

The coarse and fine sediment size classes used in the 2013 Northfield Mountain Upper Reservoir Sedimentation Study (Reference 1, Alden) were used to define the gradation of the Connecticut Riverbed for the River/Intake/Tailwater model.

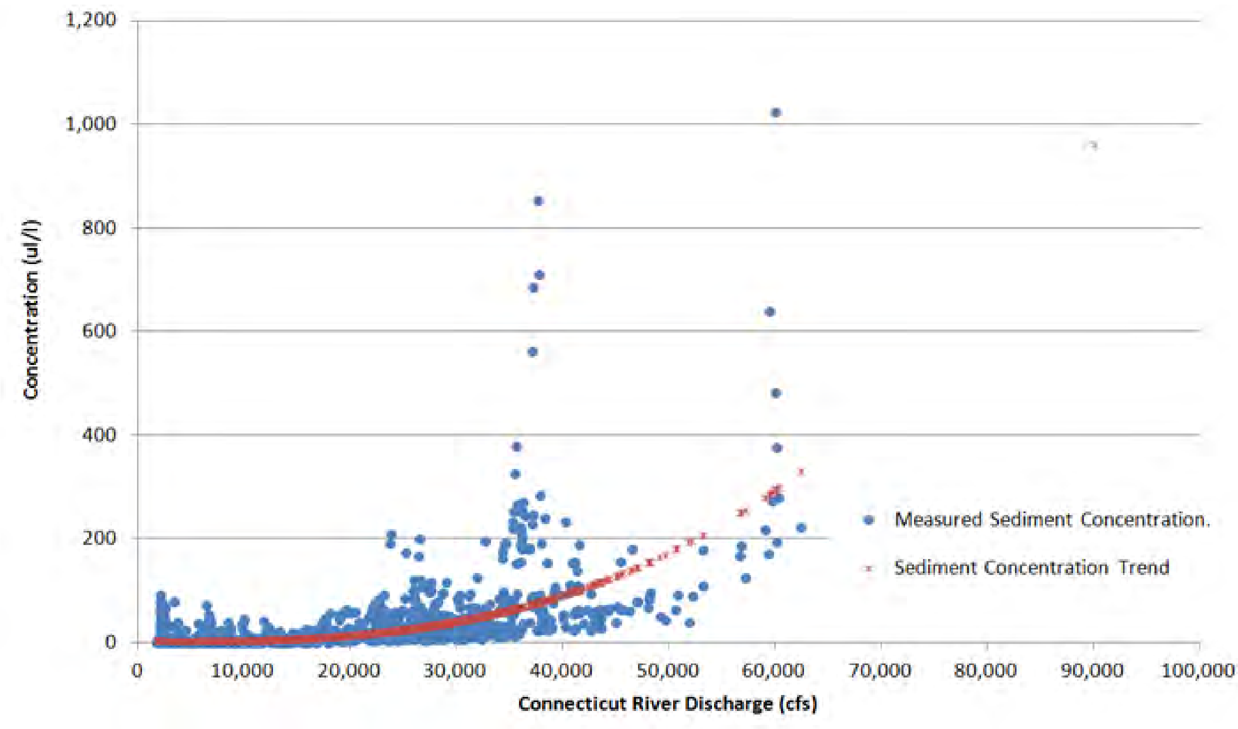

Figure 19: Connecticut River Suspended Sediment Concentration

(from Figure 11 of Reference 1)

The 2013 Alden model considered Connecticut River sediment concentration sample size information and the size of material sampled in the Upper Reservoir Deposition Zone (Figures 20 and 21) for determining the size of the coarse sediment class. Finer material found further out into the Upper Reservoir was included in the fine sediment class. Measured sediment from the Connecticut Suspended Sediment Concentration sampling had an average D50 of 0.024 mm and a maximum D50 of 0.2 mm. Coarse material found in the Upper Reservoir Deposition Zone was given a D50 of 0.15 mm based on the maximum suspended sediment size of 0.2 mm and anecdotal information. Finer material deposited further out in the reservoir had a measured D50 of 0.05 mm (Section 3.4 of Reference 1, Alden).

Figure 20: Upper Reservoir Sediment Deposition

3.5.2 Sedimention Model Parameters

The riverbed was defined as a packed sediment zone within the sediment module of FLOW-3D. Areas designated as packed sediment zones erode at appropriate hydraulic conditions (when the computed shear at a cell exceeds the critical shear value) and transport sediment throughout the model. Entrained bed material is added to inflowing sediment concentration and mobilized sediment is tracked throughout the model to the intake/tailwater boundary. Most of the Upper Reservoir deposition occurs in the Deposition Zone (Section 3.4 of Reference 1, Alden). Accordingly, the coarse sediment volume leaving the model domain at the intake/tailwater boundary under the range of model conditions was compared to observed annual deposition in this area. Sediment module coefficients, specifically the entrainment coefficient described below, were modified until model results matched typical observed annual deposition within the Upper Reservoir Deposition Zone.

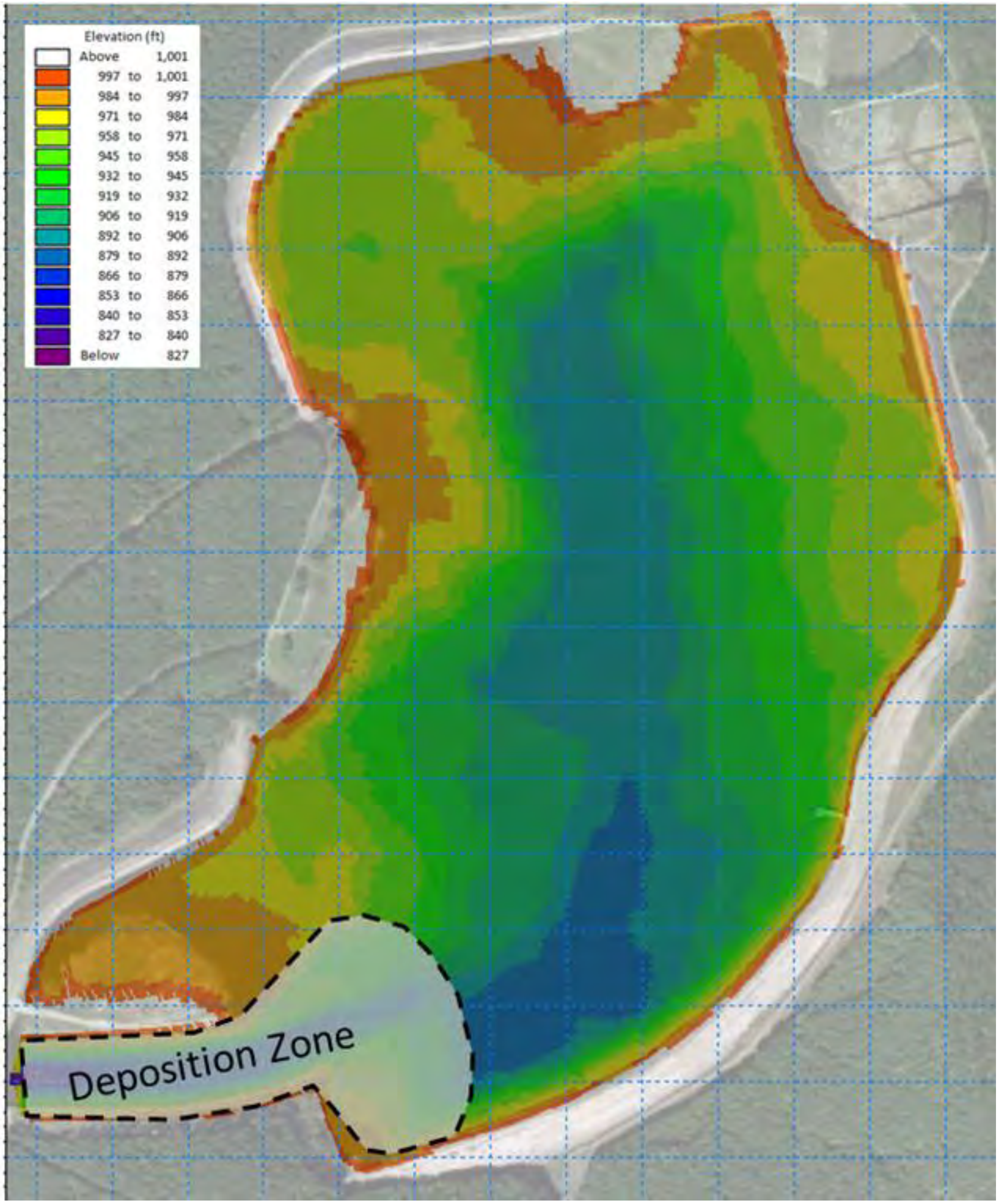

Figure 21. Upper Reservoir Deposition Zone

Critical Shields Number and a sediment entrainment coefficient were designated for each sediment size class. The critical Shields Number was assigned based on sediment size using the information in Figure 22 (Table 7.1 from Reference 11, Julien). Critical Shields Numbers of 0.33 and 0.67 were used for the fine (0.05 mm) and coarse (0.15 mm) sediment respectively.

Annual model runs were made with a series of entrainment coefficients ranging from 3E-6 to 1E-4 until the computed coarse fraction of typical annual sediment volume was consistent with an average or typical observed annual sediment deposition within the Upper Reservoir Deposition Zone as described in Section 3.7.

Table 7.1. *Threshold conditions for uniform material at 20°C*

Class name	d_s (mm)	d_*	ϕ (deg)	τ_{*c}	τ_c (Pa)	u_{*c} (m/s)
Boulder						
Very large	> 2,048	51,800	42	0.054	1,790	1.33
Large	> 1,024	25,900	42	0.054	895	0.94
Medium	> 512	12,950	42	0.054	447	0.67
Small	> 256	6,475	42	0.054	223	0.47
Cobble						
Large	> 128	3,235	42	0.054	111	0.33
Small	> 64	1,620	41	0.052	53	0.23
Gravel						
Very coarse	> 32	810	40	0.05	26	0.16
Coarse	> 16	404	38	0.047	12	0.11
Medium	> 8	202	36	0.044	5.7	0.074
Fine	> 4	101	35	0.042	2.71	0.052
Very fine	> 2	50	33	0.039	1.26	0.036
Sand						
Very coarse	> 1	25	32	0.029	0.47	0.0216
Coarse	> 0.5	12.5	31	0.033	0.27	0.0164
Medium	> 0.25	6.3	30	0.048	0.194	0.0139
Fine	>0.125	3.2	30	0.072	0.145	0.0120
Very fine	> 0.0625	1.6	30	0.109	0.110	0.0105
Silt						
Coarse	> 0.031	0.8	30	0.165	0.083	0.0091
Medium	> 0.016	0.4	30	0.25	0.065	0.0080

Figure 22: Critical Shelds Number

(from Reference 12)

3.6 Representative or Typical Pumping Year Approach

Twenty environmental/operational cases were developed to represent a typical year of river and pumping activity. The modeling approach was to combine a series of steady-state solutions representing the range of typical river and operational conditions to compute annual sediment uptake to the Upper Reservoir. Sediment conveyance in terms of mass/time for each of twenty steady-state models was multiplied by time of occurrence for that case and combined to compute typical annual reservoir uptake.

The 2000-2010 Connecticut River hourly discharge data (Reference 7, Gomez and Sullivan) was combined with the Project operational records (Reference 8, Gomez and Sullivan) to investigate the relationship between river flow and plant pumping operations. Three examples of high Connecticut River flow (Figures 23- 25) illustrate historic environmental/operational conditions.

Figure 23 shows a period of high Connecticut River flow (40,000 to 50,000 cfs) in July and August of 2009. During the July 31 pumping cycle (about 40,000 cfs Connecticut River flow) three pumps were operational. The August 1 pumping cycle (50,000 cfs Connecticut River flow) showed higher pumping rates from four operational pumps.

Figure 24 shows two days of operations in April, 2000. Both April 5 and April 6 showed two pumps operational at a high flow in the Connecticut River of 55,000 to 60,000 cfs.

Figure 25 shows a high Connecticut River flow period of 40,000 to 75,000 cfs. No pumps were operational.

Conclusions regarding plant operations being dependent on Connecticut River discharge could not be made based on historic examples of recorded data. The lack of consistency found in this initial investigation created a need for more detailed analysis of this relationship to determine a typical year of environmental and operational conditions.

The data from References 7 and 8 was combined and synchronized to provide a conditional assessment of Connecticut River flow and plant operational pumping for each hour of the available 2000-2010 record. The number of instances for each combined pumping rate (4, 3, 2, and 1 pump operational) and Connecticut River discharge (50,000 cfs to 5,000 cfs) from the twenty cases in Table 5 was computed. The period of record (39,536 hours of pumping in 3,603 days) was reduced to one year and hours for each individual case occurrence were calculated. Normally the plant pumps and generates daily; pumping activity was observed in about 45% of hours in the historic record.

Case A (high Connecticut River discharge and 4 pumps operational) typically occurs for 27 hours per year. Case J (low Connecticut River Discharge and 3 pumps operational) typically occurs for 595 hours per year. With the discretized environmental/operational scheme in place, the existing case model was run for a series of representative environmental/operational combinations. Results were used to evaluate sediment conveyance potential to the Upper Reservoir on a typical annual basis.

As mentioned in Section 3.5.2, this was an iterative process. The FLOW-3D sediment entrainment coefficient variable was adjusted until the combined representative annual sediment uptake was matched to a target volume based on observed filling of the Upper Reservoir.

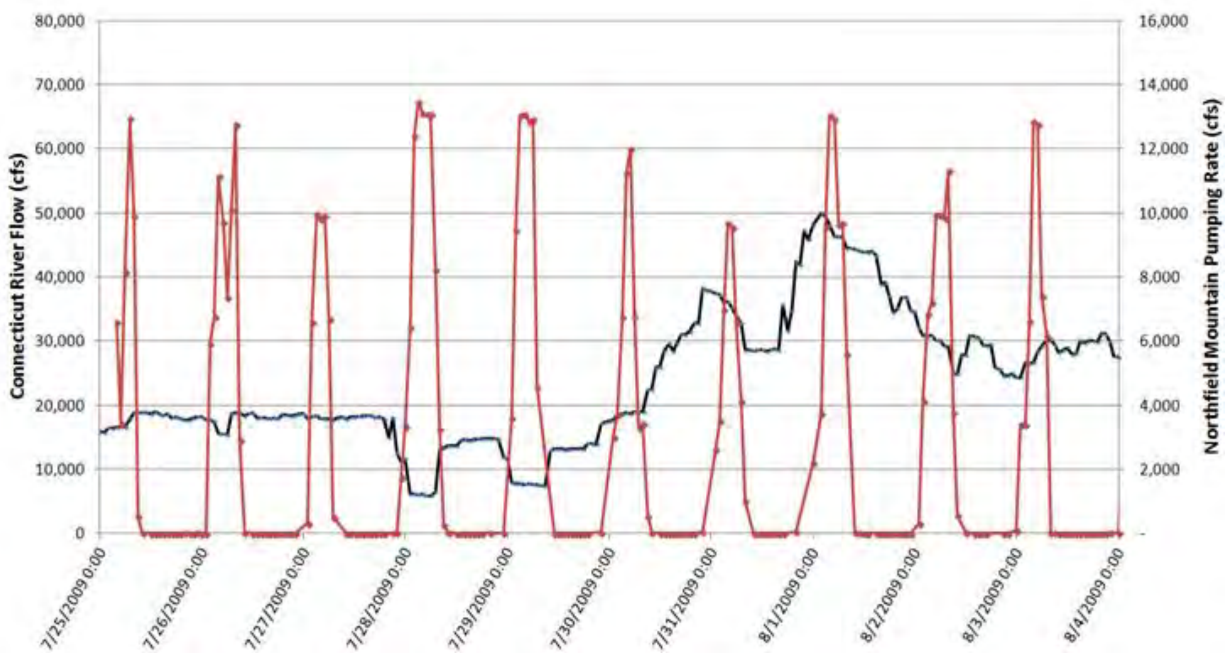

Figure 23: Connecitcut River High Flow 3 to 4 Pumps Operational (July-August 2009)

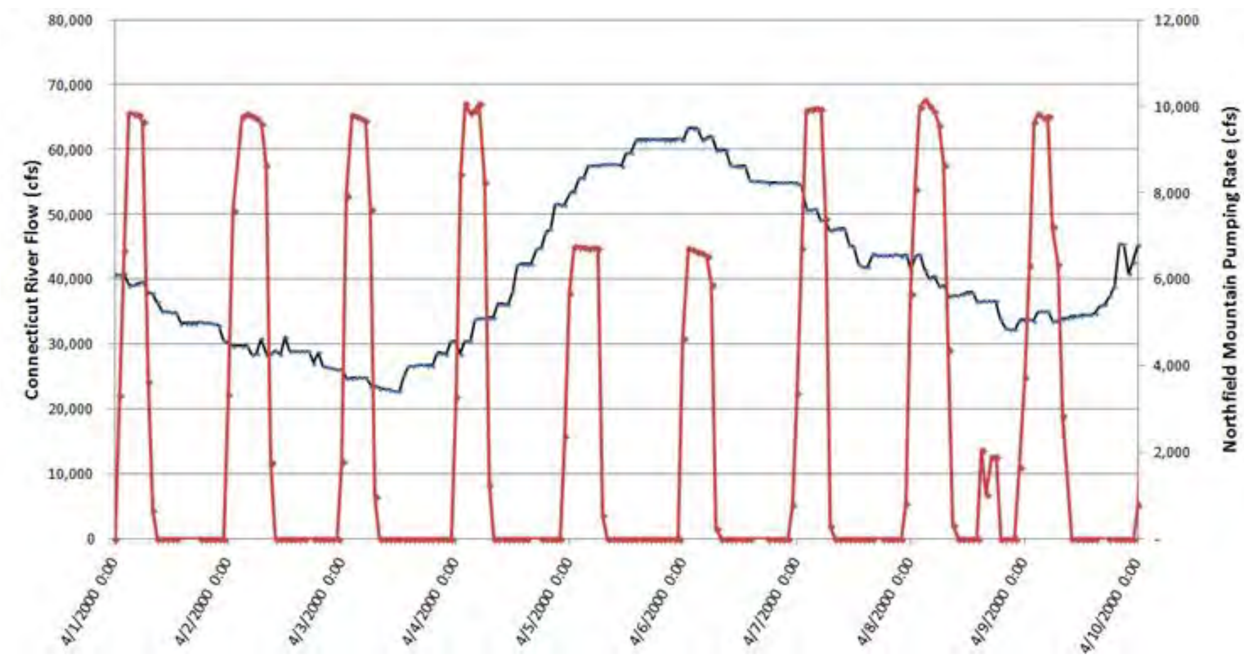

Figure 24: Connecticut River High Flow 2 Pumps Operational (April 2000)

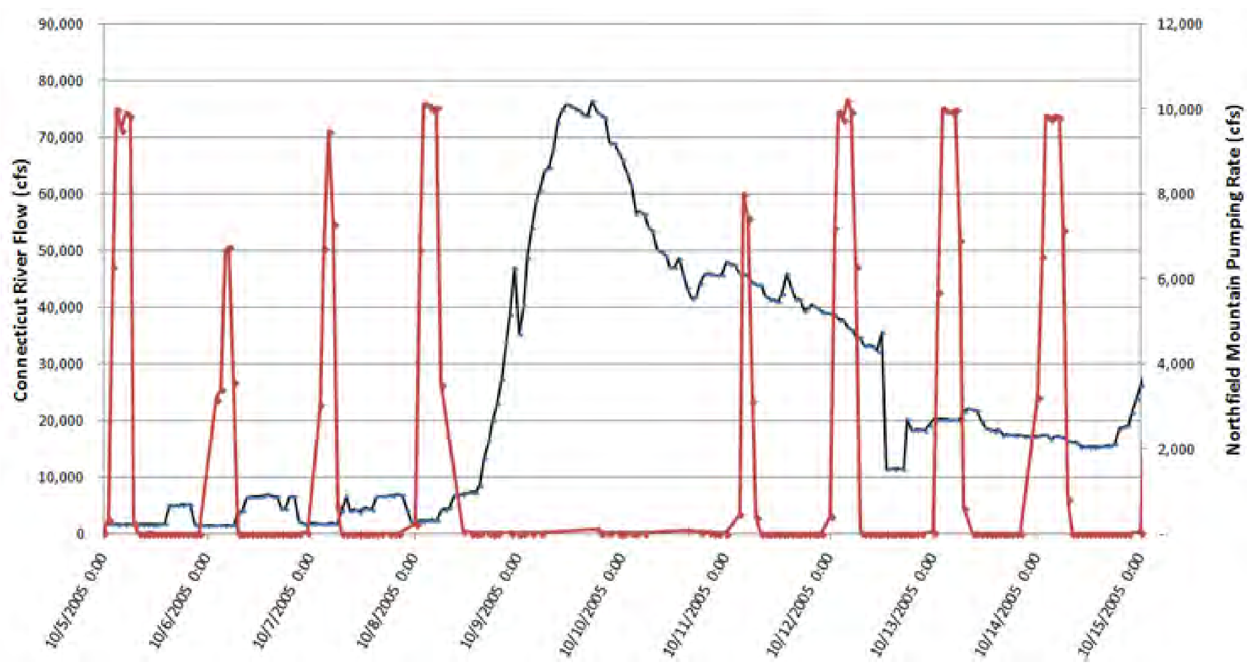

Figure 25: Connectucut River High Flow No Pumps Operational (October 2005)

Table 5: Twenty Run Model Input Parameters (including hours per year of each case)

Case	Hours	Pump Rate (cfs)	Conn. River Flow (cfs)	Turners Falls Impound Water Level (feet)	River Sediment Concentration (ppm)
A	27	12,348	50,000	185.0	175
B	18	12,348	35,000	184.6	64
C	39	12,348	25,000	183.5	26
D	109	12,348	15,000	182.6	8
E	409	12,348	5,000	182.2	3
F	58	8,585	50,000	185.0	175
G	57	8,585	35,000	184.6	64
H	117	8,585	25,000	183.5	26
I	248	8,585	15,000	182.6	8
J	595	8,585	5,000	182.2	3
K	36	5,252	50,000	185.0	175
L	19	5,252	35,000	184.6	64
M	63	5,252	25,000	183.5	26
N	130	5,252	15,000	182.6	8
O	317	5,252	5,000	182.2	3
P	78	1,278	50,000	185.0	175
Q	87	1,278	35,000	184.6	64
R	195	1,278	25,000	183.5	26
S	471	1,278	15,000	182.6	8
T	880	1,278	5,000	182.2	3

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3.7 Sedimentation Model Run Conditions

The case-wise approach described in the previous section dramatically shortens the computational time necessary to model a typical year of pumping and environmental conditions. Aggregating this series of steady-state sediment conveyance models yields a set of cases which accounts for typical observed combinations of environmental and operational conditions.

Three model conditions were simulated to understand the current sedimentation process, determine the effectiveness of a short convex sediment exclusion structure which isolates the intake/tailwater area from the bed of the Connecticut River, and to assess any benefits from a longer and concave river streamline oriented sediment exclusion structure.

3.7.1 Existing Condition

Each of the twenty steady-state sediment model environmental/operational cases were run for 4,500 computational seconds until the sediment conveyance capacity at the intake/tailwater boundary converged on a solution. Appendix A shows graphic time-wise sediment conveyance capacity output for each case of the three CFD models. Coarse sediment conveyance capacity in tons per second was multiplied by the number of seconds per year each environmental/operational case is expected to occur. These values were then combined to determine typical annual uptake for the Existing Condition Model.

The 2013 Alden Upper Reservoir sedimentation study (Reference 1, Alden) determined an average annual sediment accumulation in the Upper Reservoir Deposition Zone based on bathymetric studies performed in 2010, 2011, 2012, and 2013. An average of about 17,600 cubic yards per year of sediment uptake to the Deposition Zone was computed from the 2011-2012 and 2012-2013 surveys.

The FLOW-3D entrainment coefficient (discussed in Section 3.5.2) was adjusted until the combined conveyance capacity of the twenty environmental/operational cases was similar to the observed average 17,600 yards of deposition.

Once the Existing Condition model was calibrated, twenty environmental/operational cases were run for each of the two Sediment Exclusion Structure Alternatives shown in Figure 26.

3.7.2 Sediment Exclusion Structure Concept

A profile view of open flow in a river channel is shown in Figure 27 (from Reference 12, ASCE). The velocity profile (U) is represented by a solid red line. As depth increases from the river bed, velocity increases towards the water surface. Sediment Concentration (C) is represented by the blue dashed line. Sediment concentration is highest at the bed and decreases to its lowest value at the water surface. Building a sill at the top of the intake/tailwater channel to separate this area from the Connecticut River will block a significant amount of sediment from entering the tailrace tunnel exit and exclude that sediment from being pumped up to the Upper Reservoir.

3.7.3 Sediment Exclusion Structure Alternative 1

Sediment Exclusion Structure 1 (SES 1) is a sill built up from the bed of the Connecticut River to an elevation of 174 feet. Figure 28 shows an oblique view of SES 1. The structure is designed to isolate the intake/tailwater area from the bottom 10 to 15 feet of the Connecticut River and exclude much of the bedload from falling down into the tailrace tunnel exit (Upper Reservoir intake) under pumping. SES 1 is a convex shape along the Connecticut River spanning the shortest distance between the north and south banks of the intake/tailwater before the channel drops from 160 feet to 125 feet in elevation.

3.7.4 Sediment Exclusion Structure Alternative 2

After reviewing preliminary Alternative 1 results, the team decided to model a longer concave exclusion structure (SES 2) that would better conform to the streamlines along the east bank of the Connecticut River. Both SES alternatives share the same northern terminus into the east bank of the Connecticut River, but the concave SES 2 extends 300 feet longer to the south before meeting its endpoint on the bank of the Connecticut River. Figure 29 shows an oblique view of SES 2.

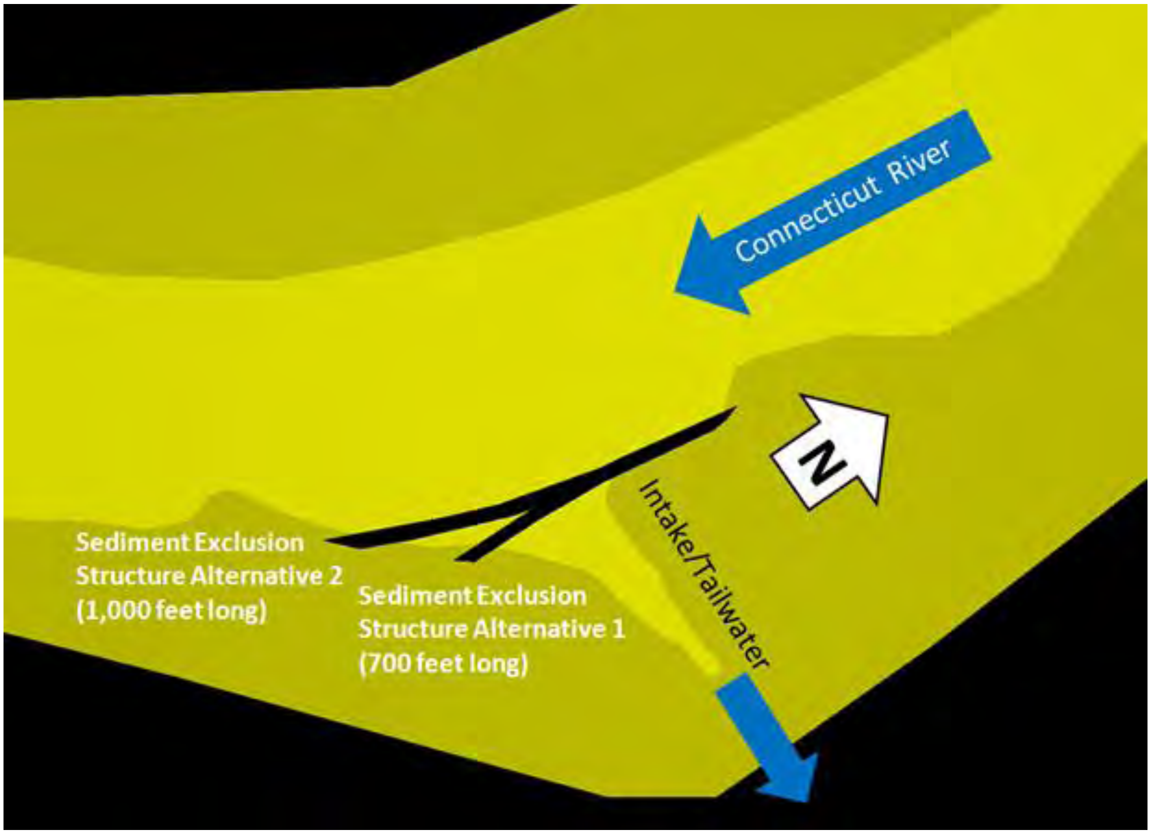

Figure 26: Sediment Exclusion Structure Alternatives (Plan View)

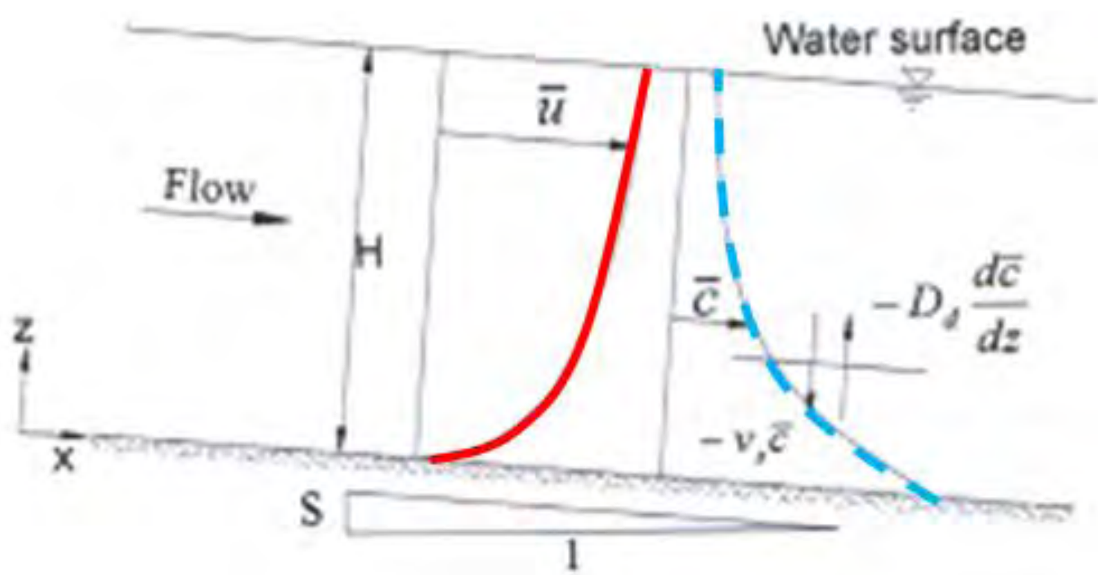

Figure 27: Velocity Profile with Sediment Concentration Curve.

(from Reference 12)

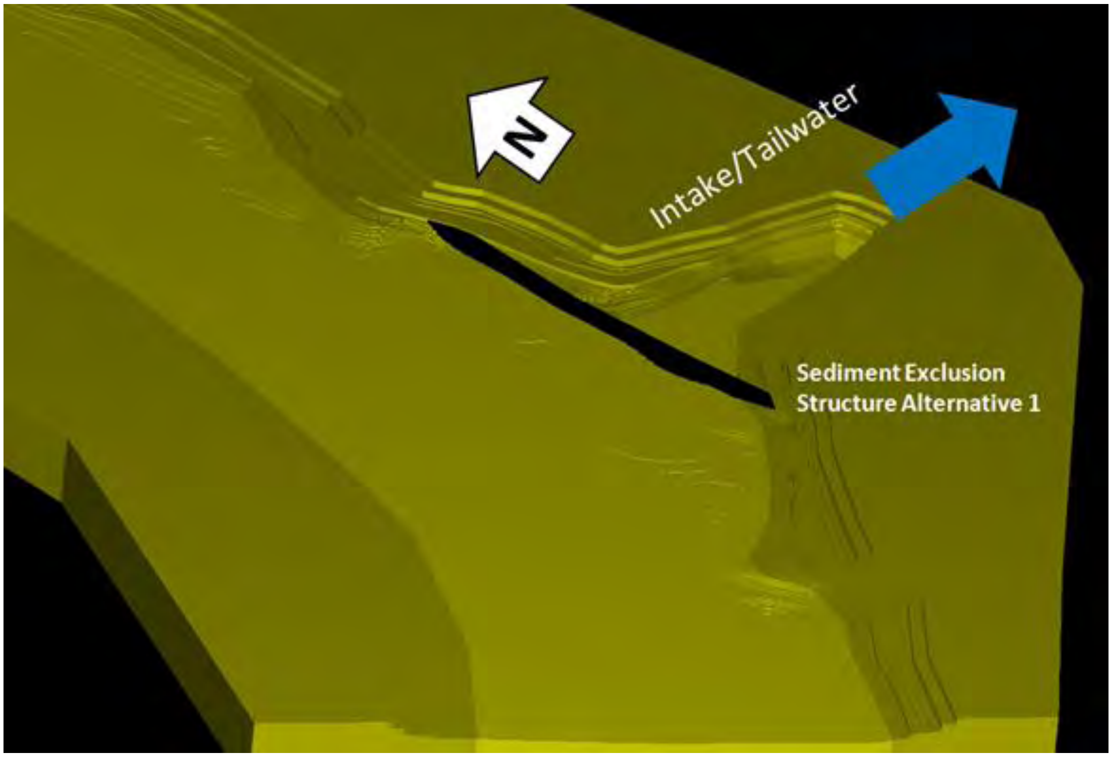

Figure 28: Sediment Exclusion Structure 1

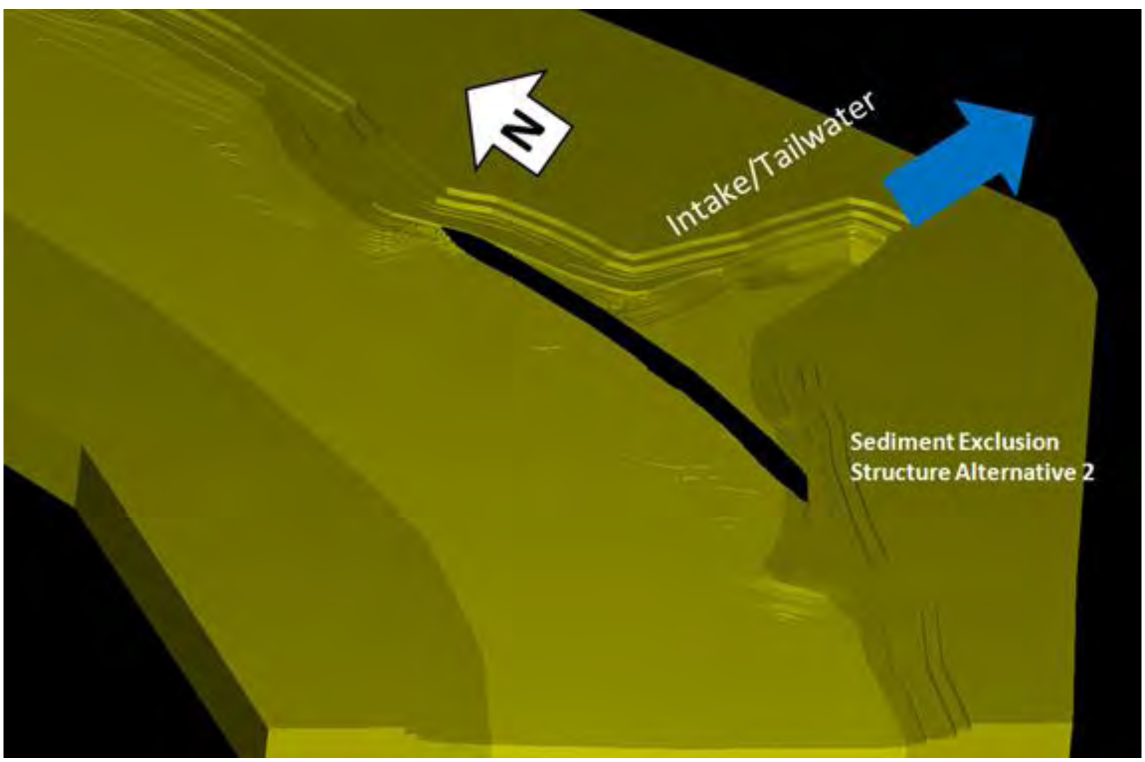

Figure 29: Sediment Exclusion Structure 2

4.0 HYDRAULIC MODEL VALIDATION

As part of the 2014 data collection effort, Gomez and Sullivan measured flow velocity at five locations in the Connecticut River (Transects M1, M2, M3, M4, and M5) and three locations in the Northfield Mountain Connecticut River Intake/Tailwater (Transects I1, I2, and I3). The location of these transects is shown in Figure 30.

The 3-D model was run with observed boundary conditions corresponding to the velocity measurement transect surveys. Connecticut River flow, Turners Falls Impoundment level, and Northfield Mountain operations (pumping or generating discharge) during the transect surveys are summarized in Table 6. In this section, model output is compared to observed velocity measurements for each of the river and intake/tailwater transects.

Figure 30: Velocity Transect Locations near Intake/Tailwater

Table 6: Field Conditions for Velocity Transect Surveys

Survey Date	Transect Location/ Conditions	Turners Falls Impoundment Level (ft)	Connecticut River Inflow (cfs)	Intake Discharge + Generating - Pumping (cfs)
6/2/2014	Connecticut River	181.7	14,790	4370
4/7/2014	Intake 2 Pumps	184	29,580	-6800
7/12/2014	Intake 4 Pumps	181.3	2,070	-13130

4.1 Velocity Comparison

The 2014 velocity data was used to validate the 3-D hydraulic model. Model performance near the intake/tailwater area can be gauged by comparing field measured velocities to CFD model output along Transects M1, M2, M3, M4, and M5, and I1, I2, and I3. Except for Transect M1 which was surveyed twice, one set of velocity transect measurements was available within the Connecticut River (Reference 4, Gomez and Sullivan). Figures 31 through 35 show the Depth, Depth Averaged Flow Rate, and Unit Width Discharge comparisons for Transects M1, M2, M3, M4, and M 5. Observed velocity along these transects is represented with dots and the CFD model output velocity is shown with solid lines. All transects are oriented left to right looking downstream. Good agreement between the measurements and computed flow velocity along transects M1 through M5 indicates that the model is performing well and adequately simulates flow patterns in the Connecticut River and entering the intake/tailwater area.

A series of one- or two-pass velocity measurements were made within the intake/tailwater area under two units pumping, 4 units pumping, 2 units generating, and 4 units generating. This study focuses on sediment entrainment potential under pumping operations. Figures 36 through 41 show the measured transect velocities compared to the 3-D model output for 2 units pumping (Figures 36, 37, and 38) and 4 units pumping (Figures 39, 40, and 41). Good agreement between the measured transect velocities and computed flow velocities for the intake/tailwater transects (I1, I2, and I3) under 2 units pumping and 4 units pumping indicates that the 3-D model hydraulic model is valid under the observed operational conditions.

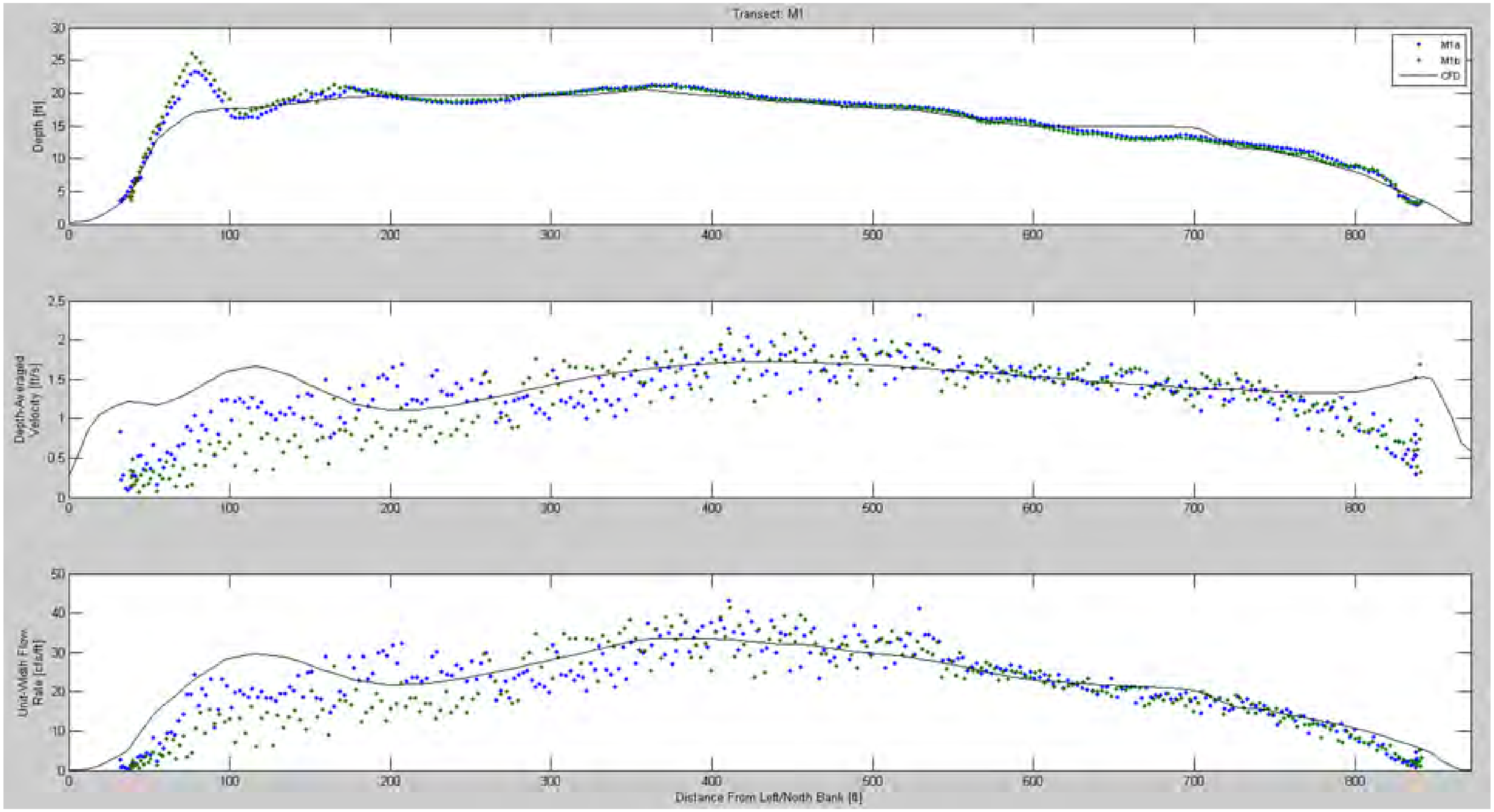

Figure 31: Transect M1 06/02/2014

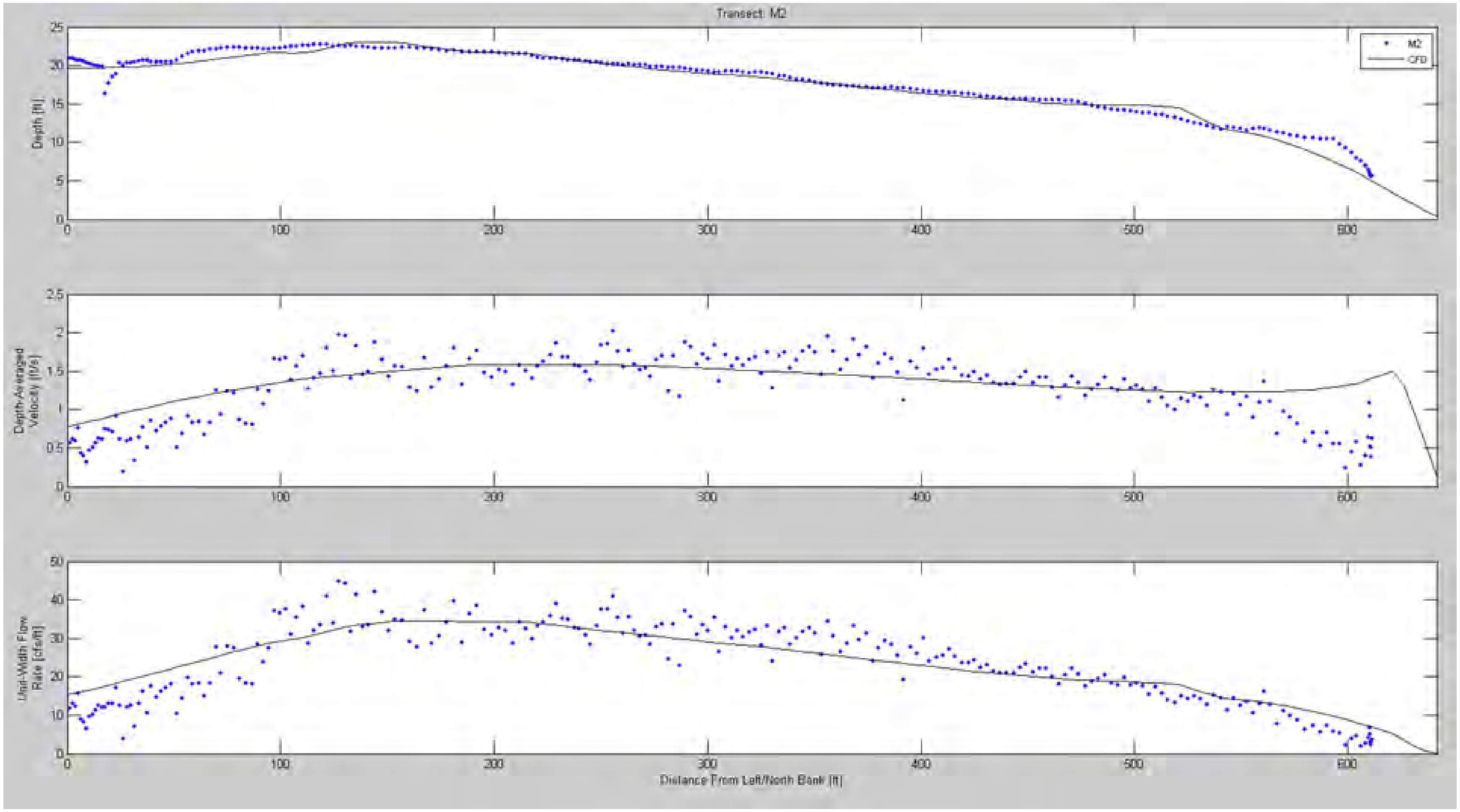

Figure 32: Transect M2 06/02/2014

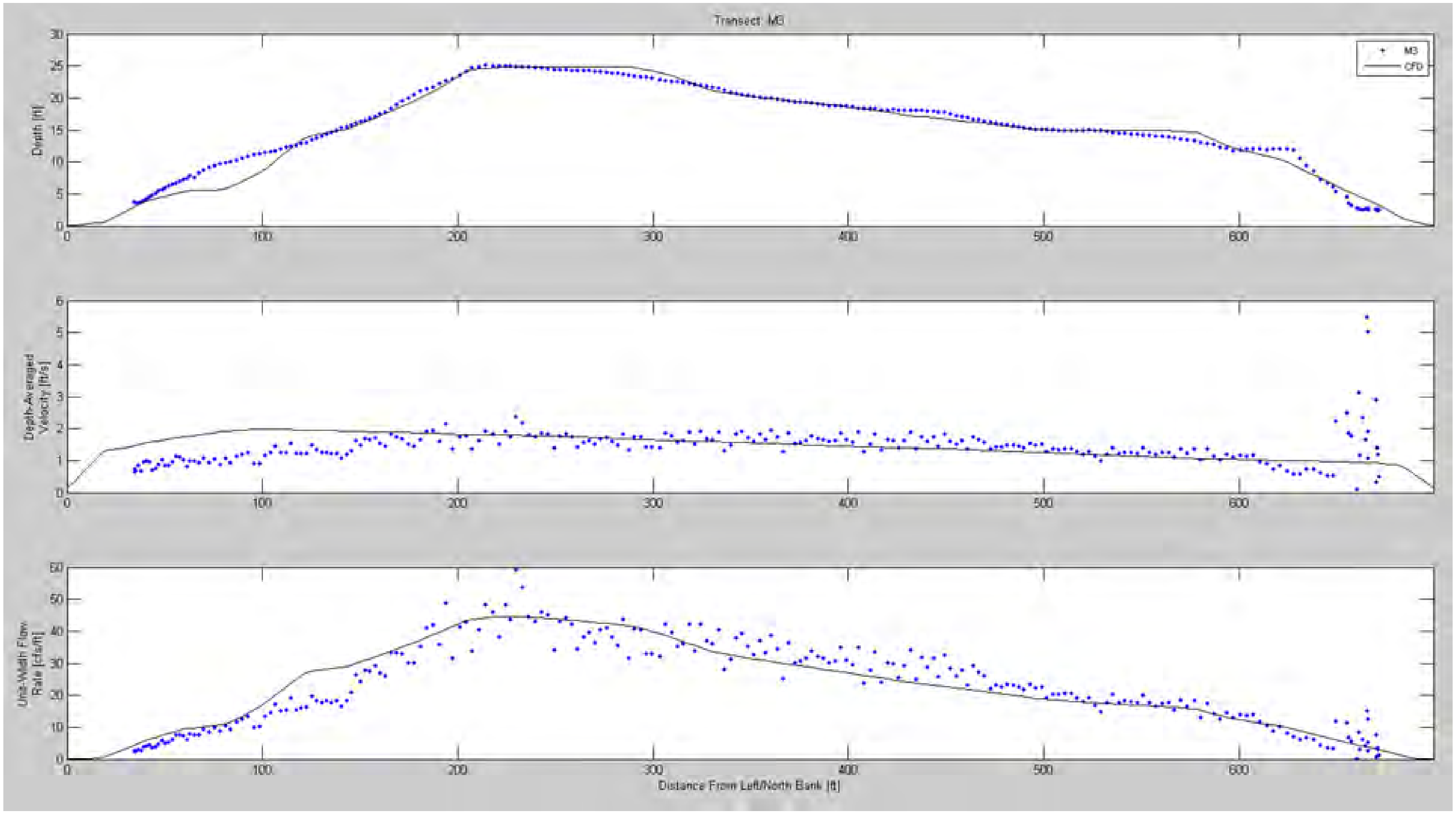

Figure 33: Transect M3 06/02/2014

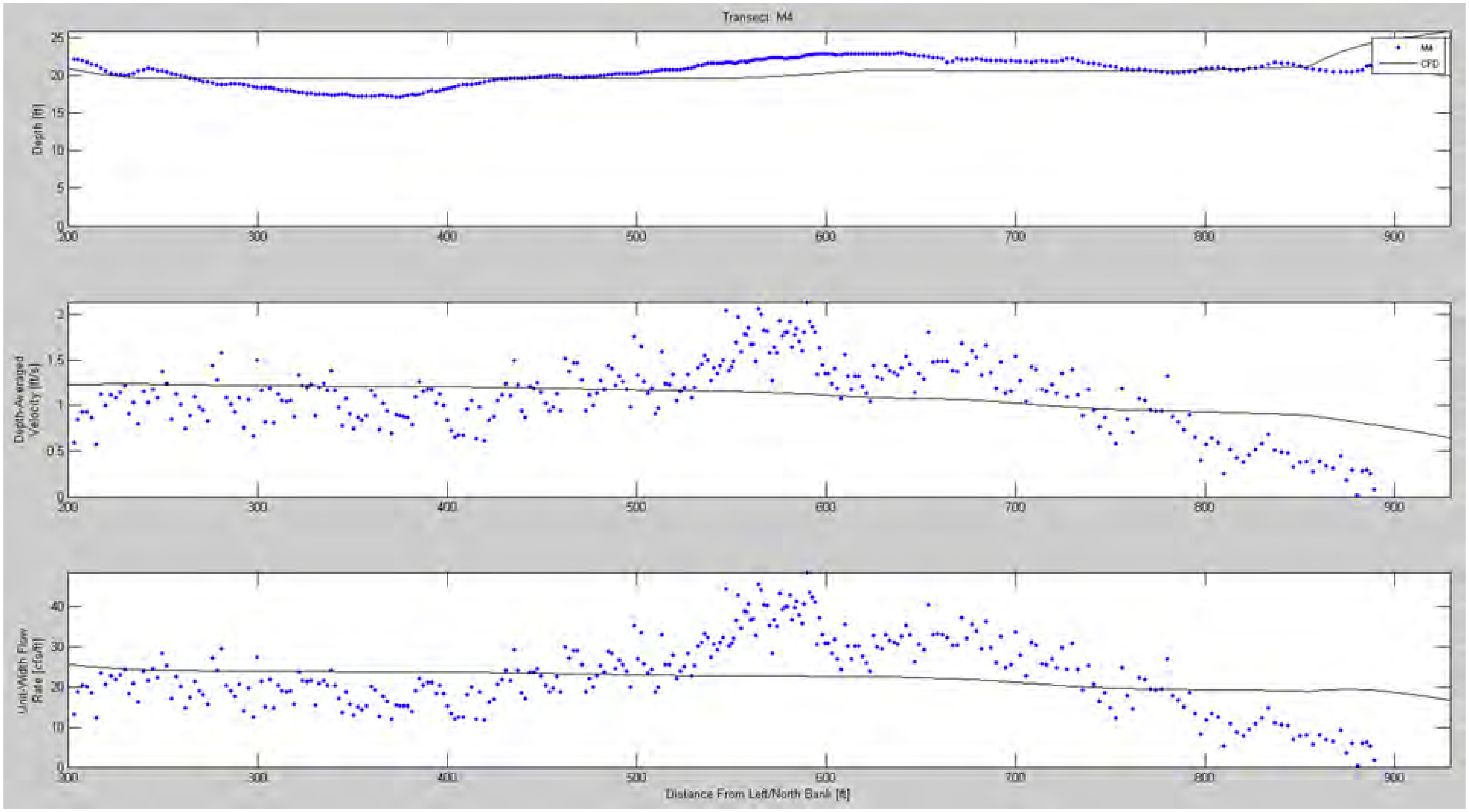

Figure 34: Transect M4 06/02/2014

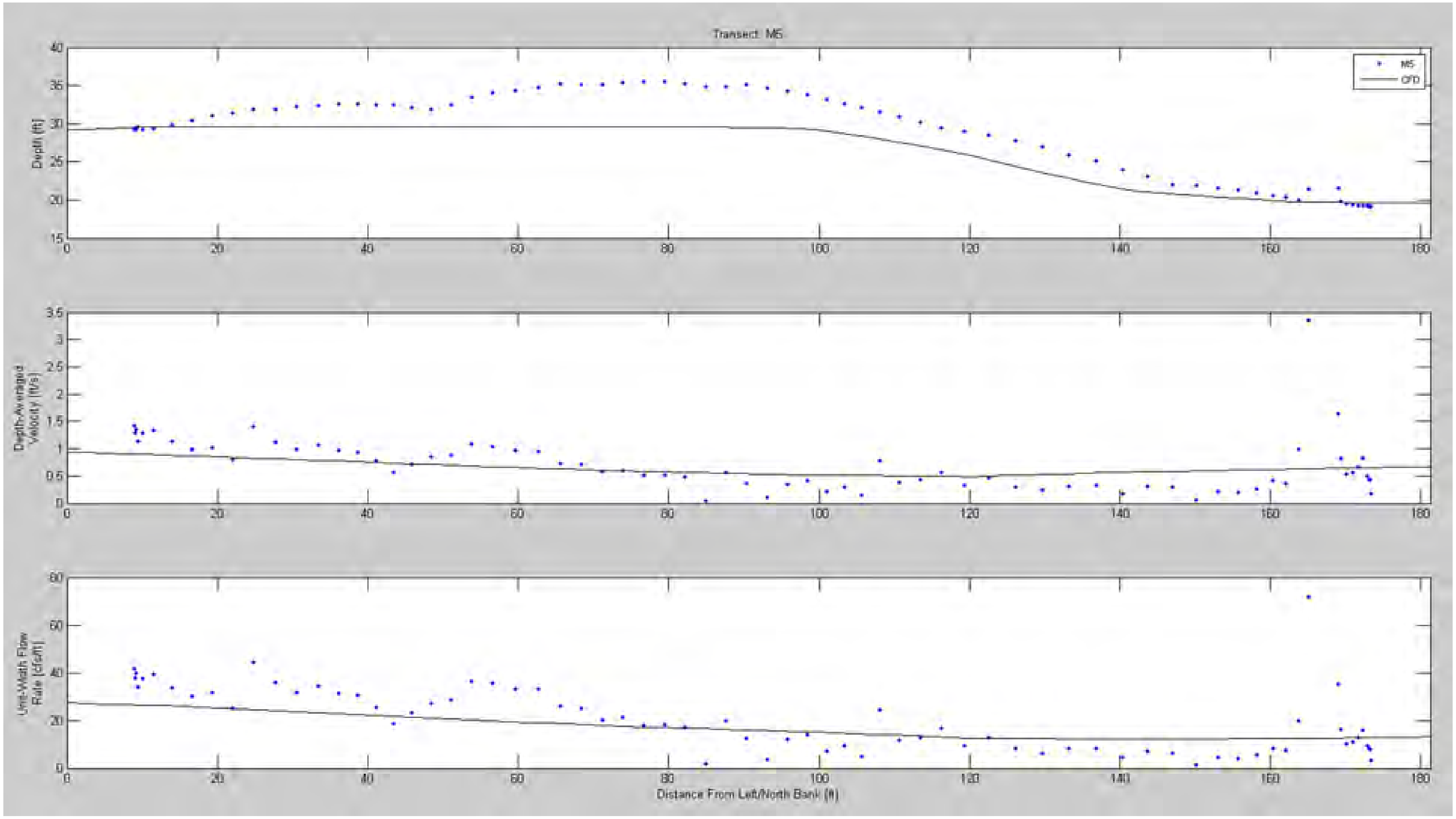

Figure 35: Transect M5 06/02/2014

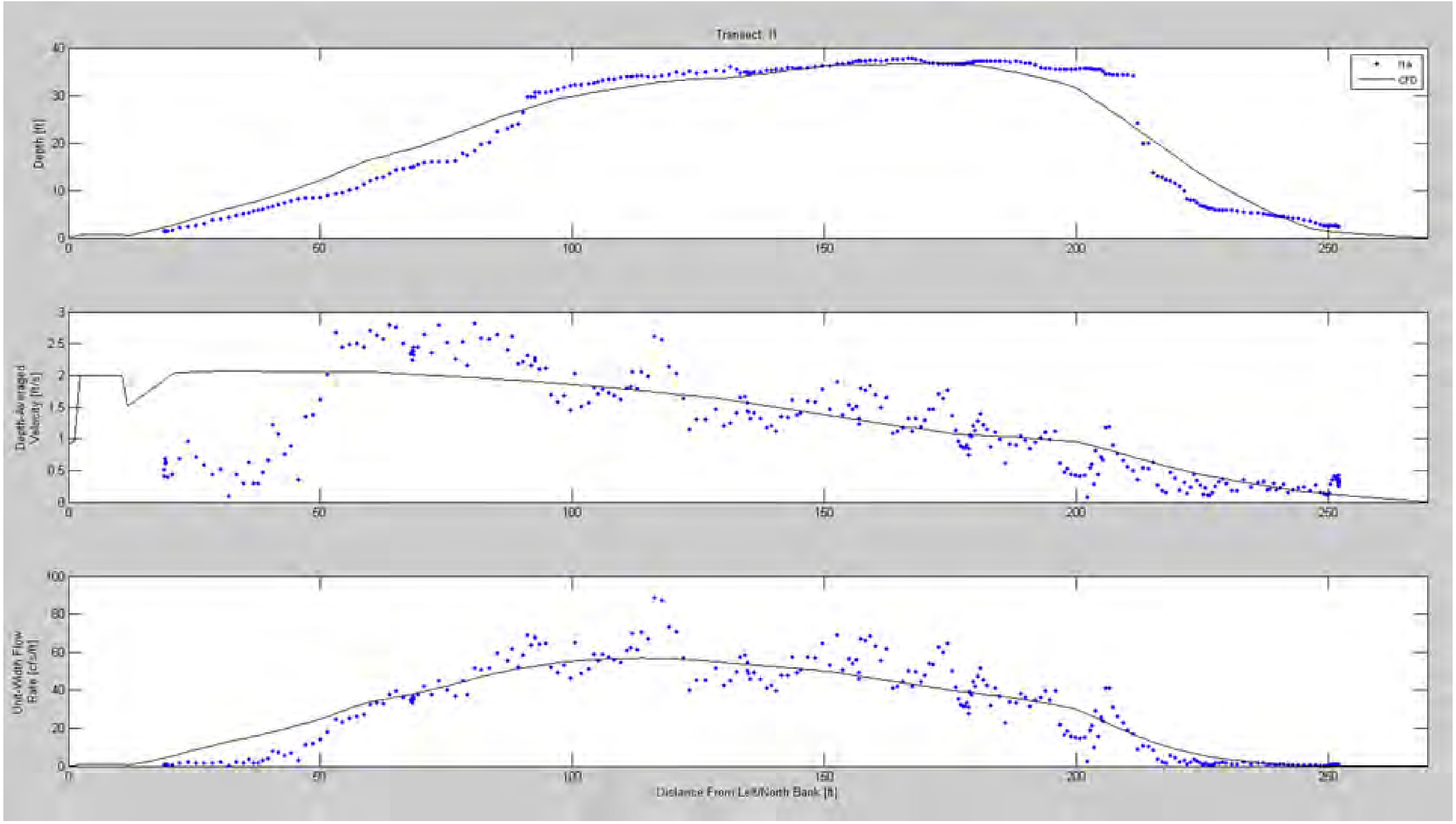

Figure 36: Transect I1 04/07/2014

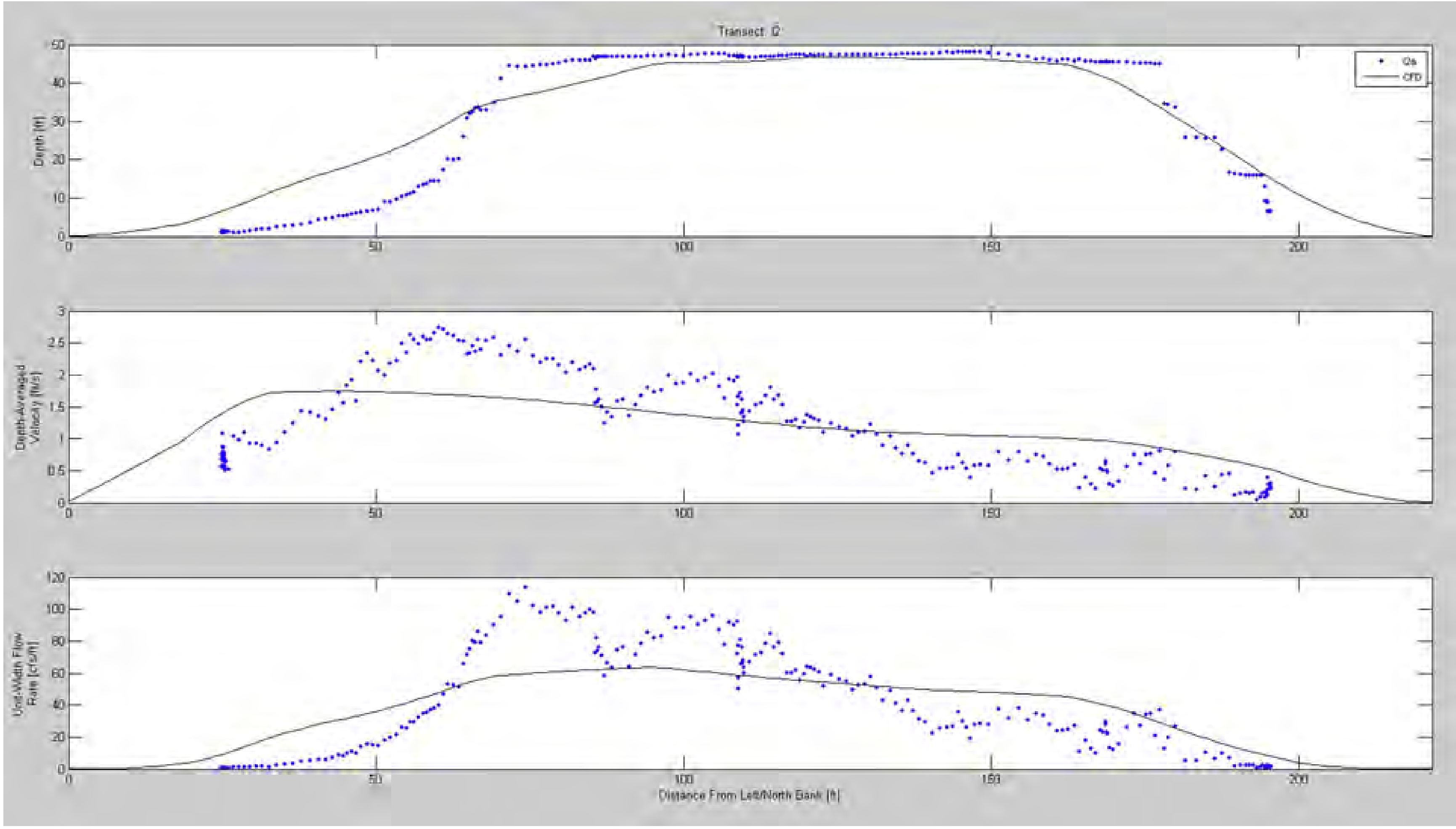

Figure 37: Transect I2 04/07/2014

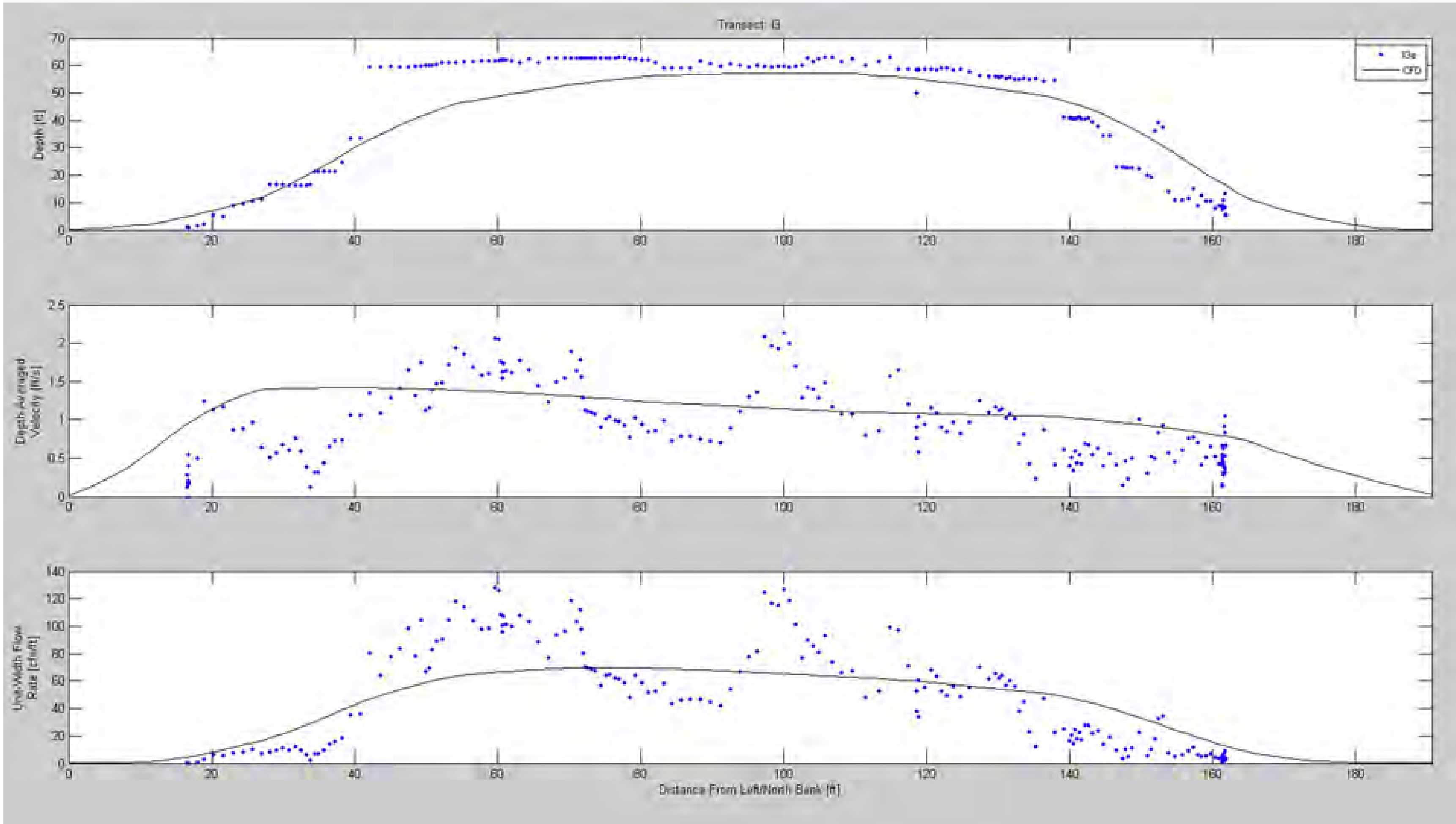

Figure 38: Transect I3 04/07/2014

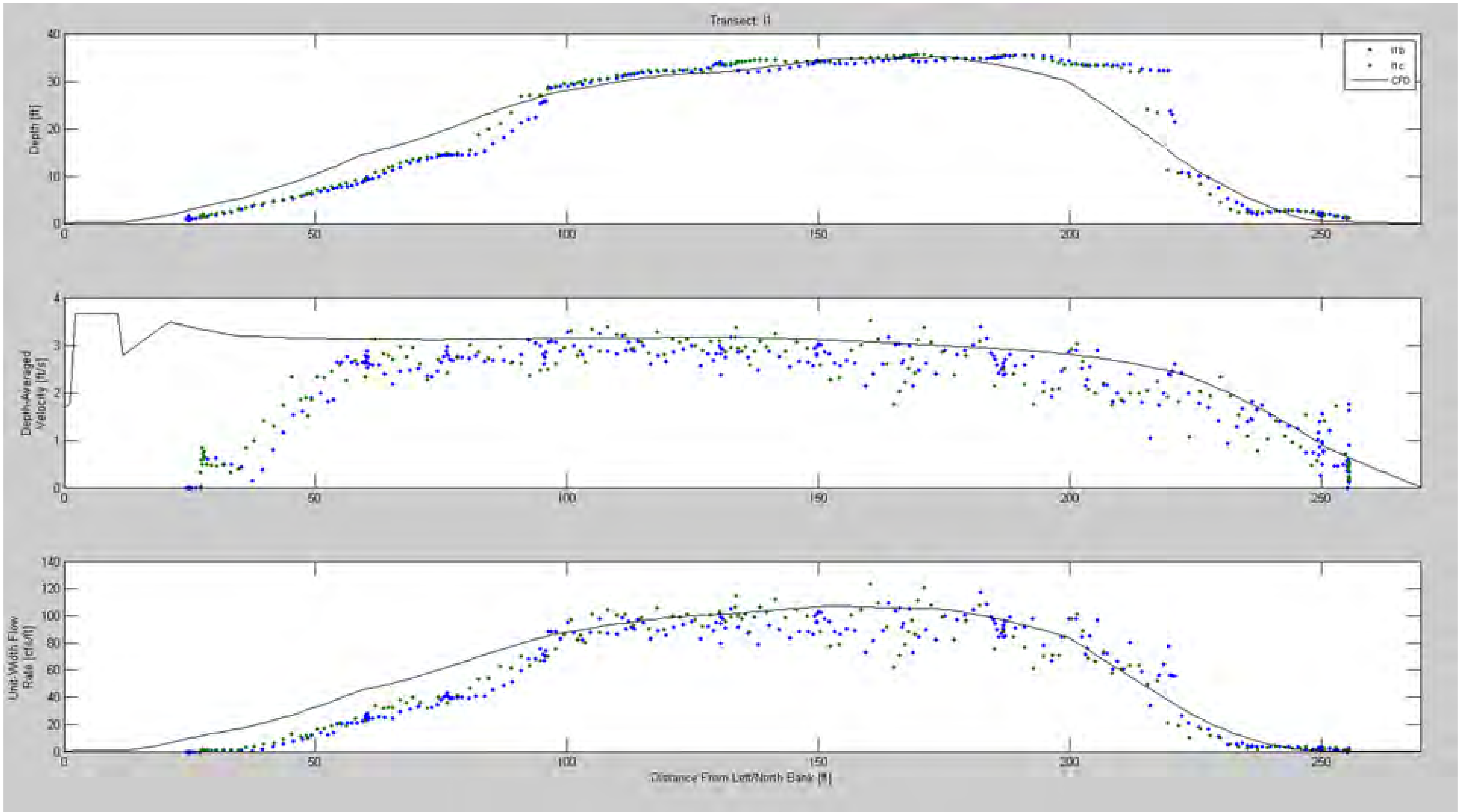

Figure 39: Transect I1 07/12/2014

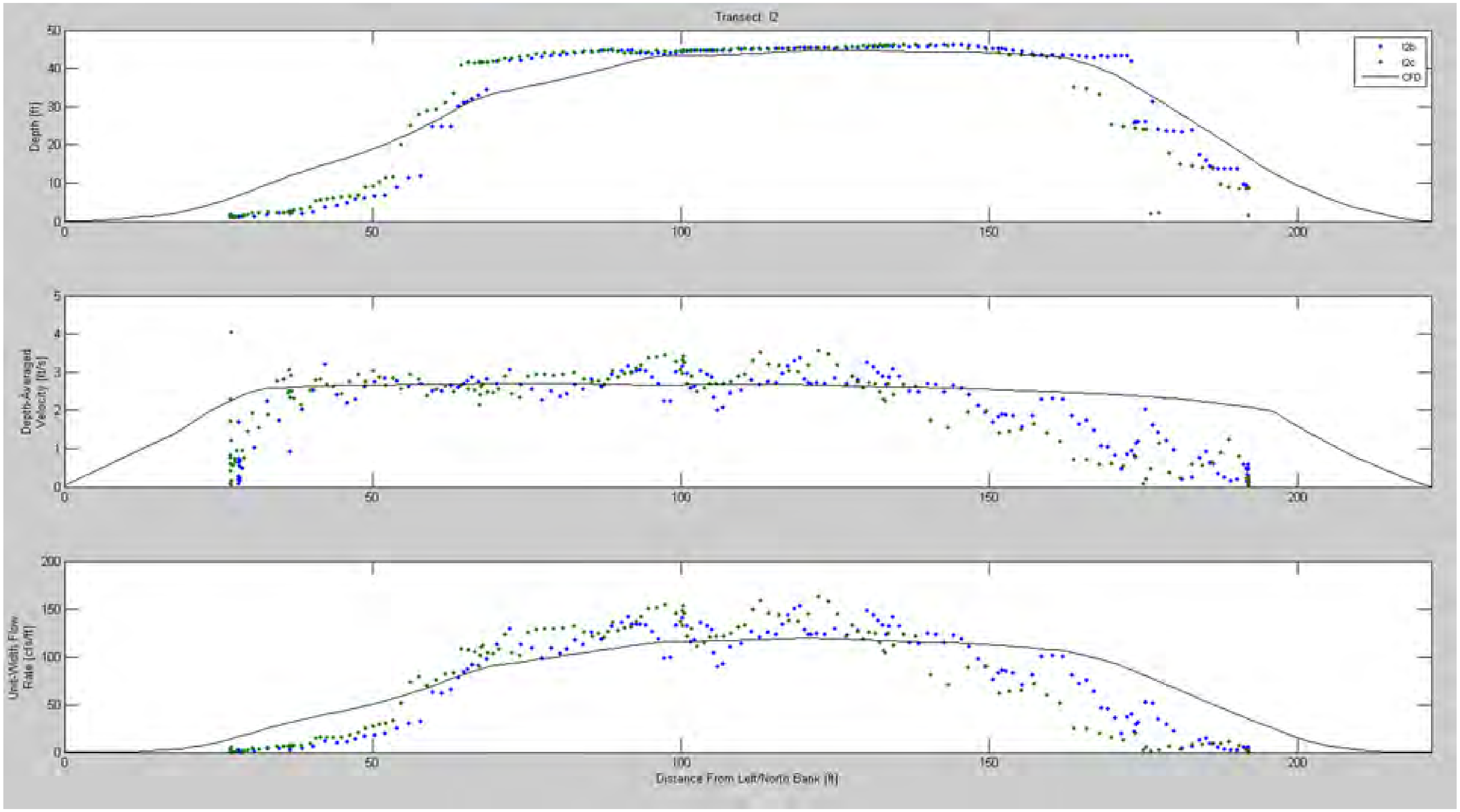

Figure 40: Transect I2 07/12/2014

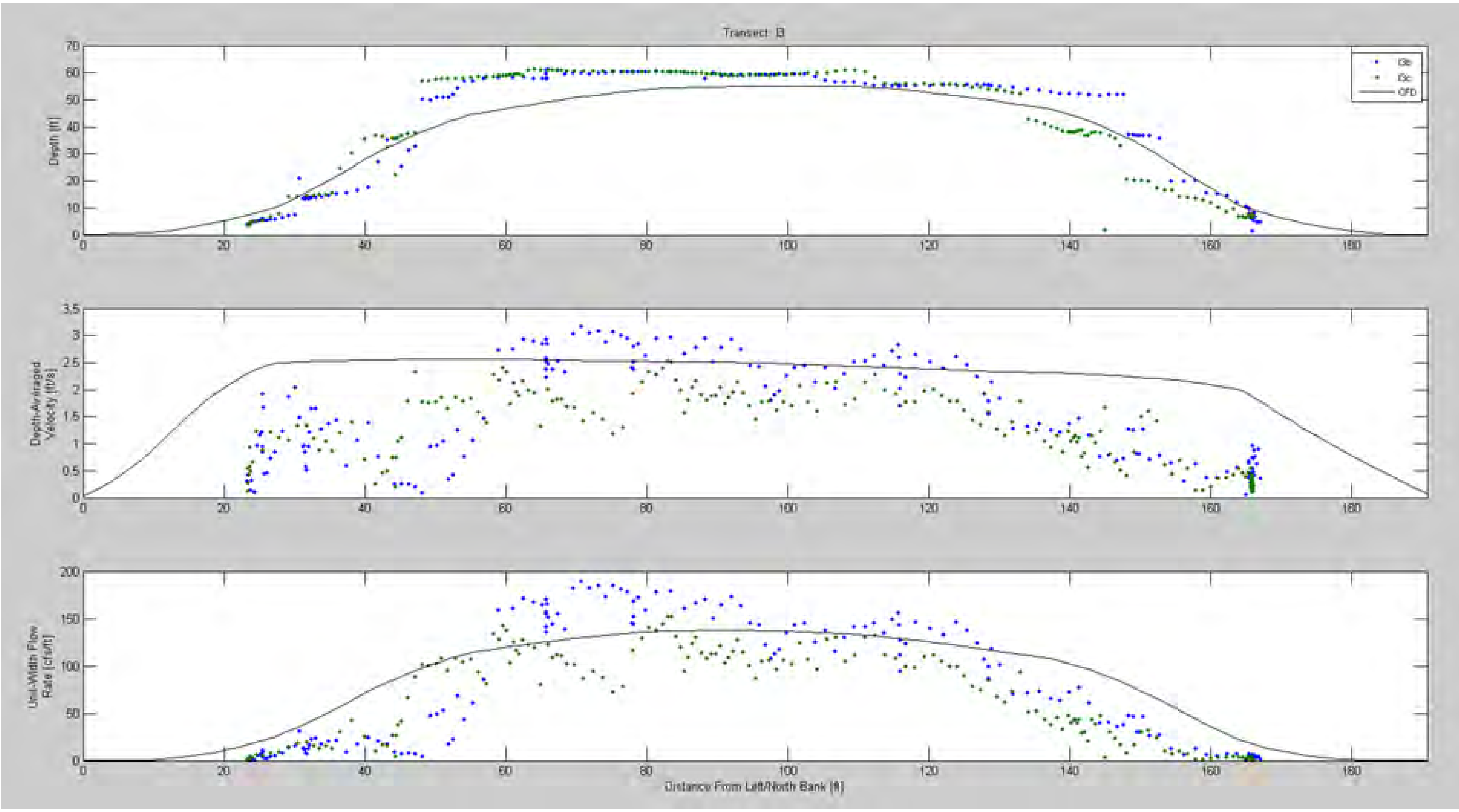

Figure 41: Transect I3 07/12/2014

5.0 INTAKE/TAILWATER SEDIMENTATION MODEL RESULTS

After validating the 3-D hydraulic CFD model with observed velocity measurements the sedimentation module was activated. The sedimentation model was calibrated to observed annual coarse material sediment deposition trends in the Upper Reservoir. In a typical year of environmental/operational conditions the amount of sediment leaving the model is similar to an average annual amount of sediment observed depositing in the Upper Reservoir. The calibrated sedimentation model was used to simulate the two sediment exclusion structure alternatives described in Section 4. Sediment conveyance output from the twenty environmental/operational cases for the SES alternatives is compared to the existing conditions model in the following sections. A series of figures showing flow patterns and velocity in the river and intake/tailwater channel for each of the cases is presented in Appendix B.

5.1 Existing Condition Sediment Model

Sediment conveyance potential in tons per second as well as tons per year uptake per case for the twenty steady-state sediment model cases is presented in Table 7. This table is arranged to show model output for 4, 3, 2, and 1 pumps operating over the range of studied Connecticut River discharge levels (5,000 to 50,000).

Highlighted cells are cases which provide more than 5% of the typical annual sediment uptake (brown 5% to 10%, yellow 11% to 15%, and red 15% to 20%). Although the 4 pumps operating cases happen relatively infrequently (6.9% of a typical year based on the ten years of hourly records in Reference 8), they are responsible for 43% of the Existing Condition annual sediment outflow. Higher flow velocity through the intake/tailwater channel results in higher sediment mobilization down to the tailrace tunnel exit and makes more sediment available for uptake to the Upper Reservoir over a short period of time.

The 3 pumps operating cases make up 12% of a typical year time-wise (almost twice the frequency of the 4 pumps operating cases) and account for 45% of sediment outflow from the model. The 2 and 1 pump operating cases make up 12% of the annual sediment transport potential. Computed annual sediment outflow from the model is 24,150 tons. Converting to cubic yards (using a sand weight of (100 lbs/ft3), the Existing Condition Sedimentation model yields 17,900 cubic yards per year (the average annual deposition from Section 3.7.1 was 17,600 cubic yards).

5.2 Sediment Exclusion Structure 1

The case-wise distribution of sediment conveyance for the first sediment exclusion structure follows the same pattern as the existing condition. Sedimentation from the 4 pumps and 3 pumps operating makes up 45% and 43% of the annual total respectively, and 2 pumps is about 9% of the annual total. Only 3% of the annual sediment yield occurs under the 1 pump operating scenario as with the existing condition. By blocking the lower portion of the sediment column, SES 1 was shown to reduce the typical annual sedimentation by over 20% (5,100 tons) compared to the existing condition results.

5.3 Sediment Exclusion Structure 2

SES 2 follows the same case-wise distribution trends as seen in the existing condition and SES 1 models. The 4 pumps and 3 pumps operational conditions produce most of the annual sedimentation (46% and 43% respectively), 2 pumps yields about 9% and 1 pump operational conditions yields only 3% of the annual total. SES 2 results in a 12% annual sediment reduction over existing conditions which is somewhat counter intuitive. SES 2 does not appear to be effective in reducing sedimentation in 3 and 4 pump operational conditions at low river flow, specifically Cases E and J. Figure 42 shows a comparison between SES 1 which is effective at reducing sediment in these cases and SES 2. The higher sediment conveyance results from the SES 2 model may be due to the large vortex at the upstream end of the structure which forces more flow to the west or right bank of the Connecticut River and results in higher velocities in that area (which can convey more sediment).

Table 7: Case-wise Annual Sediment Transport Summary

				Existing Condition			Sediment Exclusion 1			Sediment Exclusion 2		
	Case	River Flow (cfs)	% of one year	Sed Transport (tons/sec)	Tons per Case	% of one year	Sed Transport (tons/sec)	Tons per Case	% of one year	Sed Transport (tons/sec)	Tons per Case	% of one year
4 Pumps	A	50,000	0.3%	0.0290	2,775	11.5%	0.0240	2,296	12.1%	0.0235	2,249	10.6%
4 Pumps	B	35,000	0.2%	0.0145	916	3.8%	0.0110	694	3.6%	0.0115	728	3.4%
4 Pumps	C	25,000	0.4%	0.0102	1,432	5.9%	0.0073	1,031	5.4%	0.0074	1,047	4.9%
4 Pumps	D	15,000	1.2%	0.0060	2,361	9.8%	0.0047	1,844	9.7%	0.0046	1,805	8.5%
4 Pumps	E	5,000	4.7%	0.0020	2,878	11.9%	0.0018	2,712	14.2%	0.0026	3,872	18.3%
			6.9%			42.9%			45.0%			45.8%
3 Pumps	F	50,000	0.7%	0.0159	3,329	13.8%	0.0135	2,826	14.8%	0.0130	2,722	12.9%
3 Pumps	G	35,000	0.6%	0.0076	1,553	6.4%	0.0057	1,169	6.1%	0.0058	1,190	5.6%
3 Pumps	H	25,000	1.3%	0.0051	2,131	8.8%	0.0031	1,309	6.9%	0.0035	1,468	6.9%
3 Pumps	I	15,000	2.8%	0.0029	2,566	10.6%	0.0019	1,710	9.0%	0.0019	1,719	8.1%
3 Pumps	J	5,000	6.8%	0.0006	1,271	5.3%	0.0006	1,238	6.5%	0.0009	1,964	9.3%
			12.3%			44.9%			43.3%			42.8%
2 Pumps	K	50,000	0.4%	0.0079	1,032	4.3%	0.0070	914	4.8%	0.0070	914	4.3%
2 Pumps	L	35,000	0.2%	0.0027	185	0.8%	0.0024	164	0.9%	0.0025	169	0.8%
2 Pumps	M	25,000	0.7%	0.0017	390	1.6%	0.0011	258	1.4%	0.0012	261	1.2%
2 Pumps	N	15,000	1.5%	0.0009	433	1.8%	0.0005	244	1.3%	0.0007	308	1.5%
2 Pumps	O	5,000	3.6%	0.0001	124	0.5%	0.0001	75	0.4%	0.0001	139	0.7%
			6.4%			9.0%			8.7%			8.5%
1 Pump	P	50,000	0.9%	0.0019	537	2.2%	0.0013	368	1.9%	0.0014	404	1.9%
1 Pump	Q	35,000	1.0%	0.0003	110	0.5%	0.0003	105	0.6%	0.0003	103	0.5%
1 Pump	R	25,000	2.2%	0.0002	118	0.5%	0.0001	78	0.4%	0.0001	74	0.3%
1 Pump	S	15,000	5.4%	0.0000	15	0.1%	0.0000	15	0.1%	0.0000	22	0.1%
1 Pump	T	5,000	10.0%	0.0000	0	0.0%	0.0000	0	0.0%	0.0000	0	0.0%
			19.5%			3.2%			3.0%			2.8%
				total uptake	24,155	tons	total uptake	19,052	tons	total uptake	21,158	tons
								21% Reduction over Existing			**12%** Reduction over Existing	

Legend:
- 0% to 4%
- 5% to 10%
- 11% to 15%
- 15% to 20%

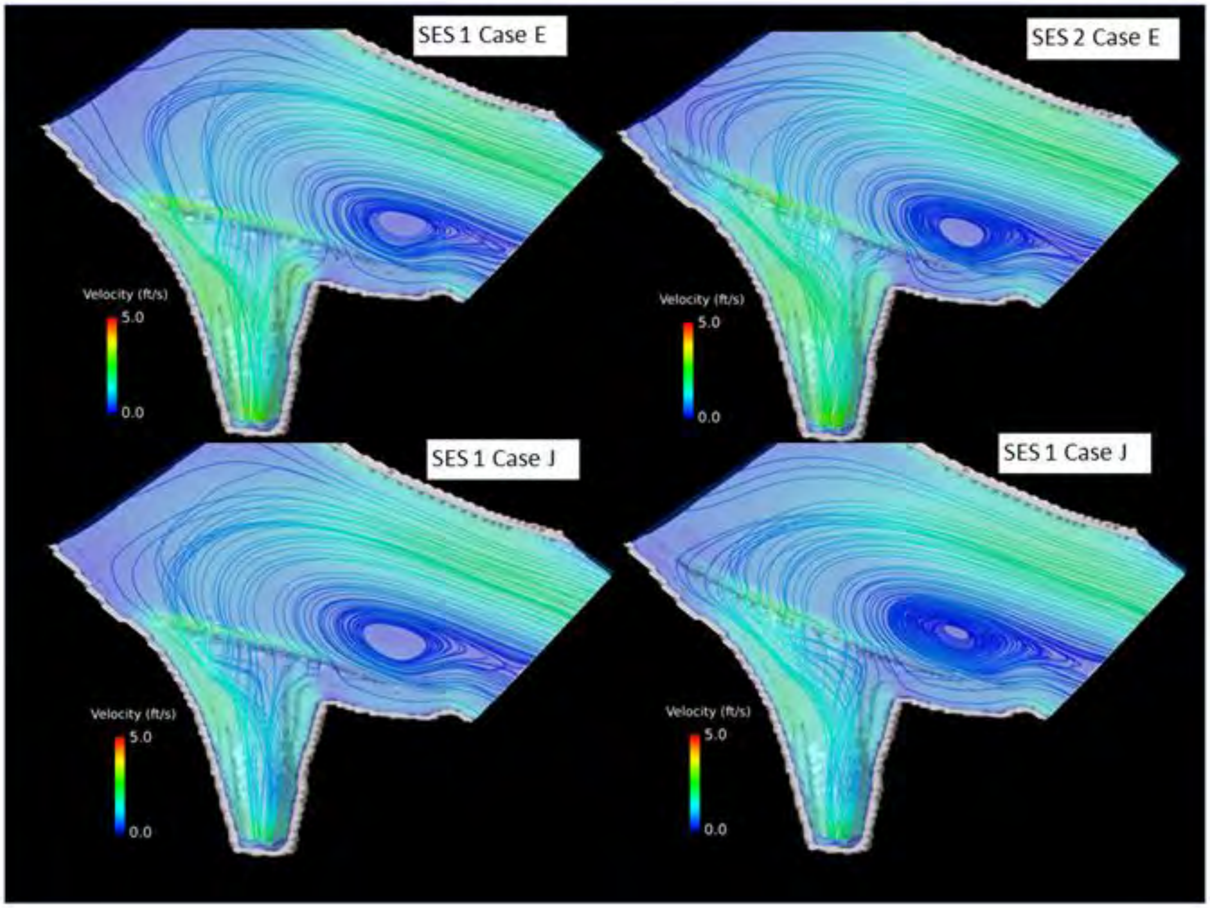

Figure 42: Sediment Exclusion Structure Velocity Comparison at Cases E and J

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6.0 CONCLUSIONS

The 2013 Northfield Reservoir sedimentation study (Reference 1, Alden) indicated that structural or operational changes to Upper Reservoir management (periodic drawdowns) could reduce sedimentation in the Upper Reservoir by about 5%. An early finding of this study is that the tailrace tunnel exit is the lowest part of the system (about 37 feet below the Connecticut River bed). Figure 42 shows the relative elevations of the Connecticut River and the intake/tailrace channel. Any management of the Upper Reservoir levels to flush deposited sediment back to the Connecticut River would deposit that sediment at the tailrace tunnel exit for potential re-entrainment on the next pumping cycle.

This study quantified sedimentation trends within the Connecticut River and intake/tailrace channel with the goal of designing structures to exclude sediment uptake to the Reservoir.

The first sediment exclusion structure alternative, SES 1, is more effectively decreases sedimentation to the intake/tailwater channel than the longer SES 2. There does not appear to be any benefit by adding length to the sediment exclusion structure to match the river bank. Additional refinement to the design may be worthwhile if this type of structural measure is an attractive option.

Since the river is perched 37 feet above the bottom of the tailrace tunnel exit structure/ Upper Reservoir river intake (see Figure 43), any sediment in the Connecticut River has the potential to be mobilized to the Upper Reservoir under pumping.

Model results show that plant operations and pumping rates have an influence on the amount of sediment uptake to the Upper Reservoir.

A sediment exclusion structure (sill built above the bed of the intake/tailwater channel) can be expected to decrease sediment mobilization to the Upper Reservoir by 10% to 20%.

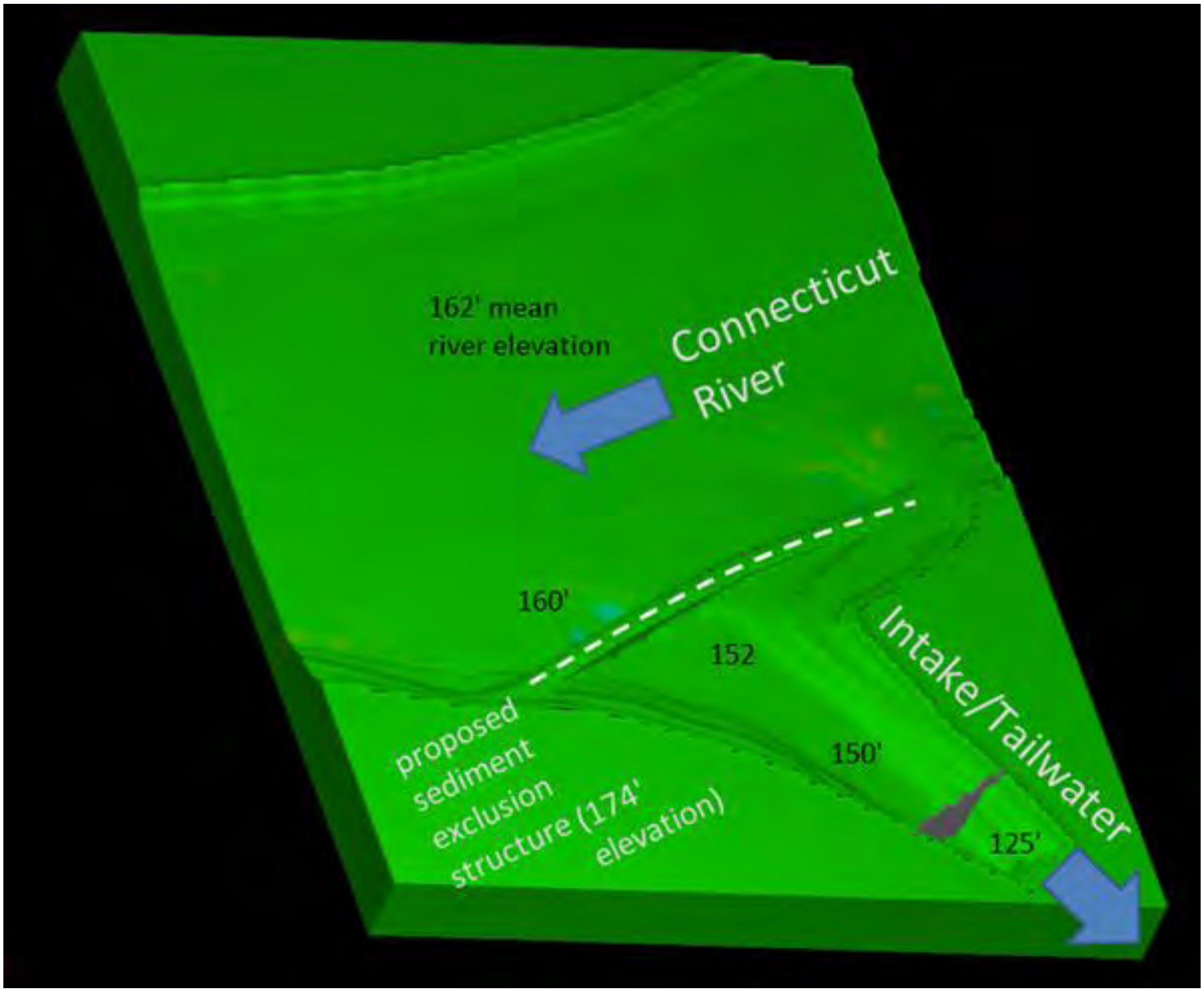

Figure 43: Relative River and Intake/Tailwater Bed Elevations

7.0 REFERENCES

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APPENDIX A: Sedimentation Model Transport Capacity Results

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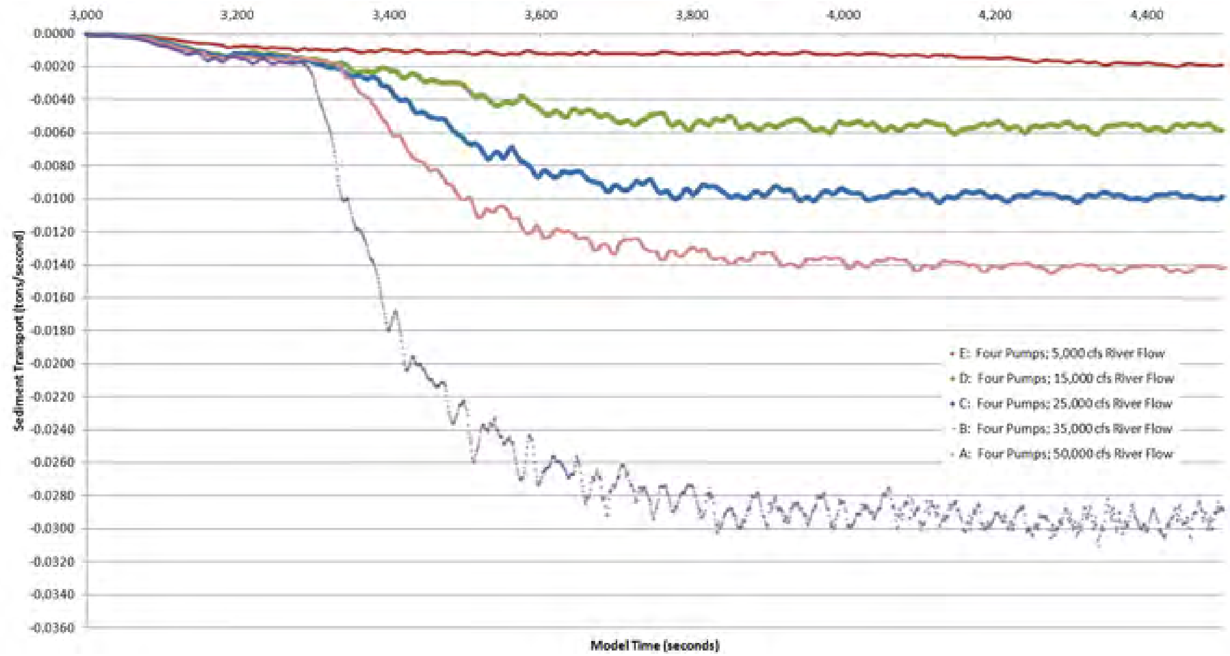
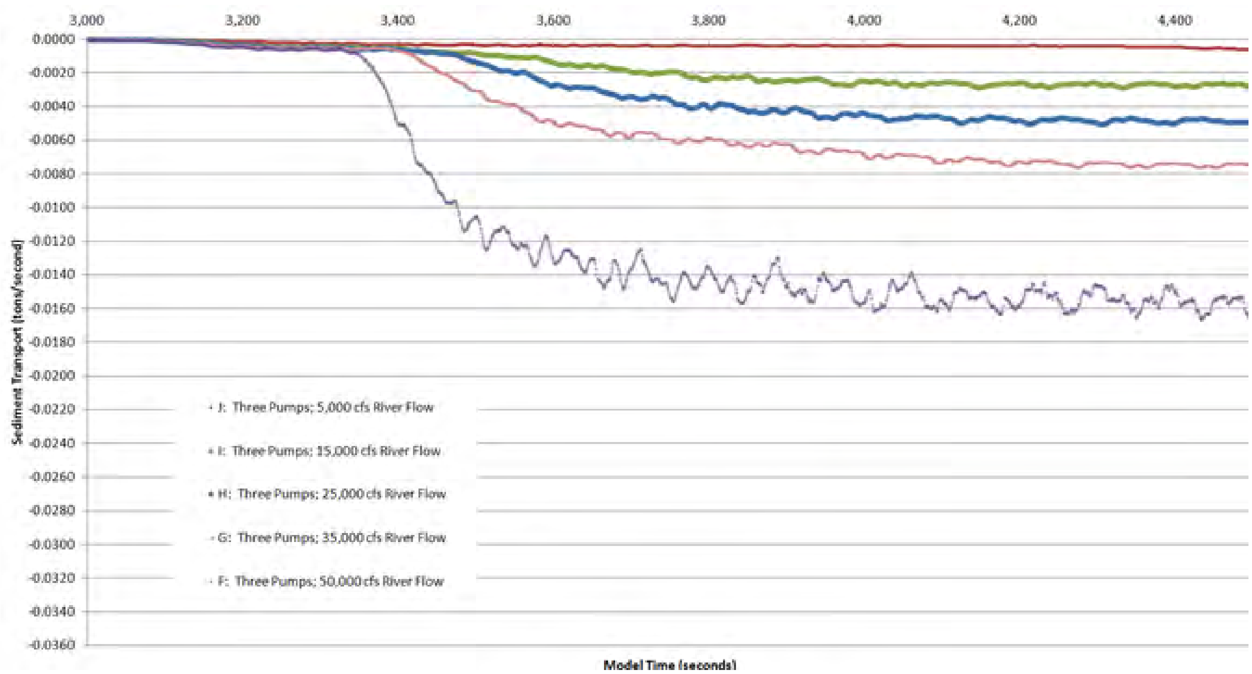
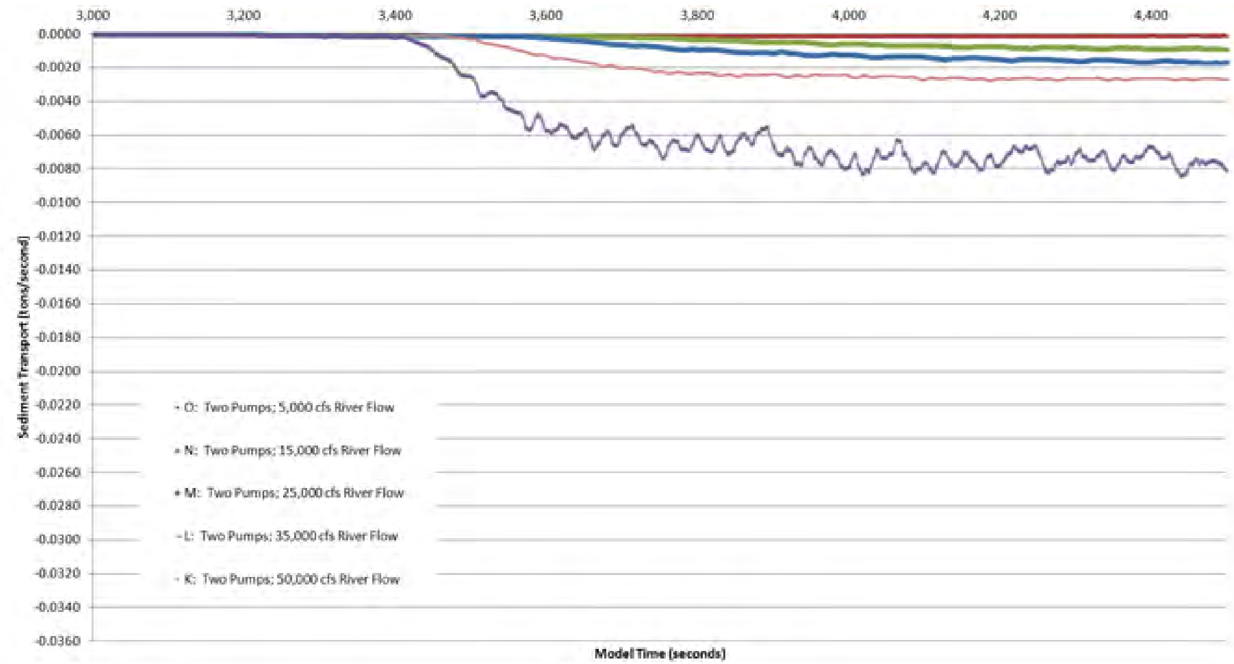
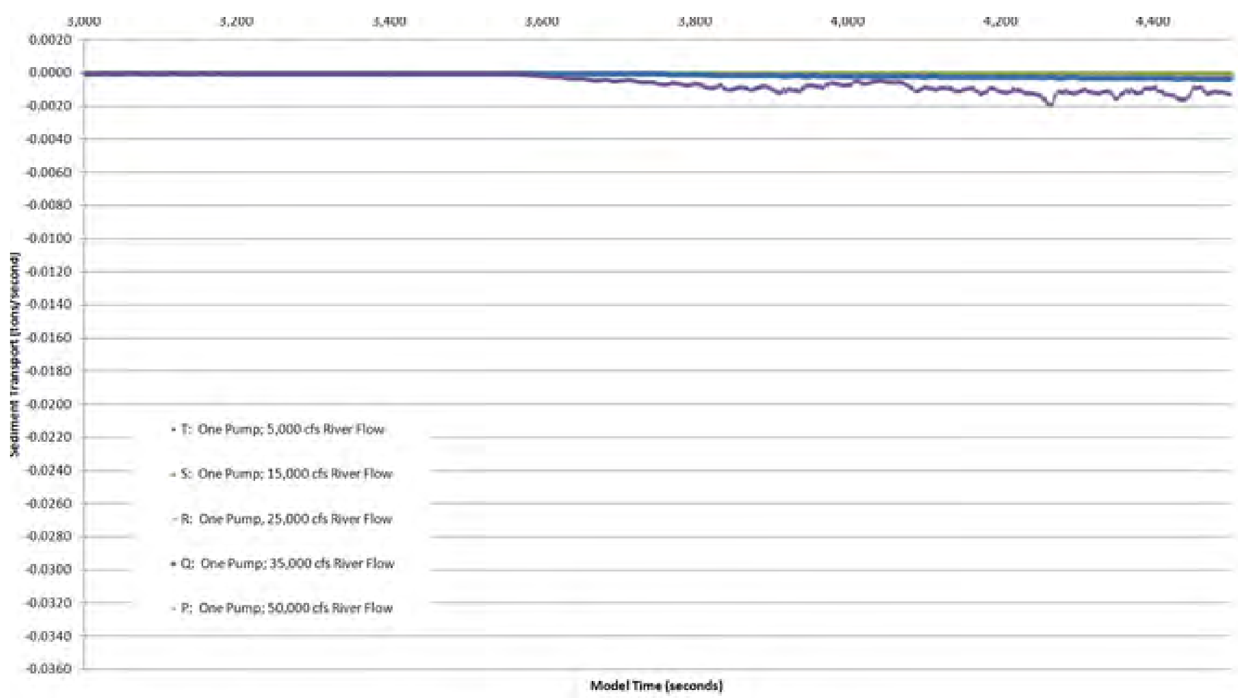
Existing Condition





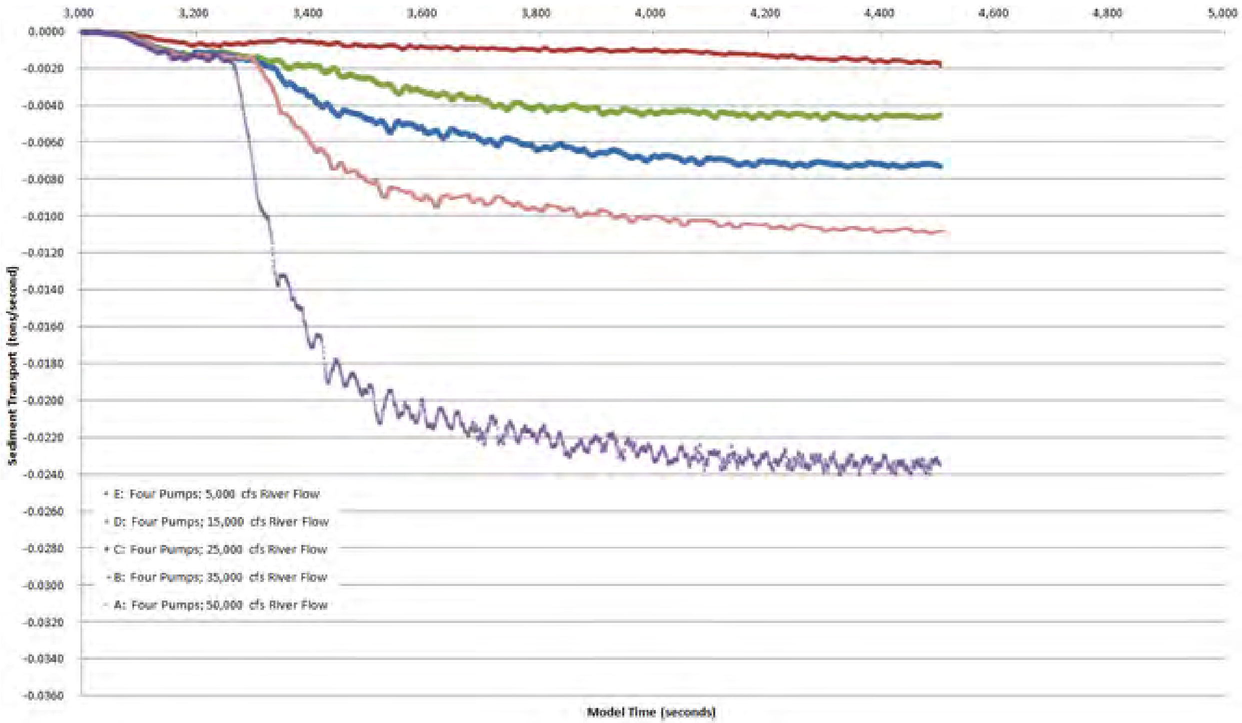


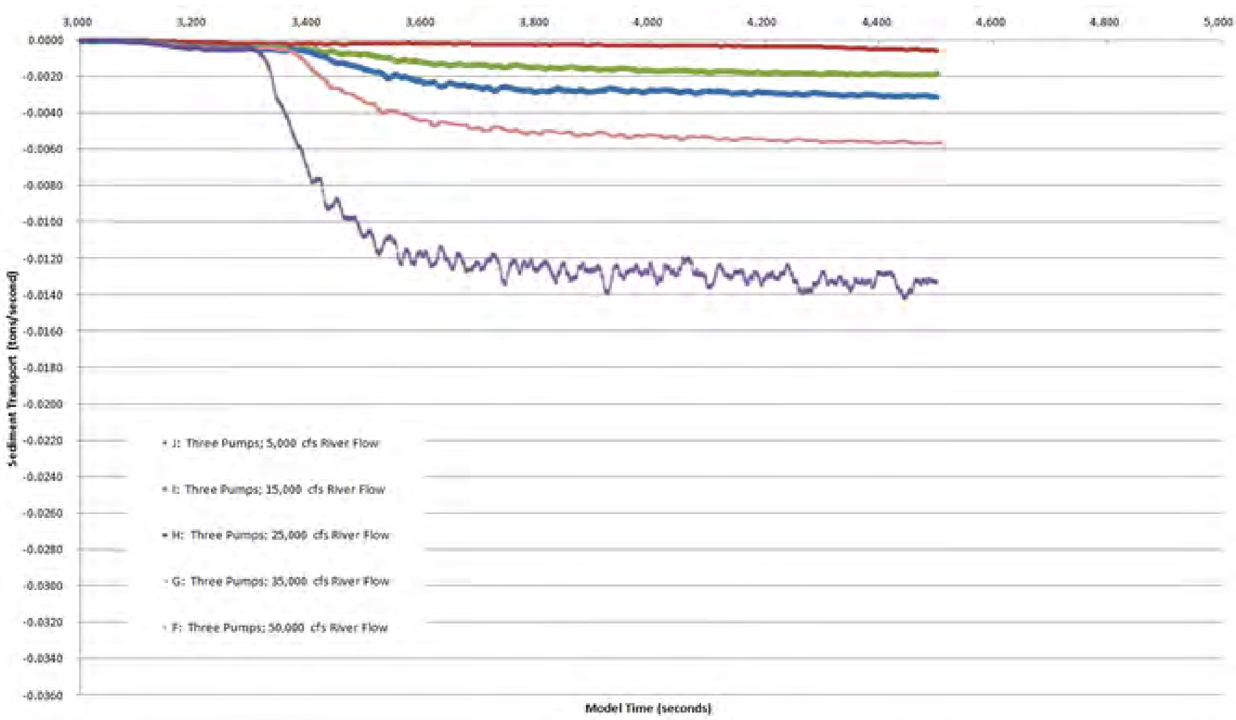
Sediment Transport (tons/second)
Model Time (seconds)
O: Two Pumps; 5,000 cfs River Flow
N: Two Pumps; 15,000 cfs River Flow
M: Two Pumps; 25,000 cfs River Flow
L: Two Pumps; 35,000 cfs River Flow
K: Two Pumps; 50,000 cfs River Flow

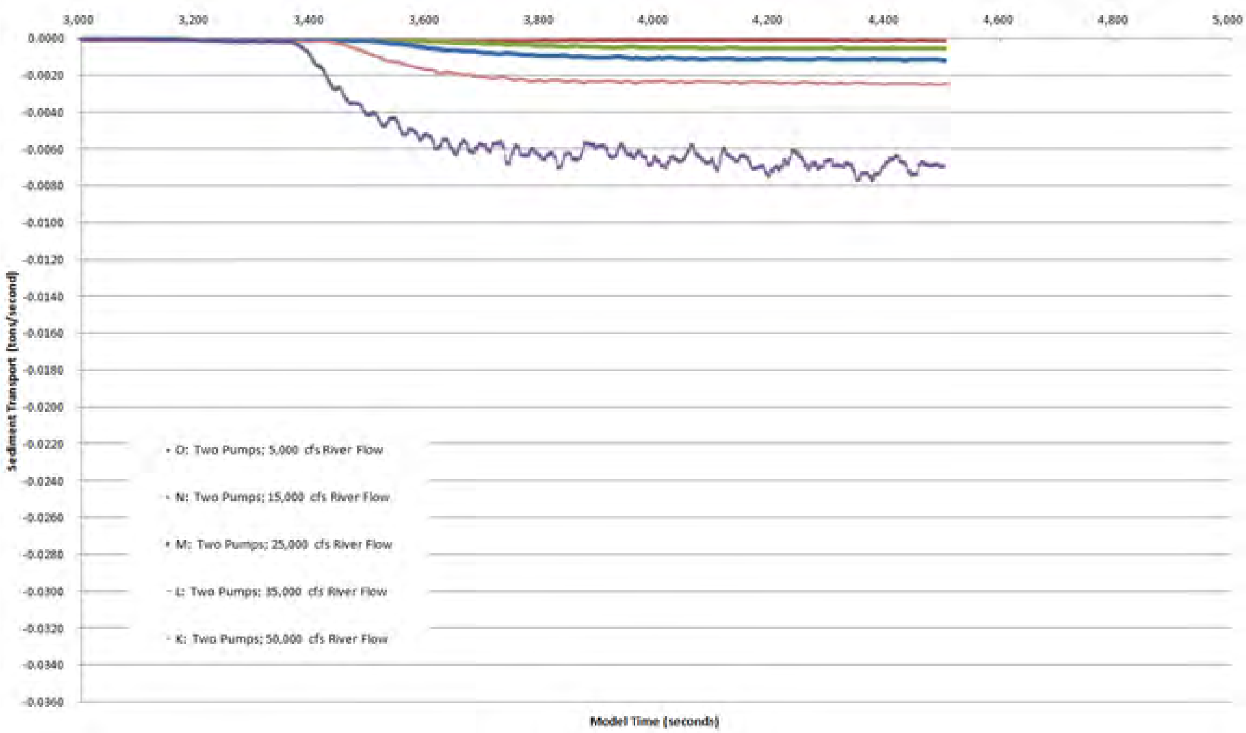


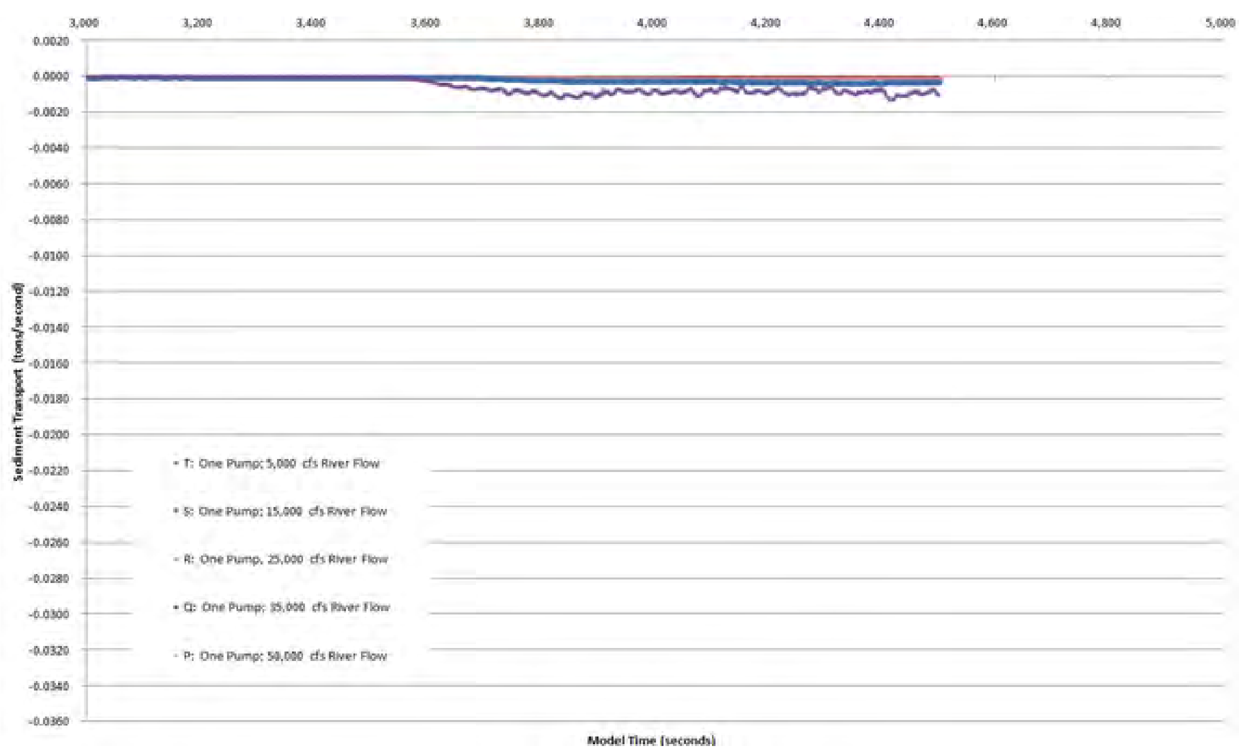
Sediment Transport (tons/second)
Model Time (seconds)
T: One Pump; 5,000 cfs River Flow
S: One Pump; 15,000 cfs River Flow
R: One Pump, 25,000 cfs River Flow
Q: One Pump; 35,000 cfs River Flow
P: One Pump; 50,000 cfs River Flow

Sediment Exclusion Alternative 1

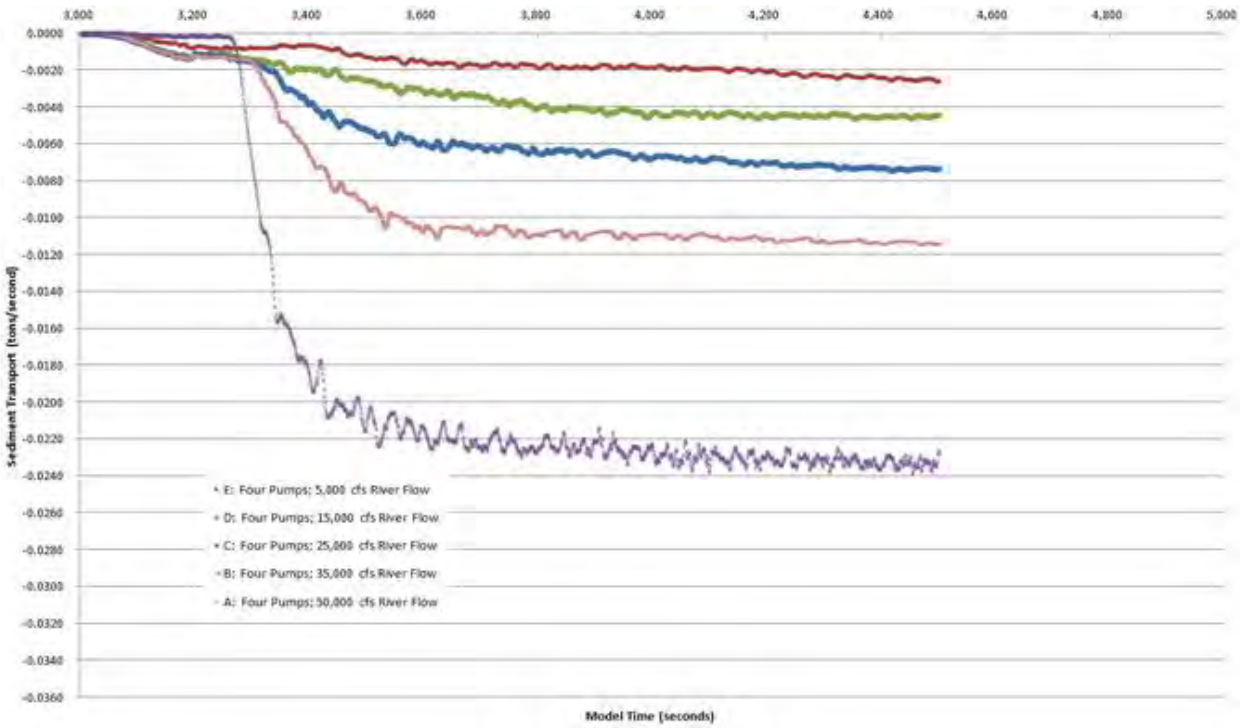


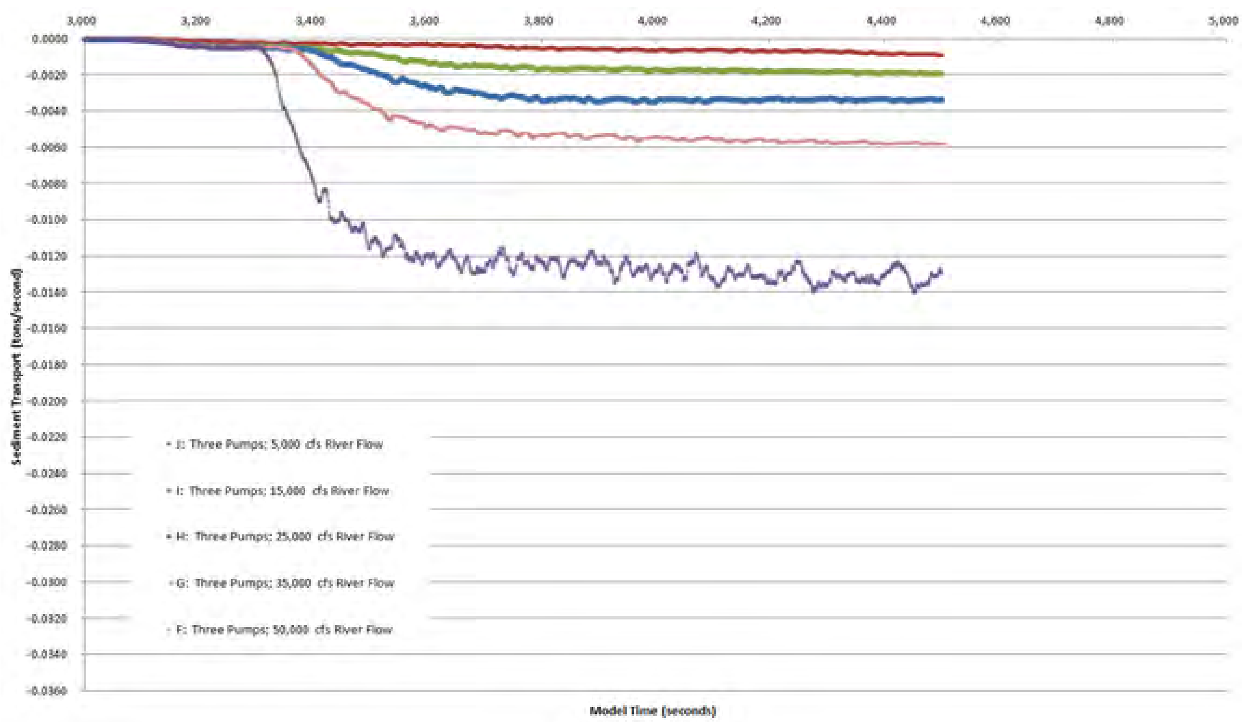


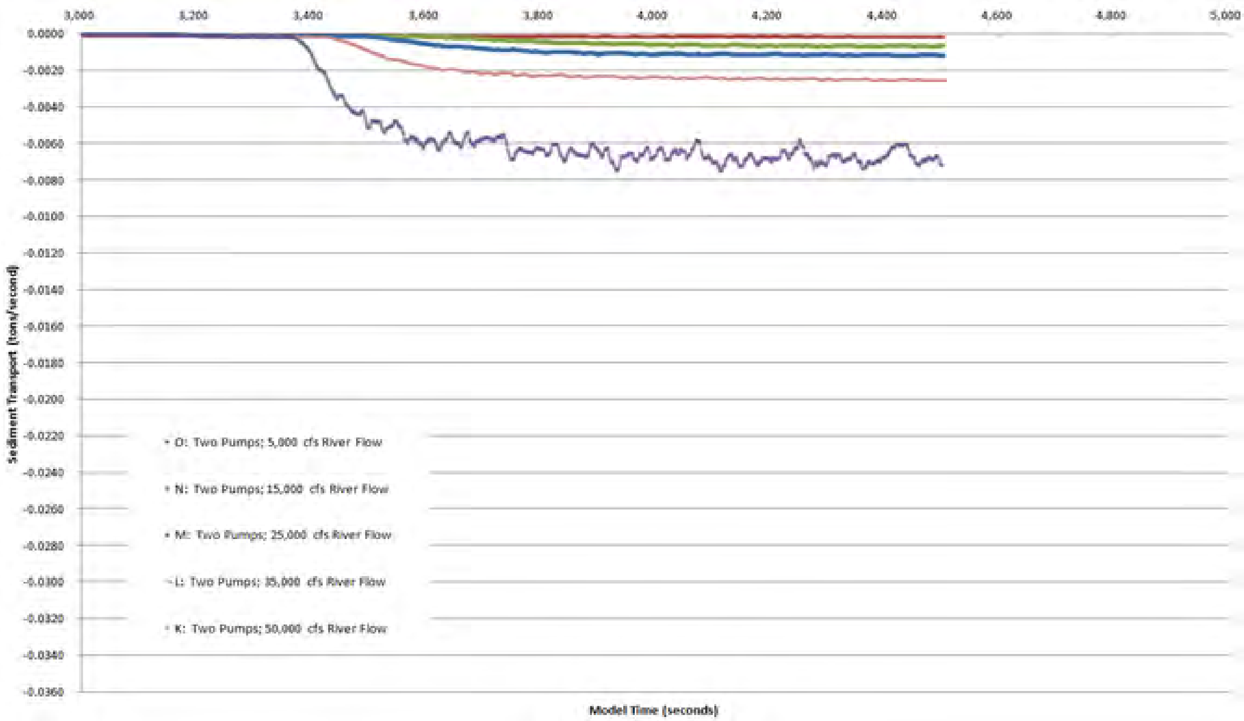

Sediment Transport (tons/second)
Model Time (seconds)
O: Two Pumps; 5,000 cfs River Flow
N: Two Pumps; 15,000 cfs River Flow
M: Two Pumps; 25,000 cfs River Flow
L: Two Pumps; 35,000 cfs River Flow
K: Two Pumps; 50,000 cfs River Flow


Sediment Transport (tons/second)
Model Time (seconds)
T: One Pump; 5,000 cfs River Flow
S: One Pump; 15,000 cfs River Flow
R: One Pump, 25,000 cfs River Flow
Q: One Pump; 35,000 cfs River Flow
P: One Pump; 50,000 cfs River Flow

Sediment Exclusion Alternative 2







3,000
3,200
3,400
3,600
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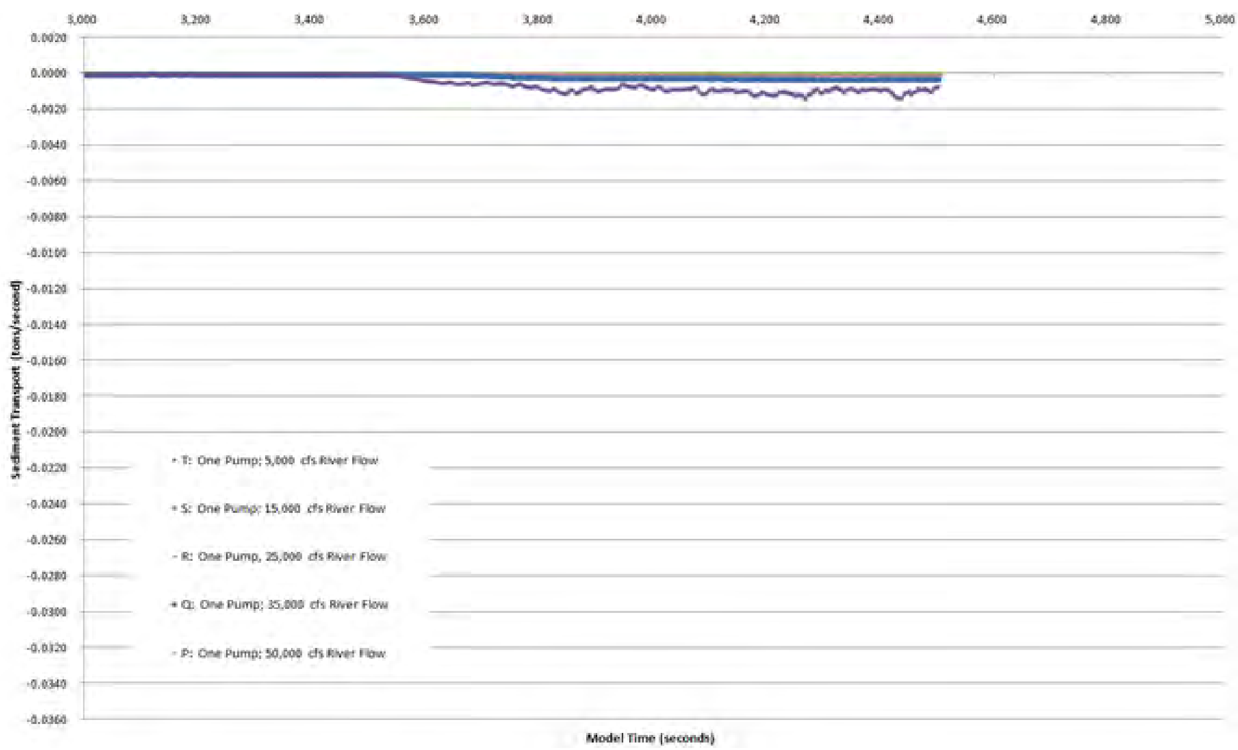
4,600
4,800
5,000
0.0000
-0.0020
-0.0040
-0.0060
-0.0080
-0.0100
-0.0120
-0.0140
-0.0160
-0.0180
-0.0200
-0.0220
-0.0240
-0.0260
-0.0280
-0.0300
-0.0320
-0.0340
-0.0360
Sediment Transport (tons/second)
O: Two Pumps; 5,000 cfs River Flow
N: Two Pumps; 15,000 cfs River Flow
M: Two Pumps; 25,000 cfs River Flow
L: Two Pumps; 35,000 cfs River Flow
K: Two Pumps; 50,000 cfs River Flow
Model Time (seconds)



3,000
3,200
3,400
3,600
3,800
4,000
4,200
4,400
4,600
4,800
5,000
0.0020
0.0000
-0.0020
-0.0040
-0.0060
-0.0080
-0.0100
-0.0120
-0.0140
-0.0160
-0.0180
-0.0200
-0.0220
-0.0240
-0.0260
-0.0280
-0.0300
-0.0320
-0.0340
-0.0360
Sediment Transport (tons/second)
T: One Pump; 5,000 cfs River Flow
S: One Pump; 15,000 cfs River Flow
R: One Pump, 25,000 cfs River Flow
Q: One Pump; 35,000 cfs River Flow
P: One Pump; 50,000 cfs River Flow
Model Time (seconds)

APPENDIX B: Velocity Plots

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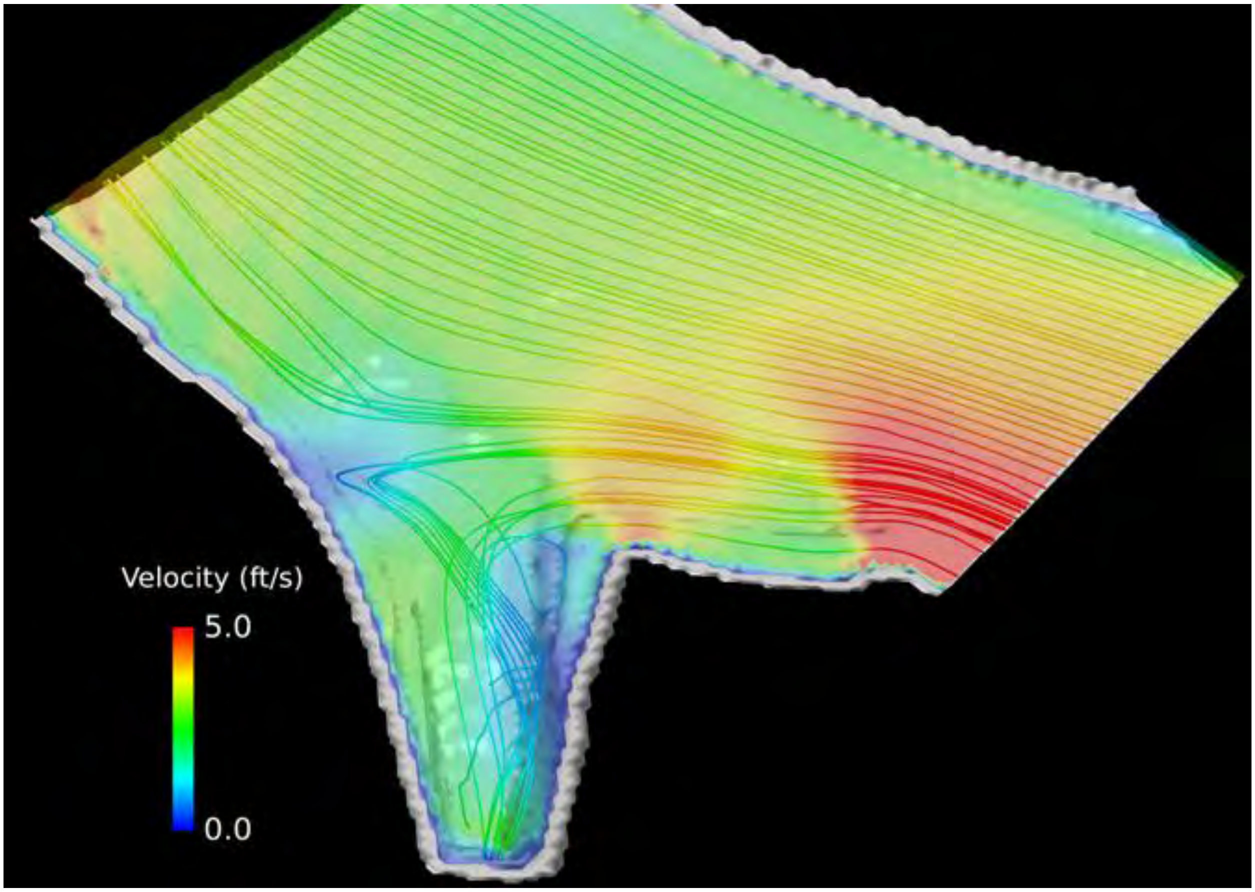
Existing Condition Case A



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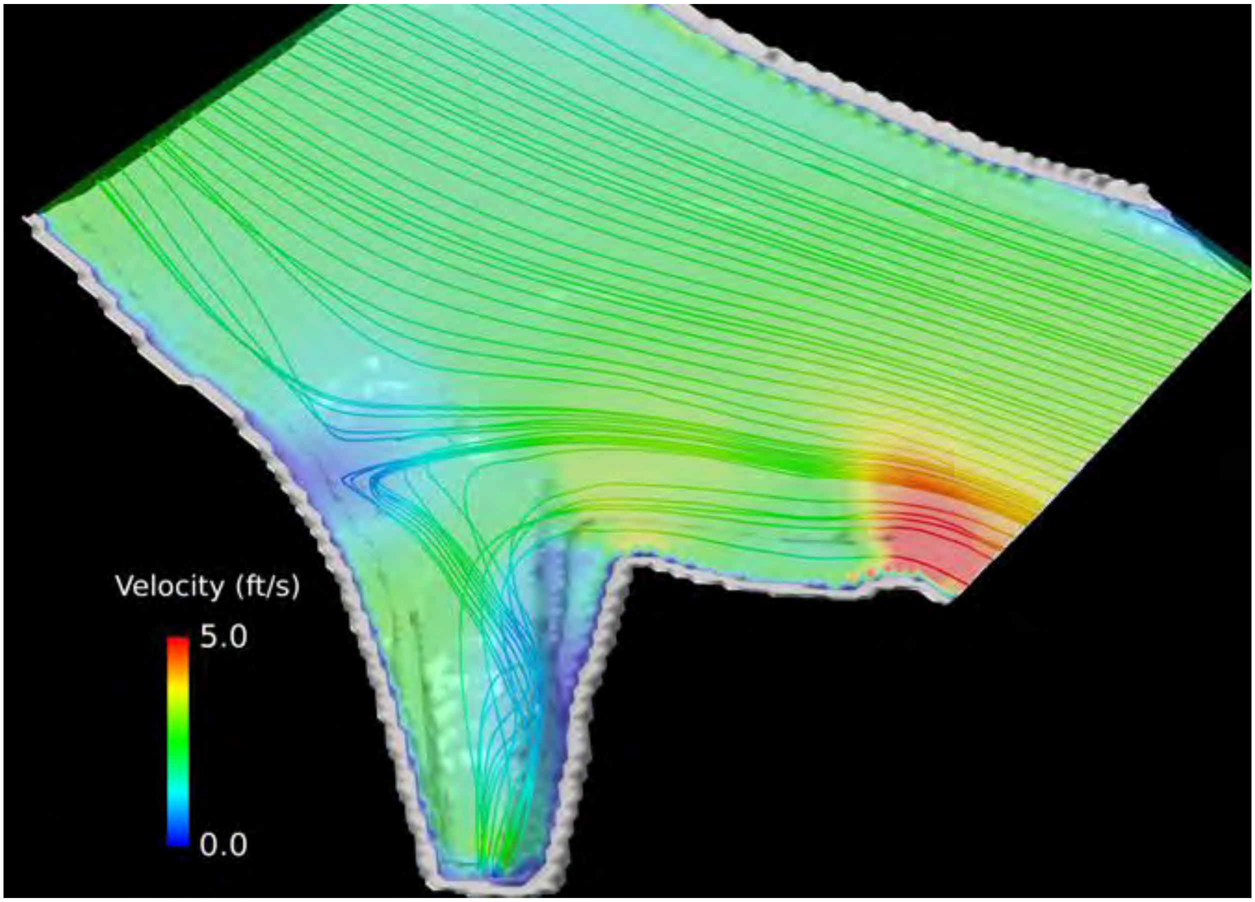

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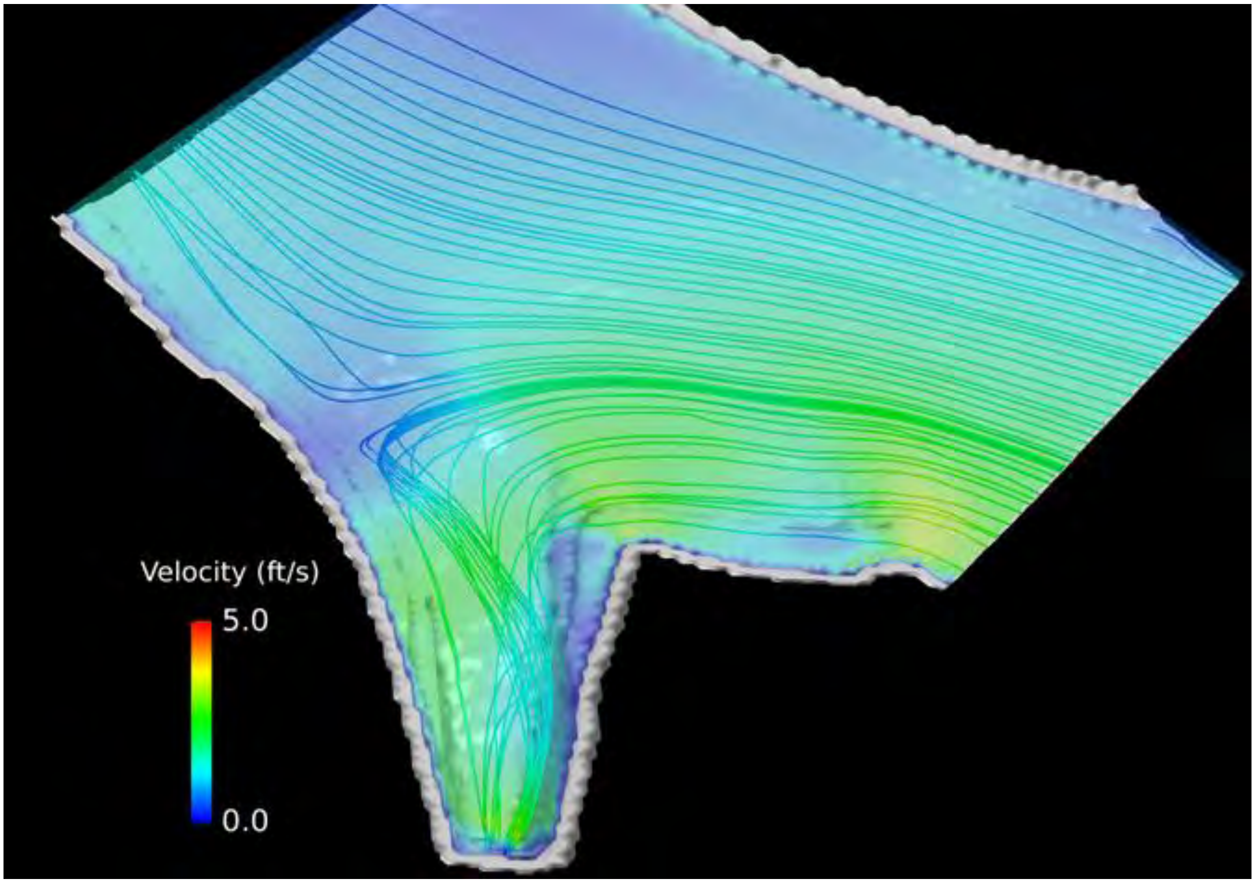

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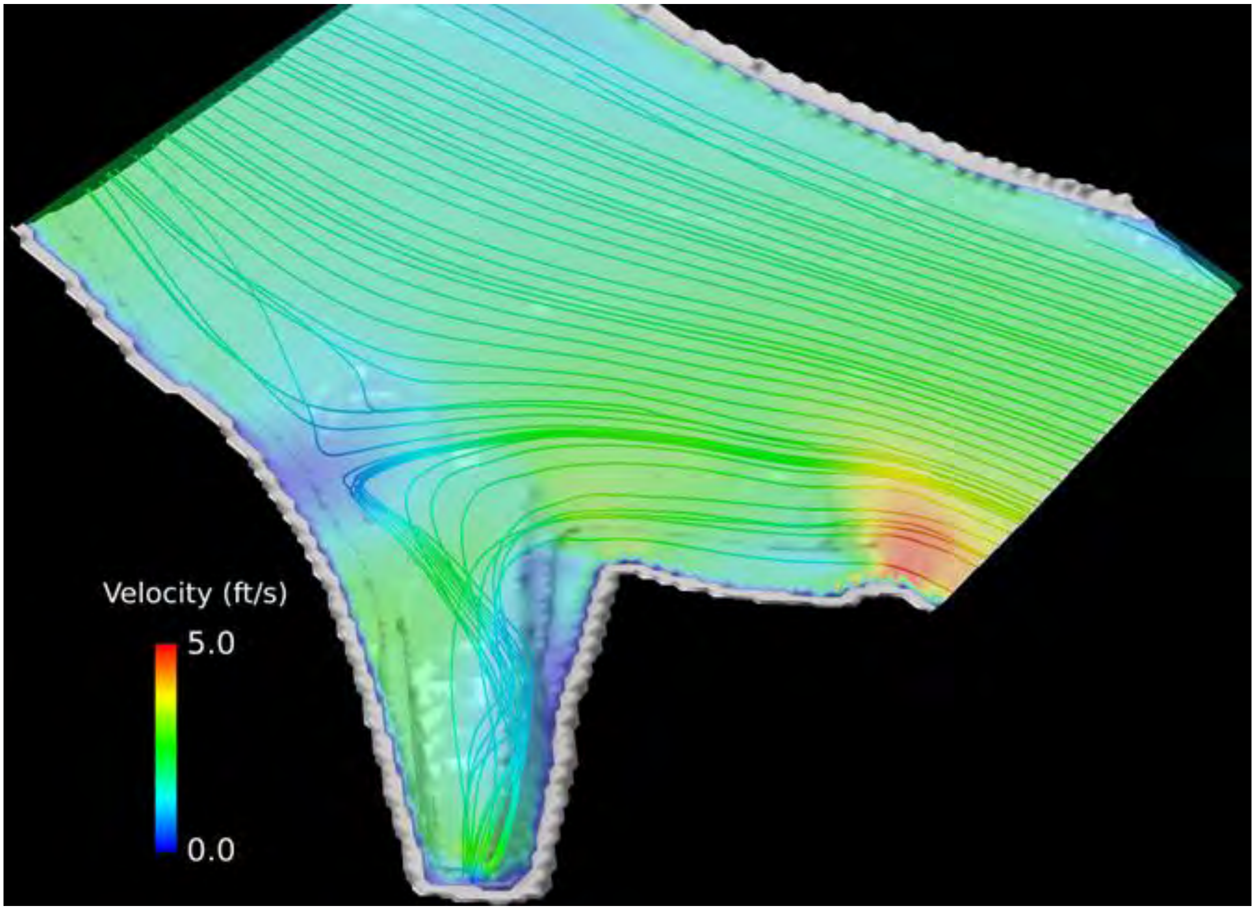

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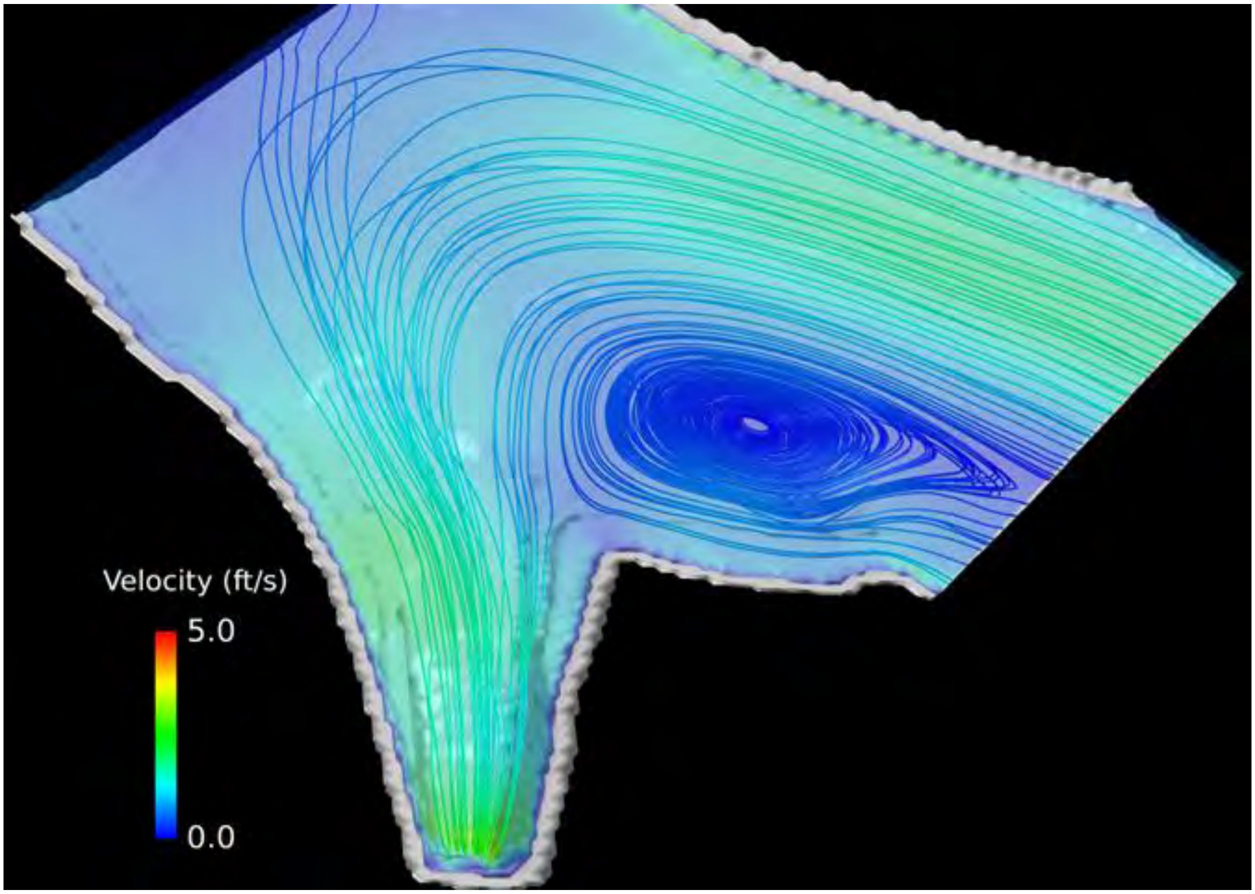

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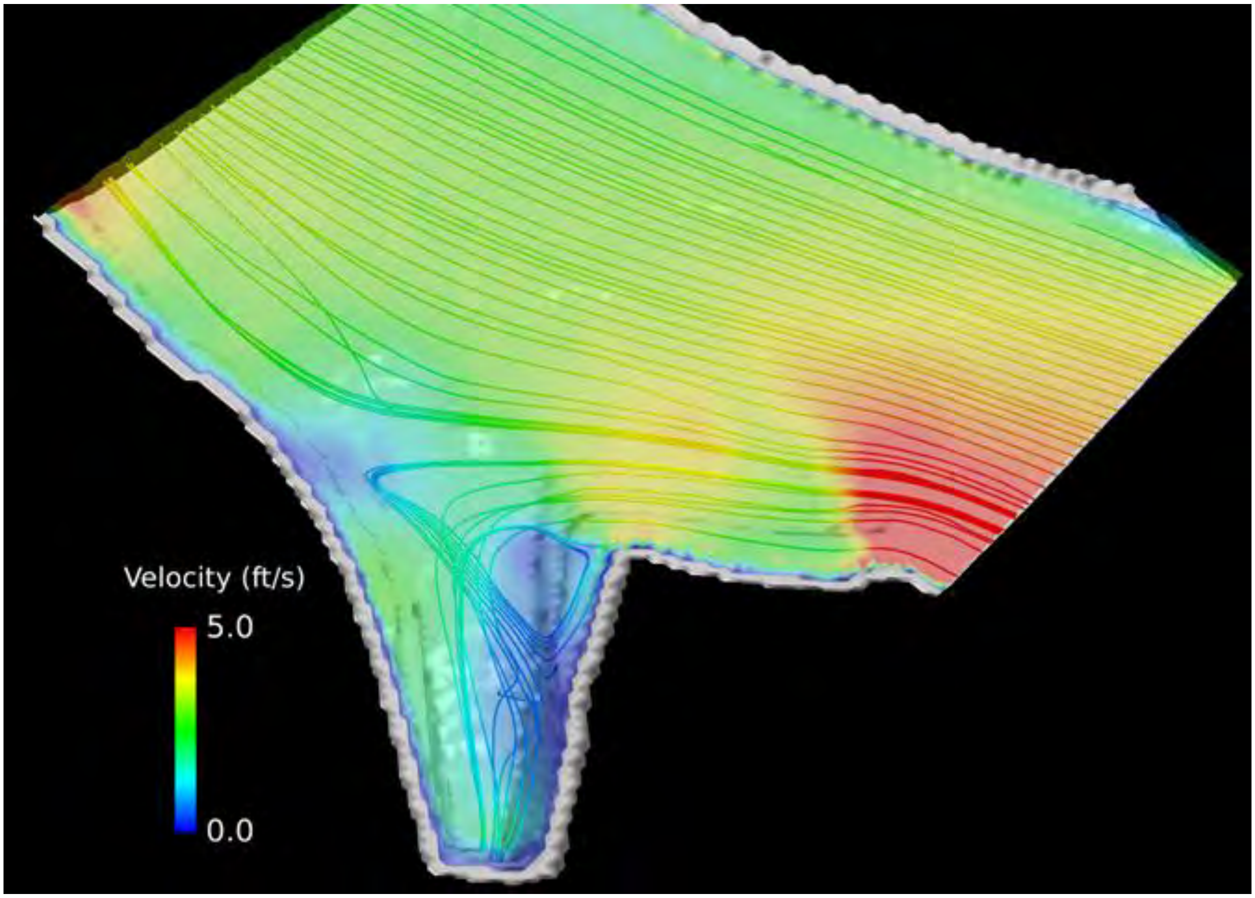

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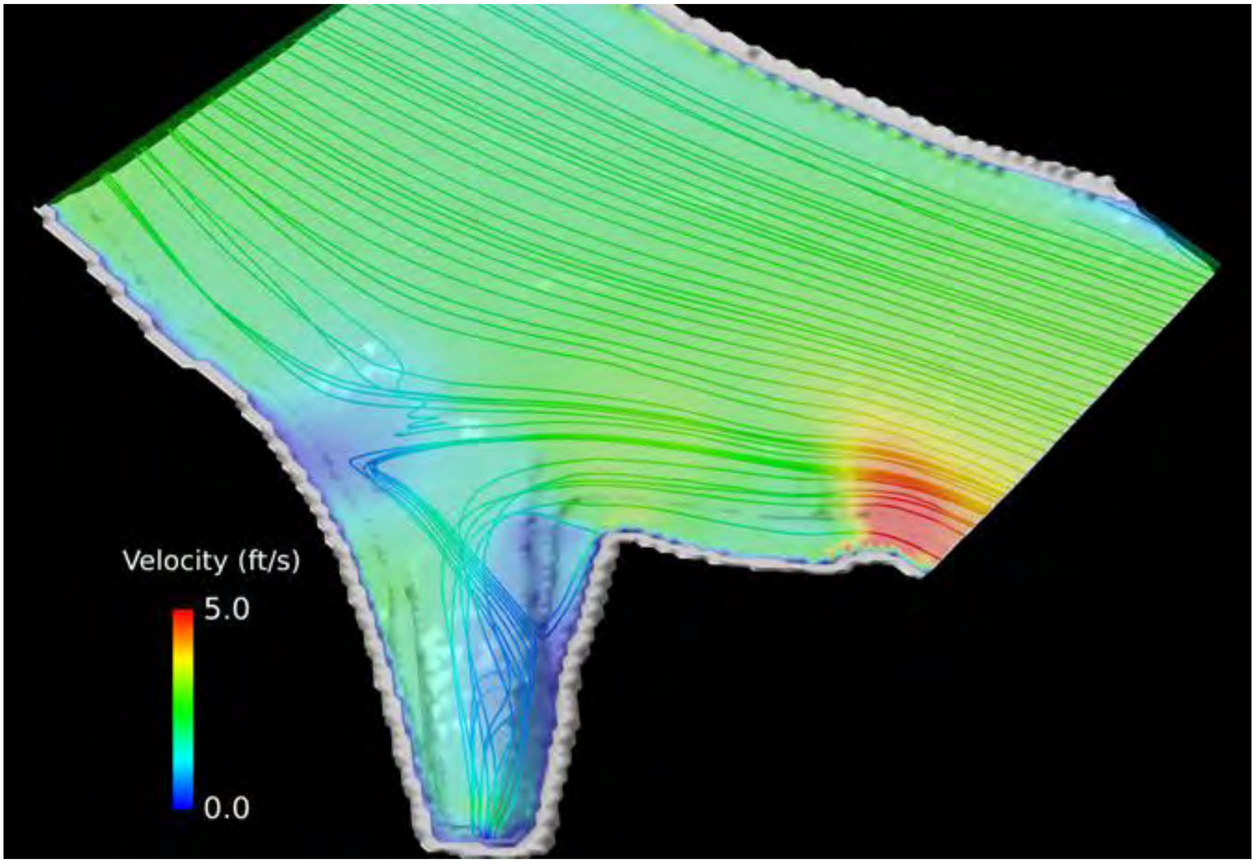

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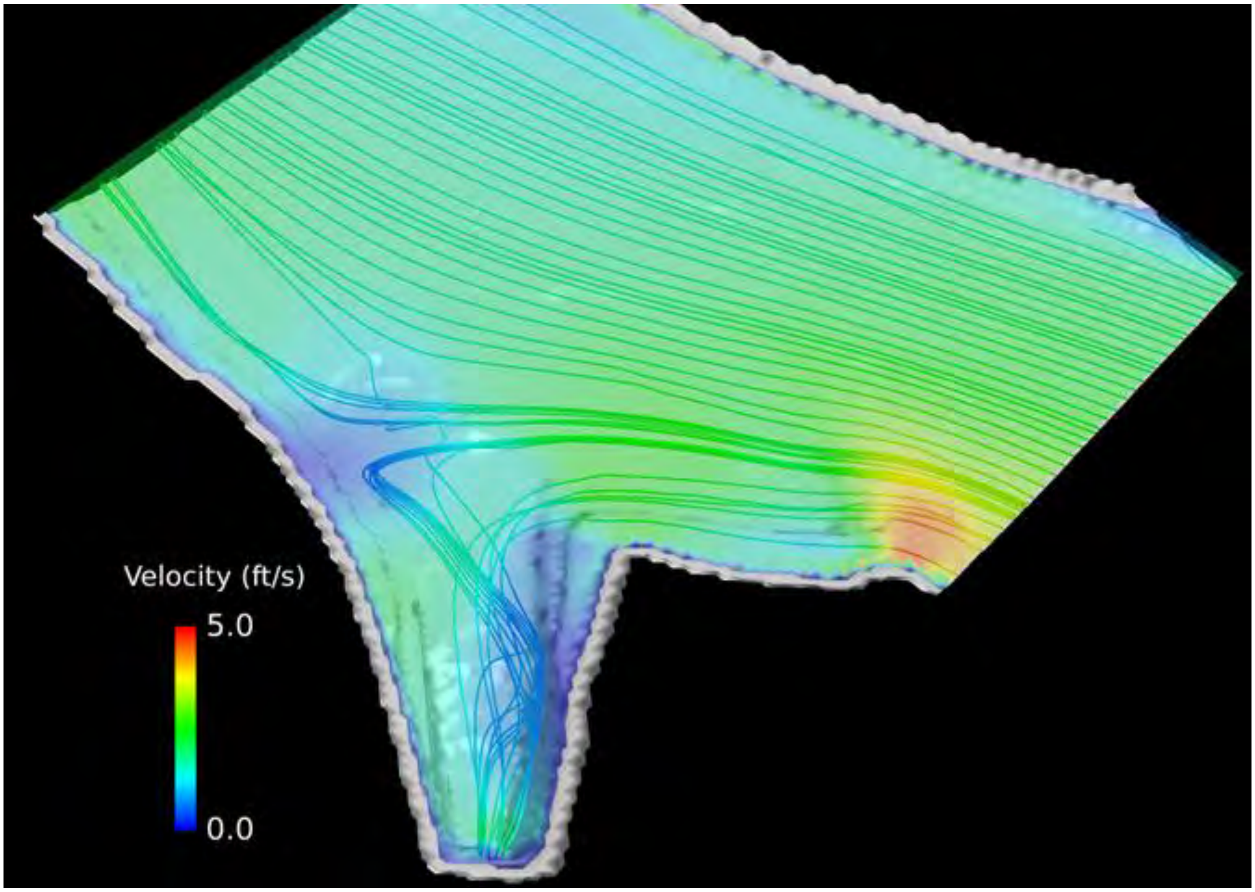

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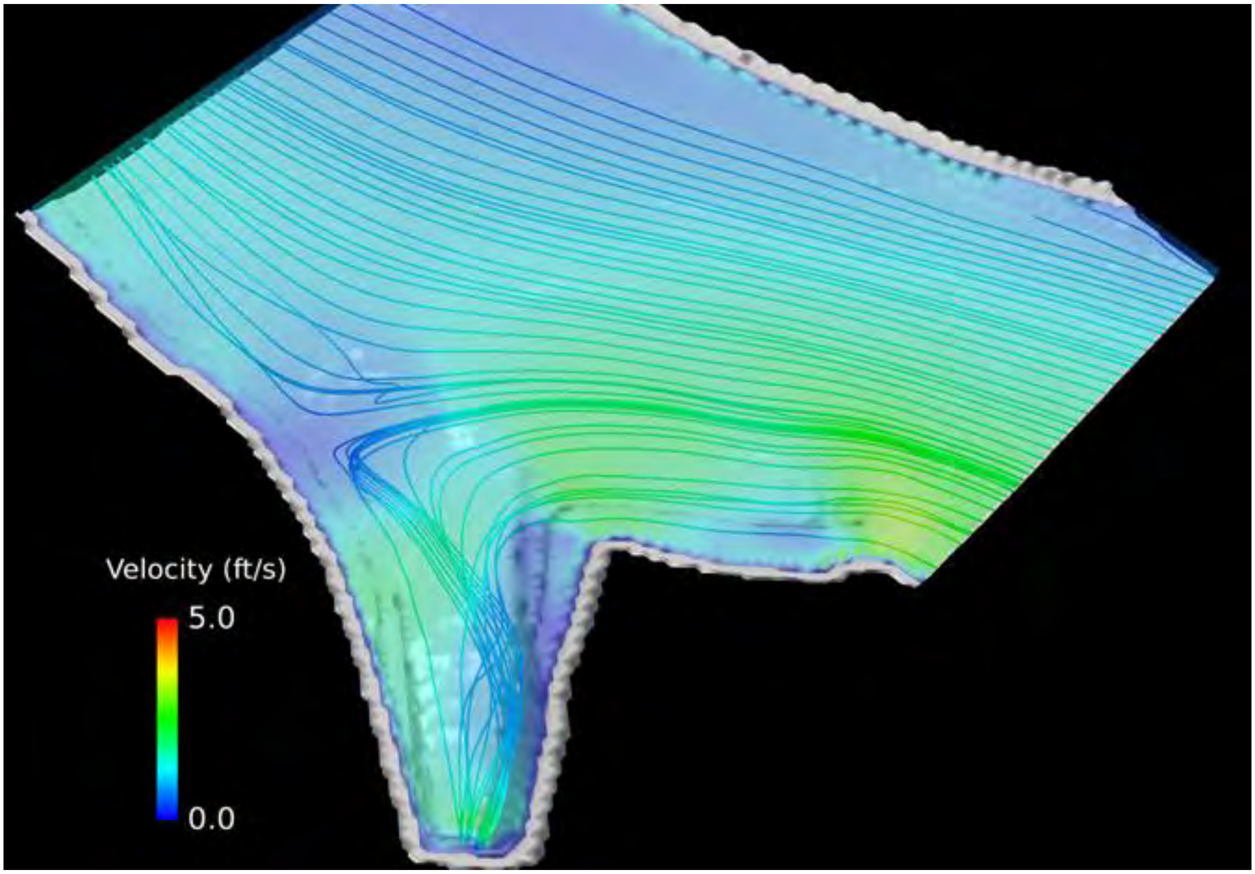

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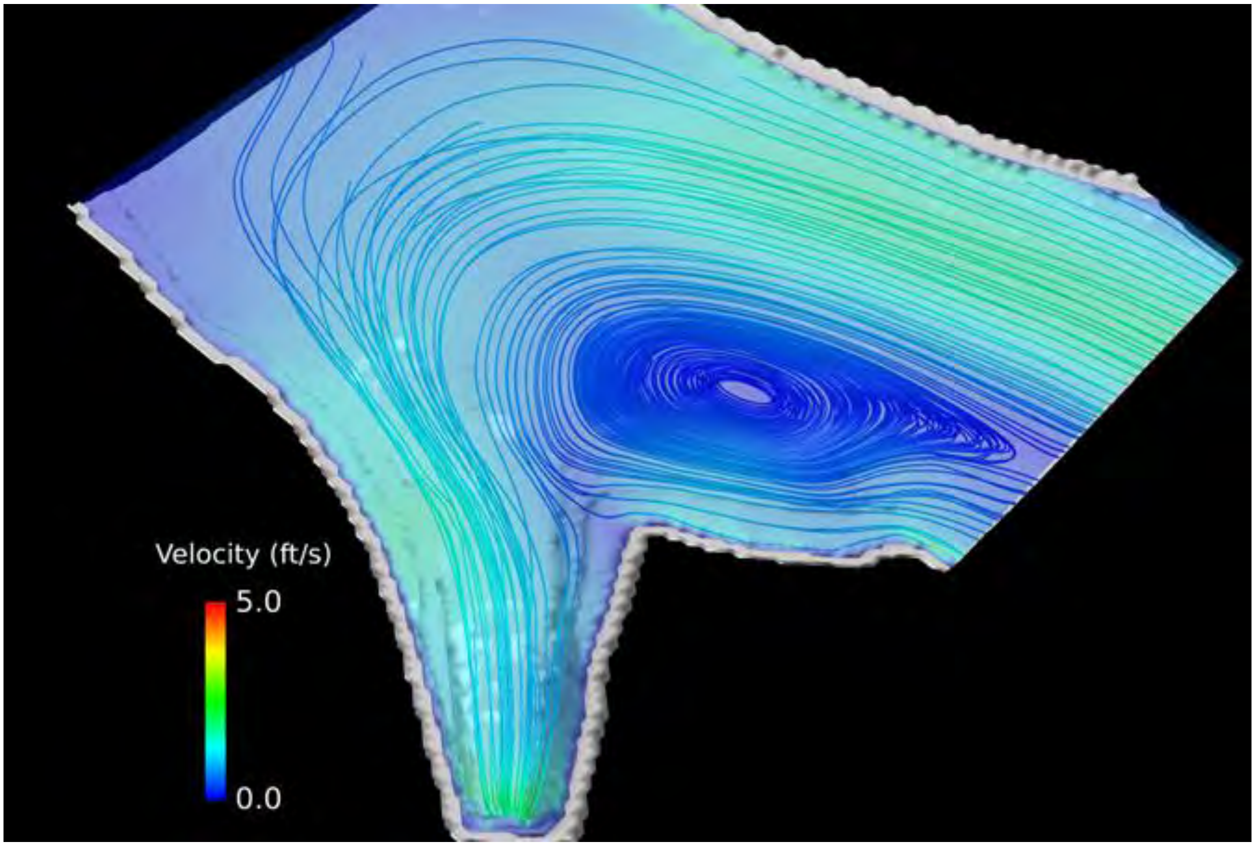

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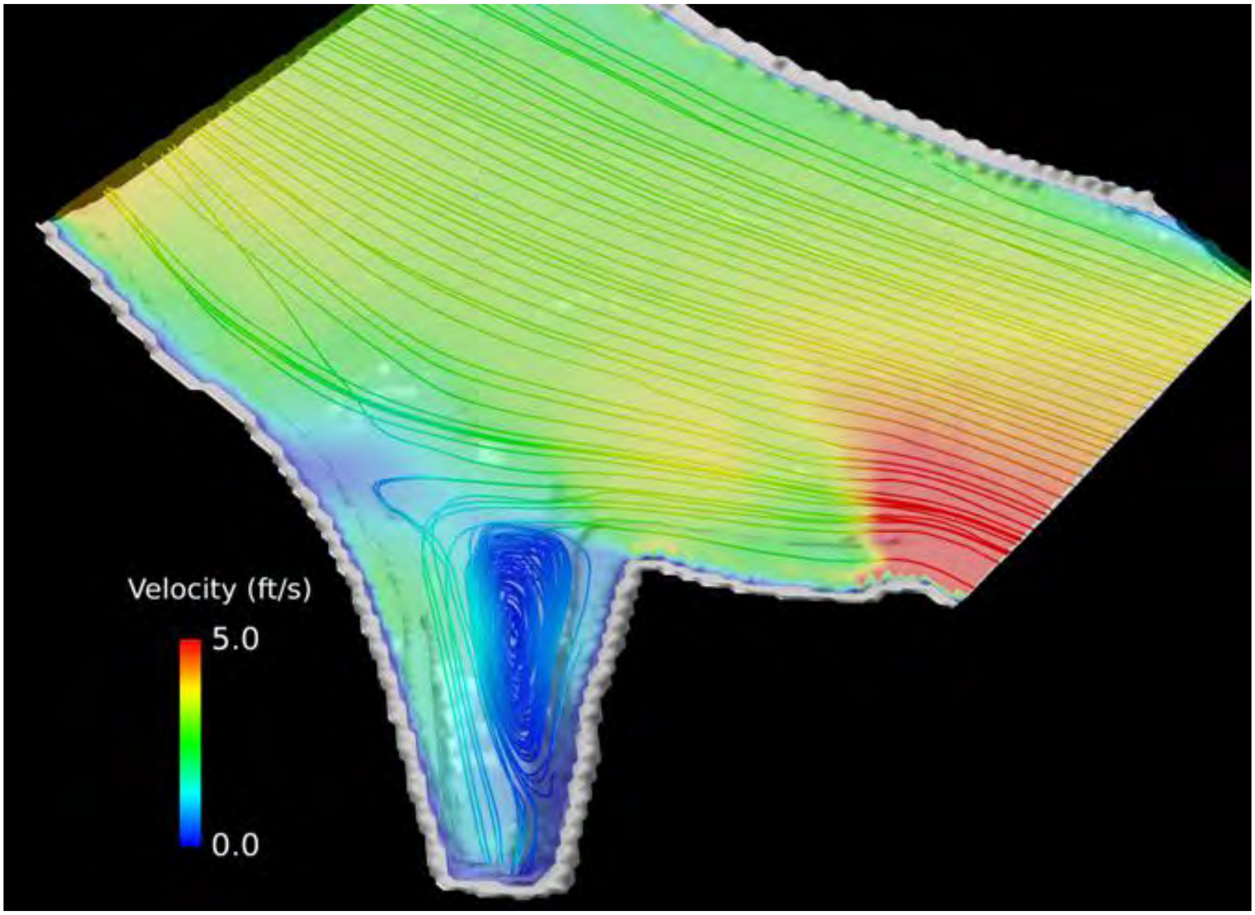

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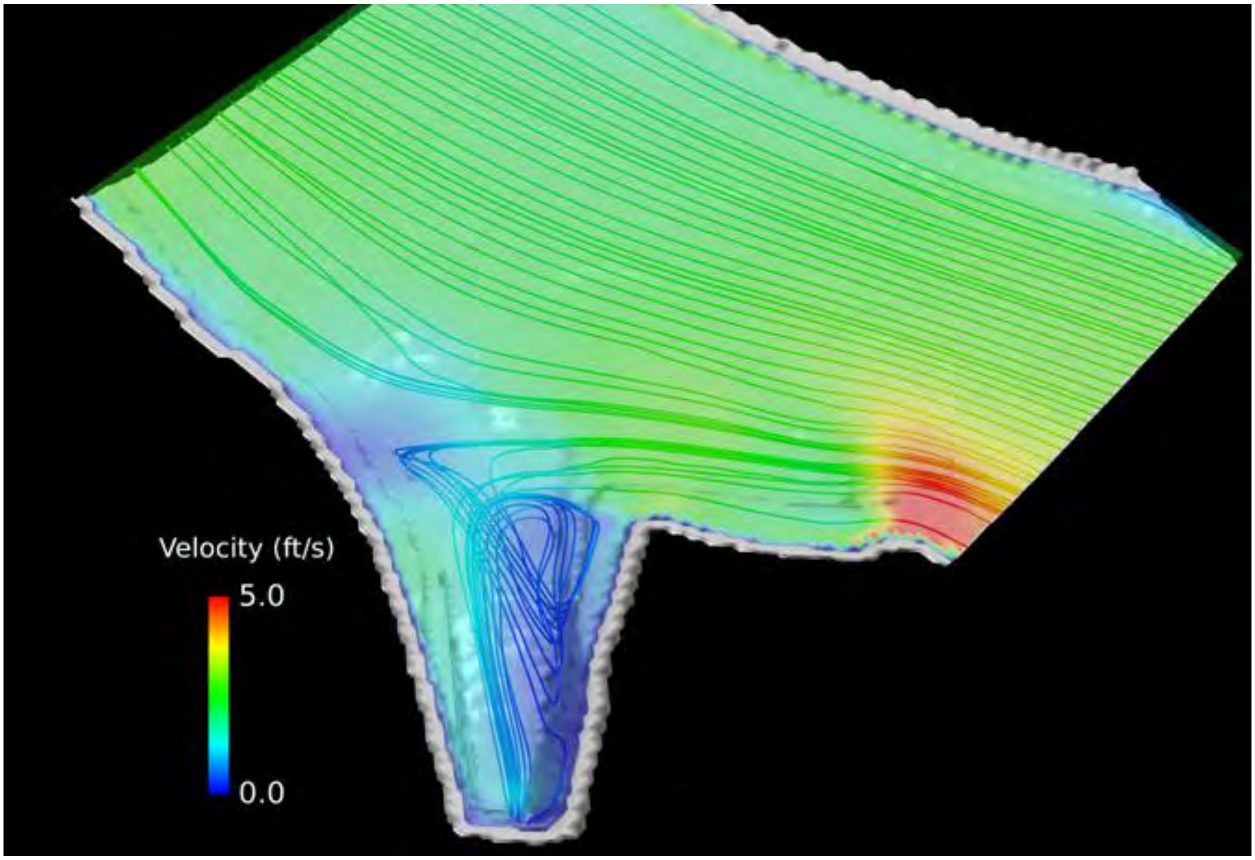

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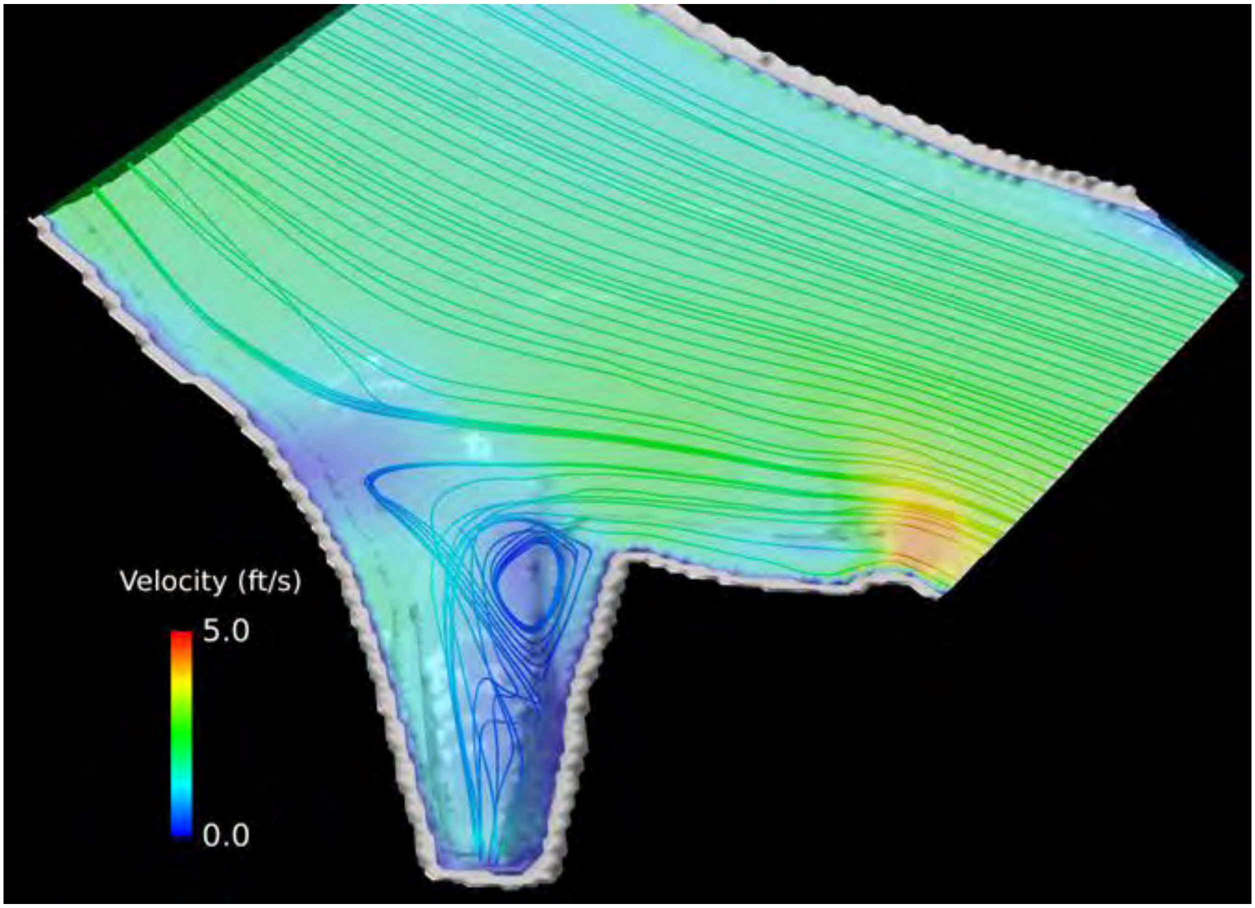

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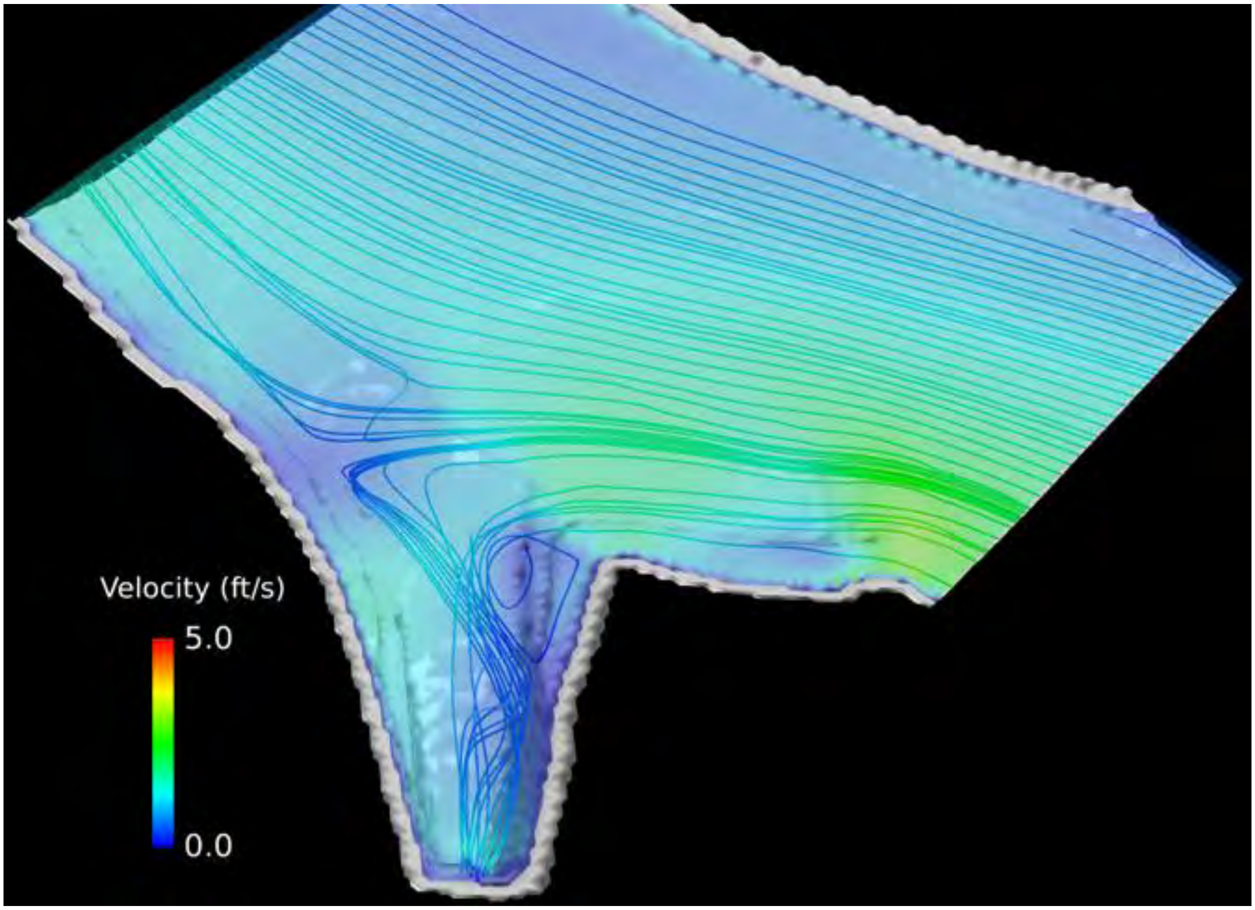

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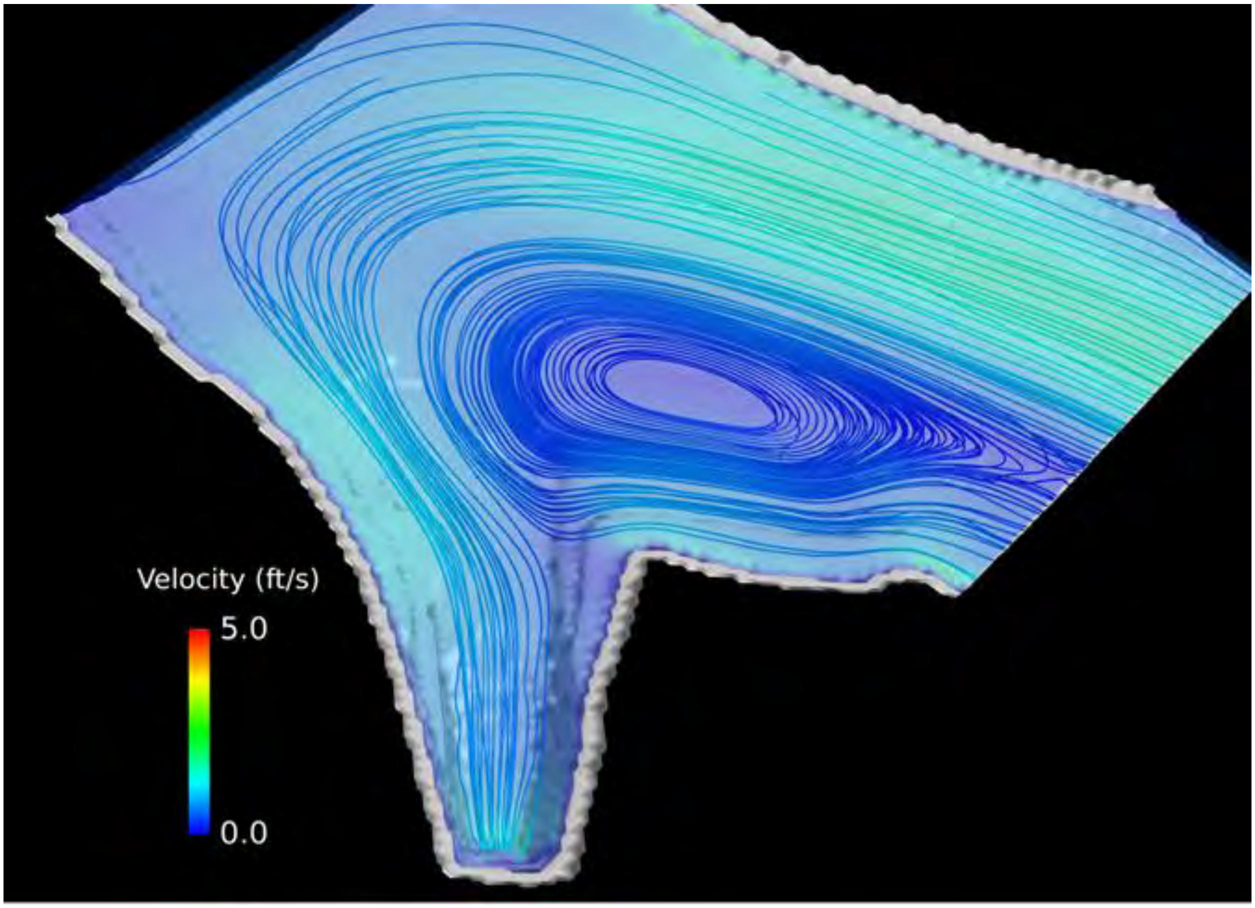

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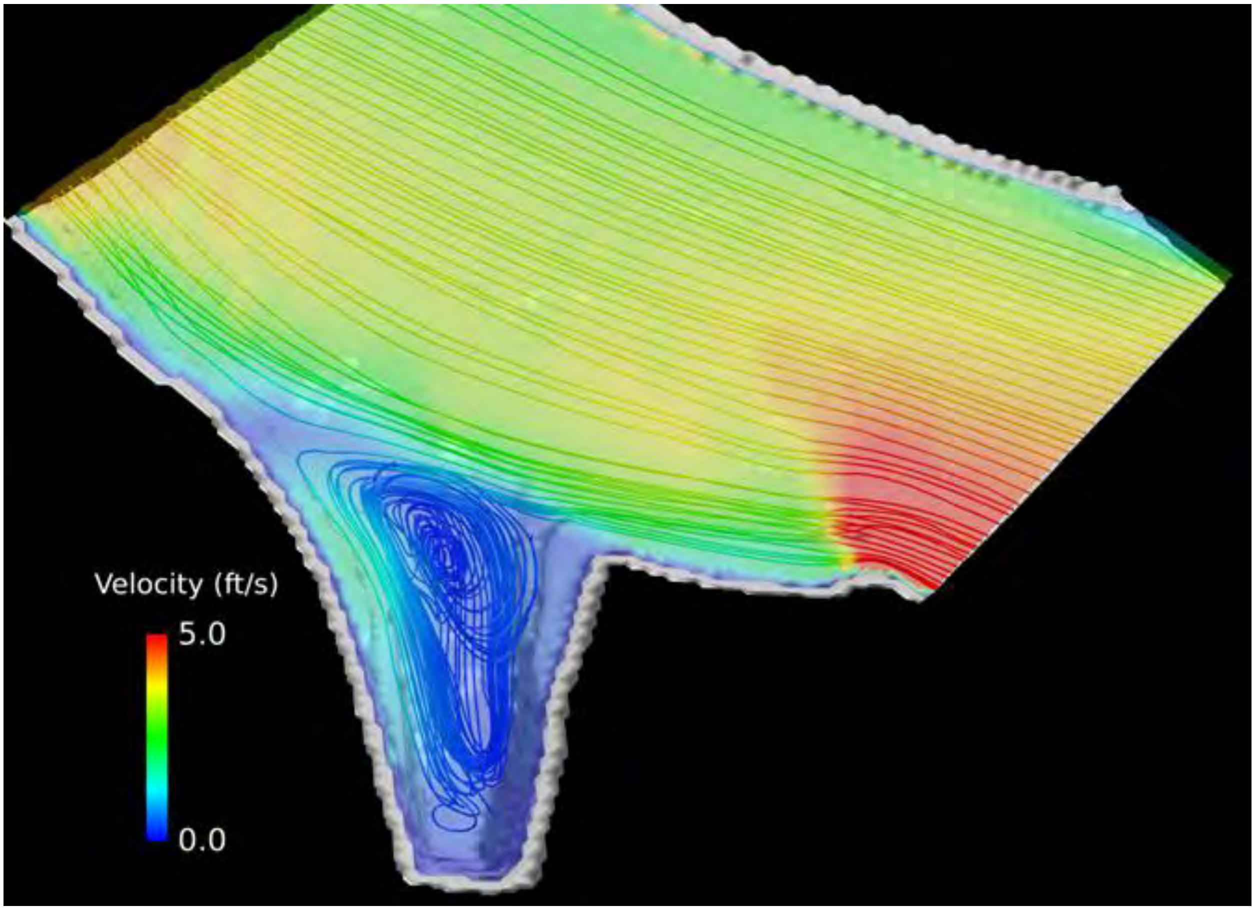

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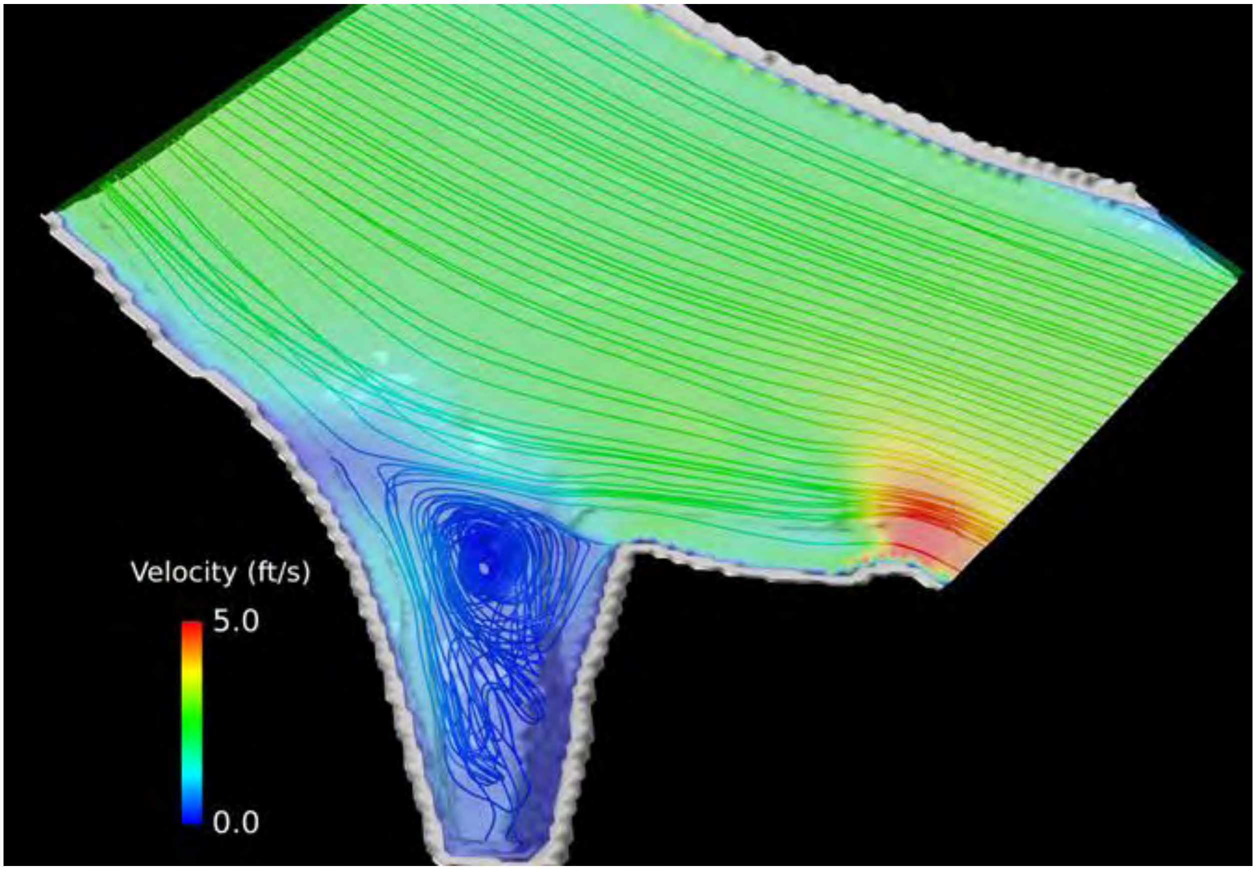

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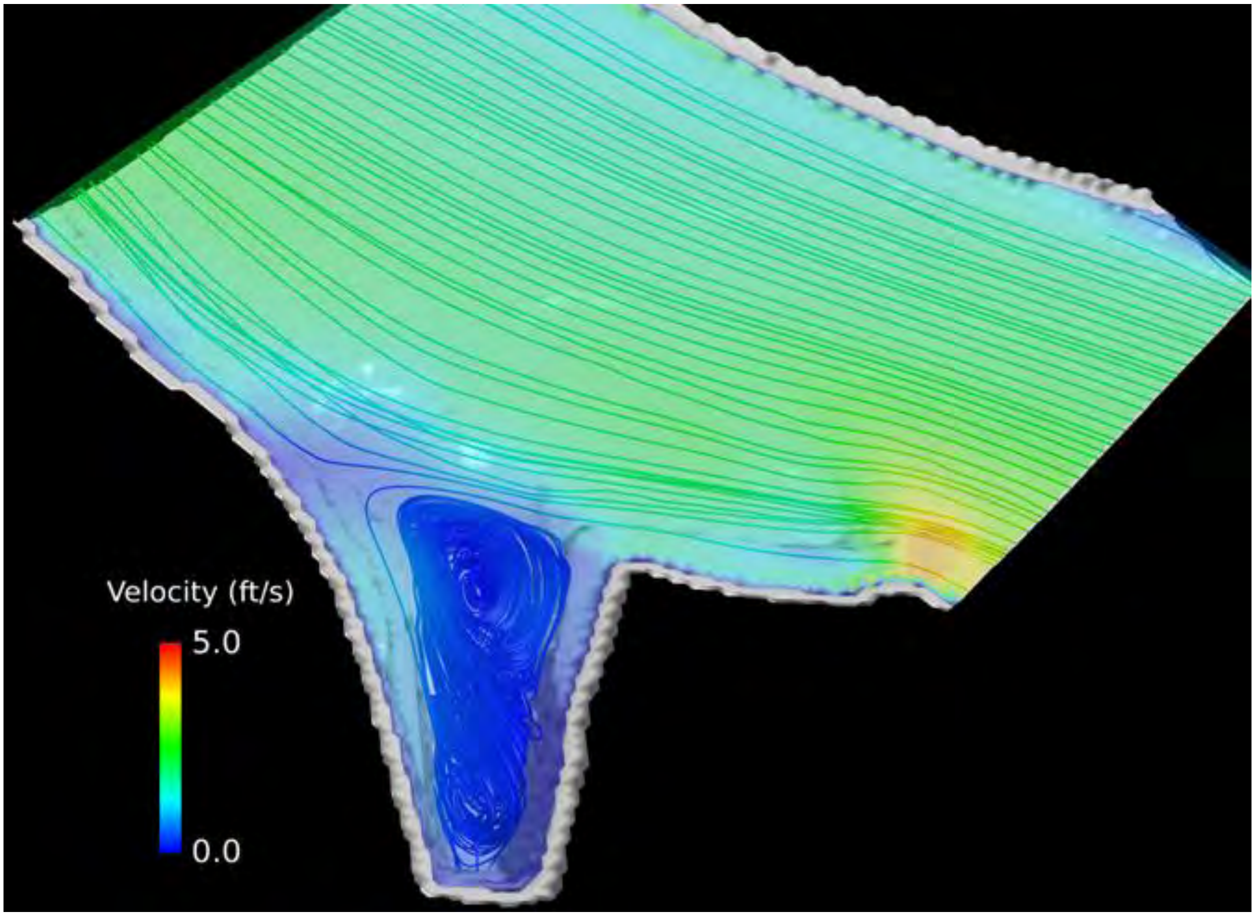

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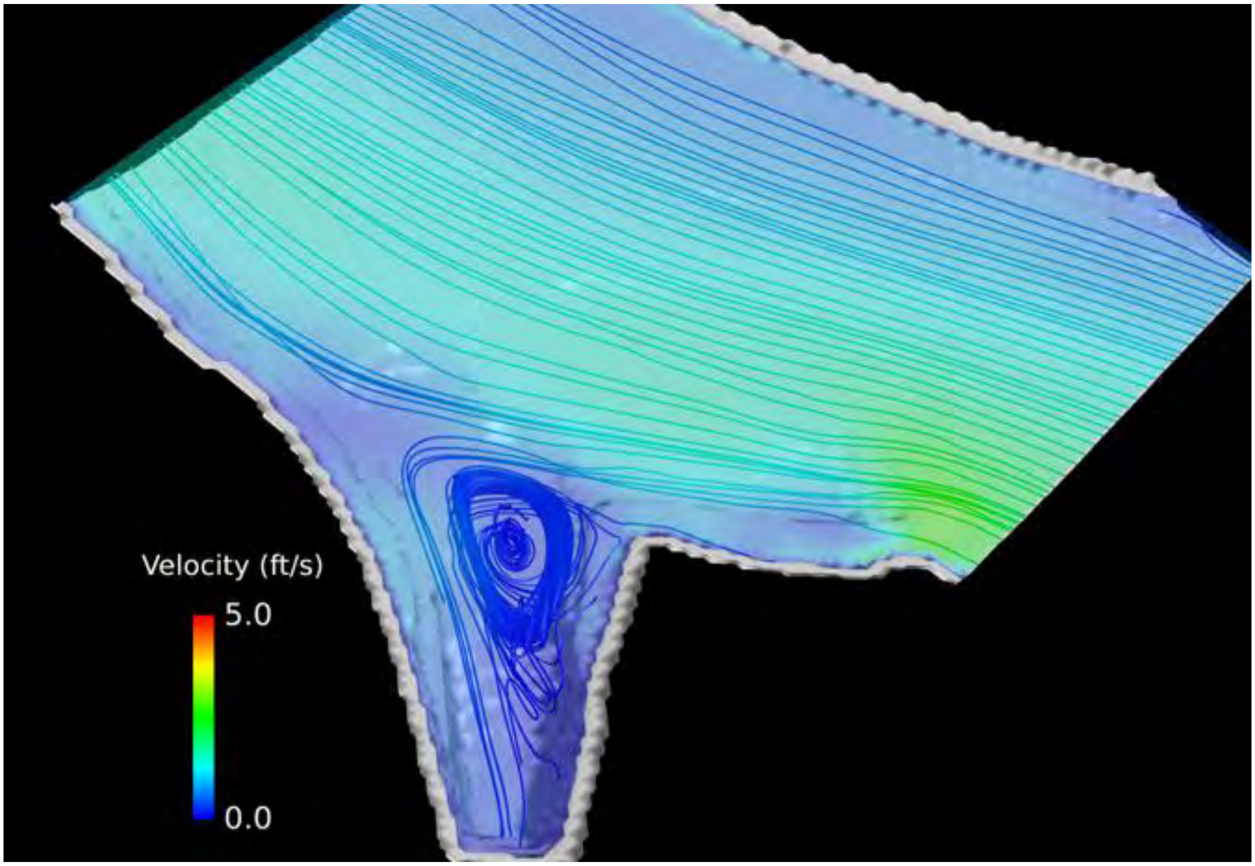

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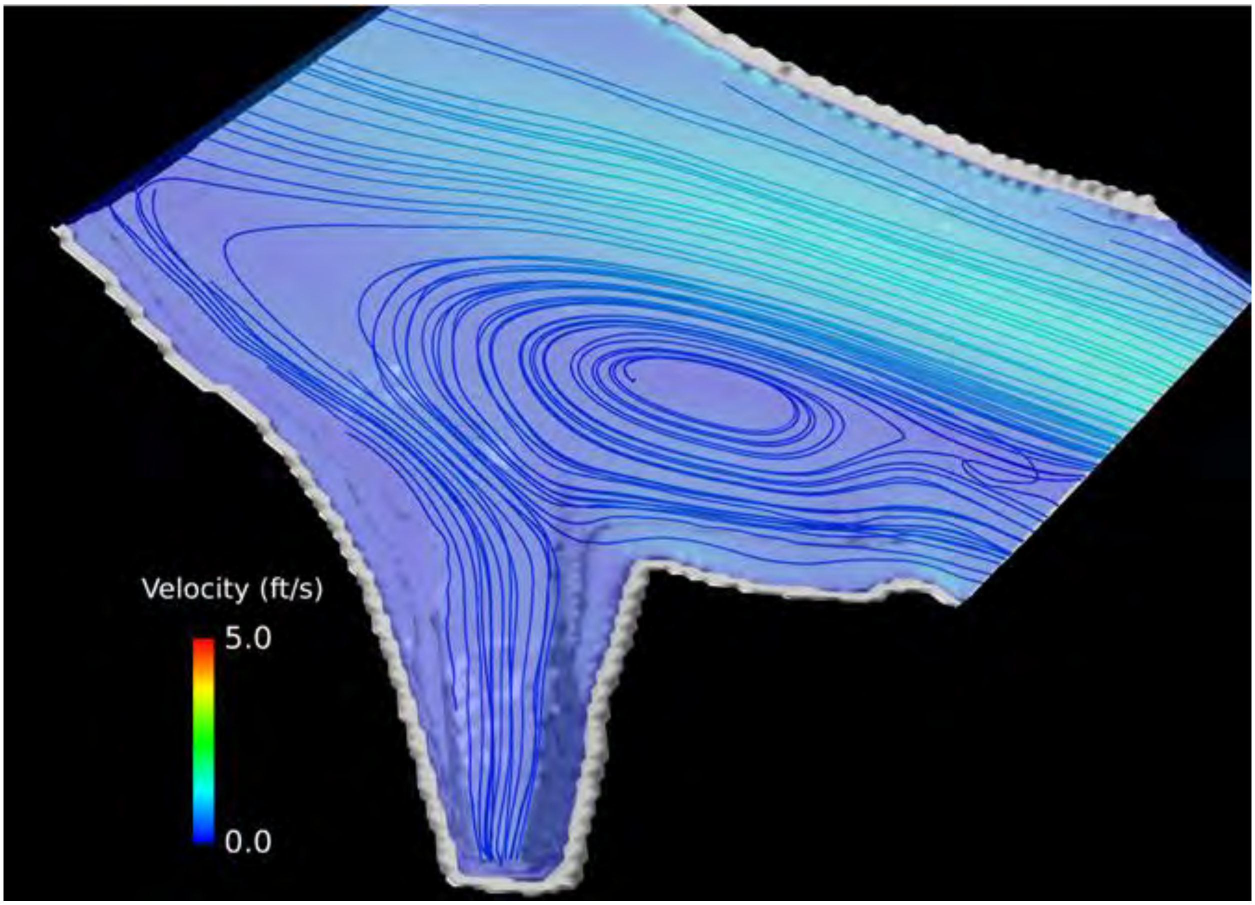
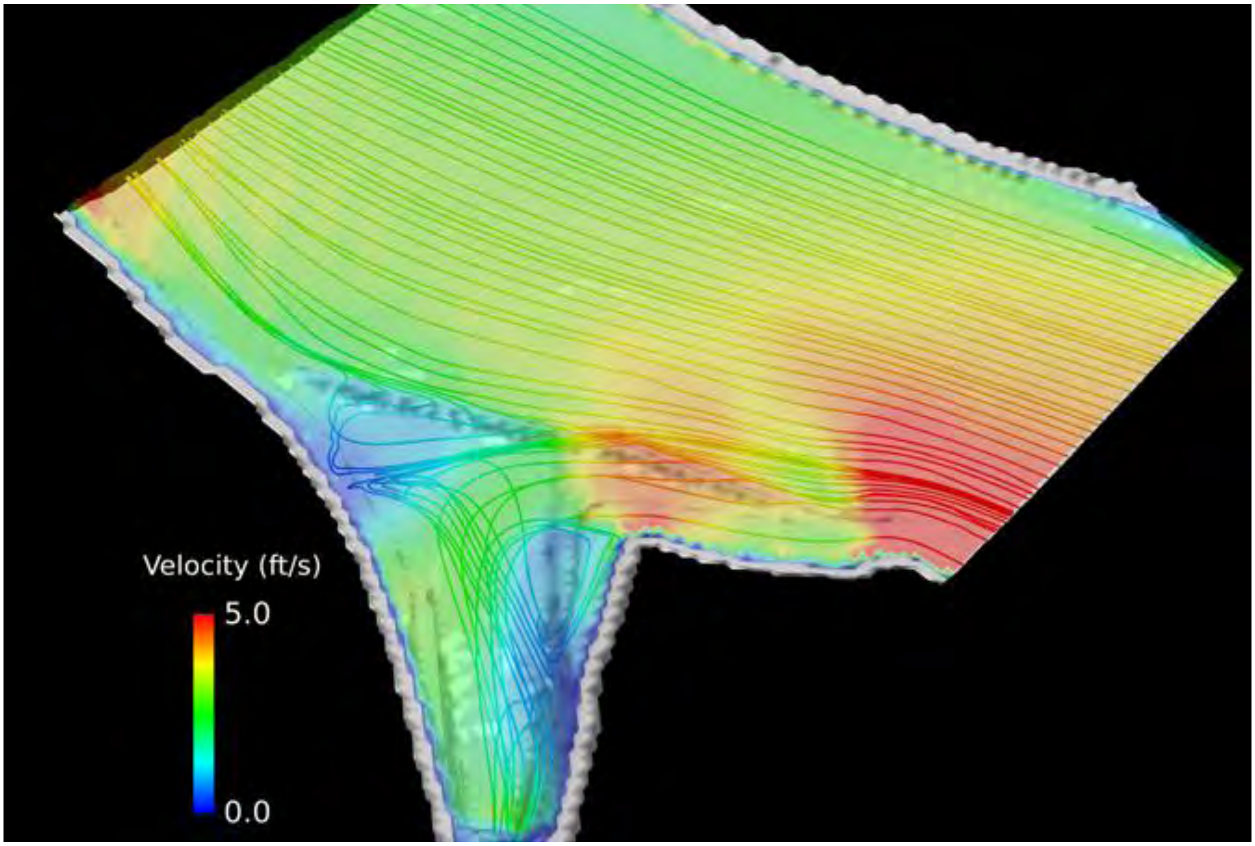


Sediment Exclusion Structure 1 Case A



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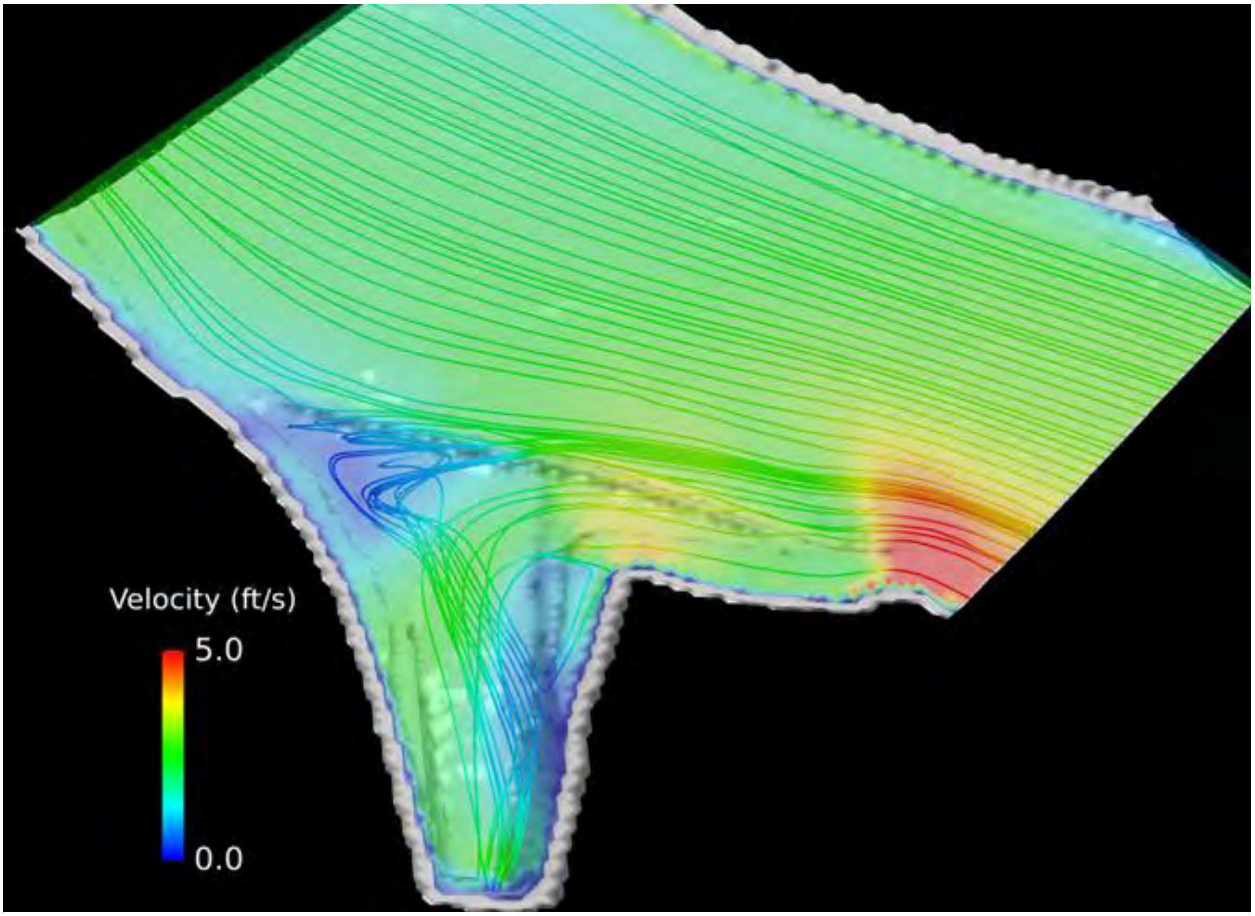

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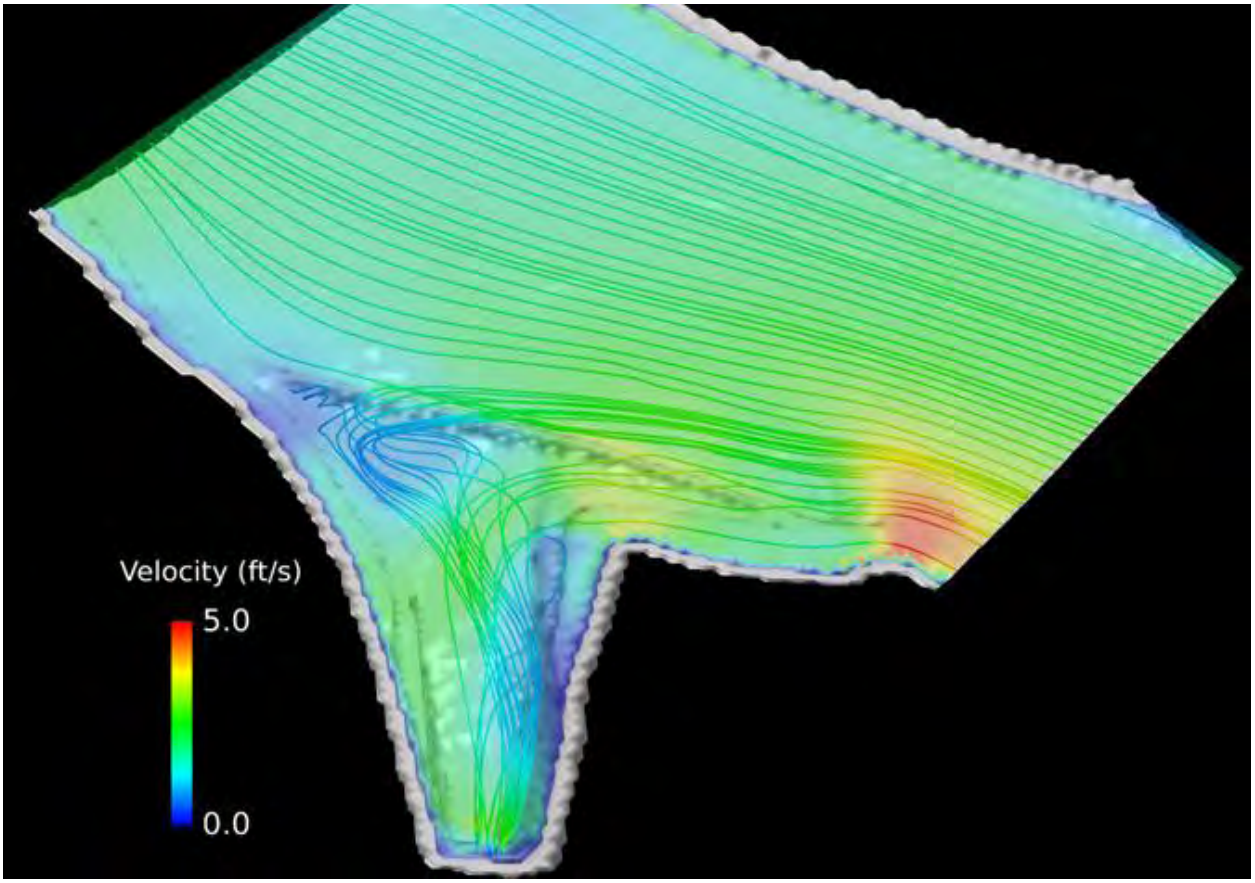

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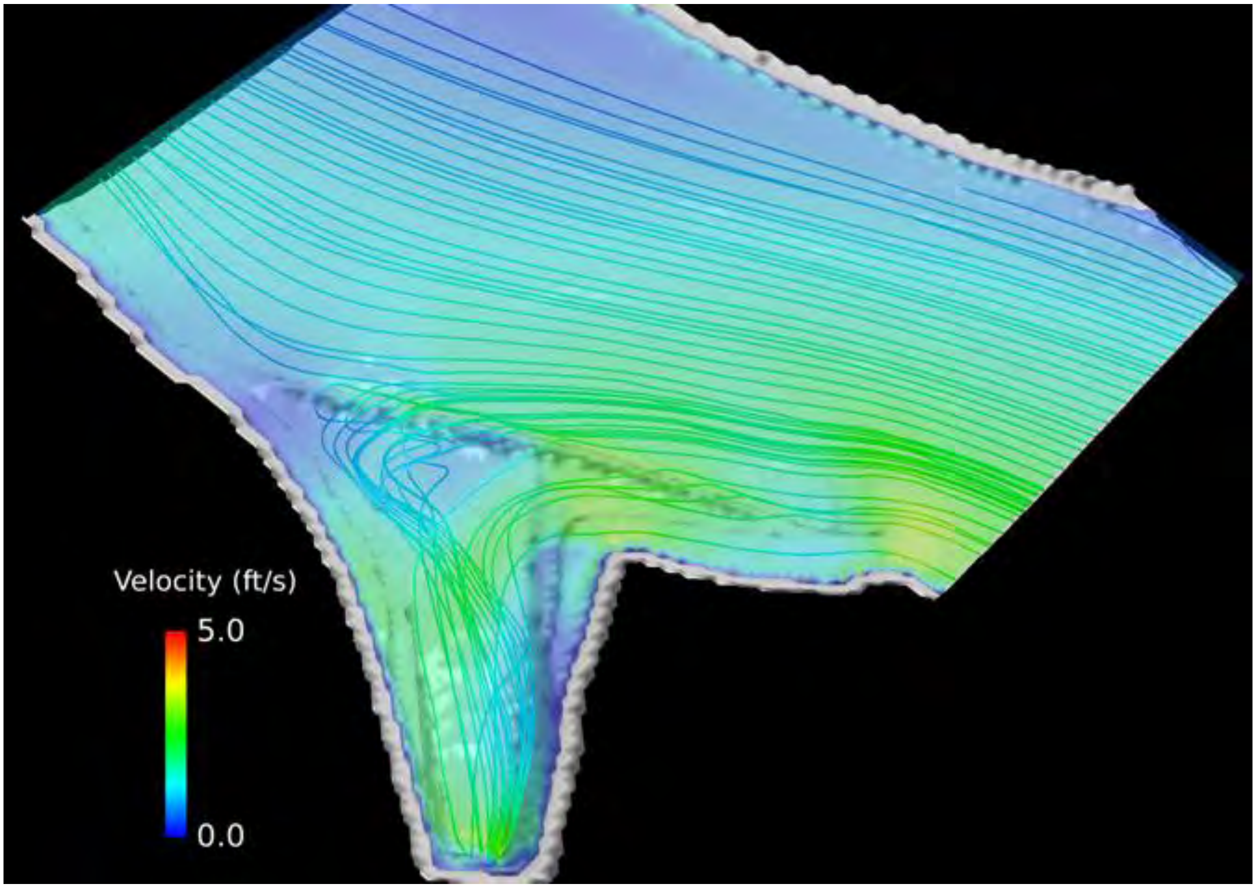

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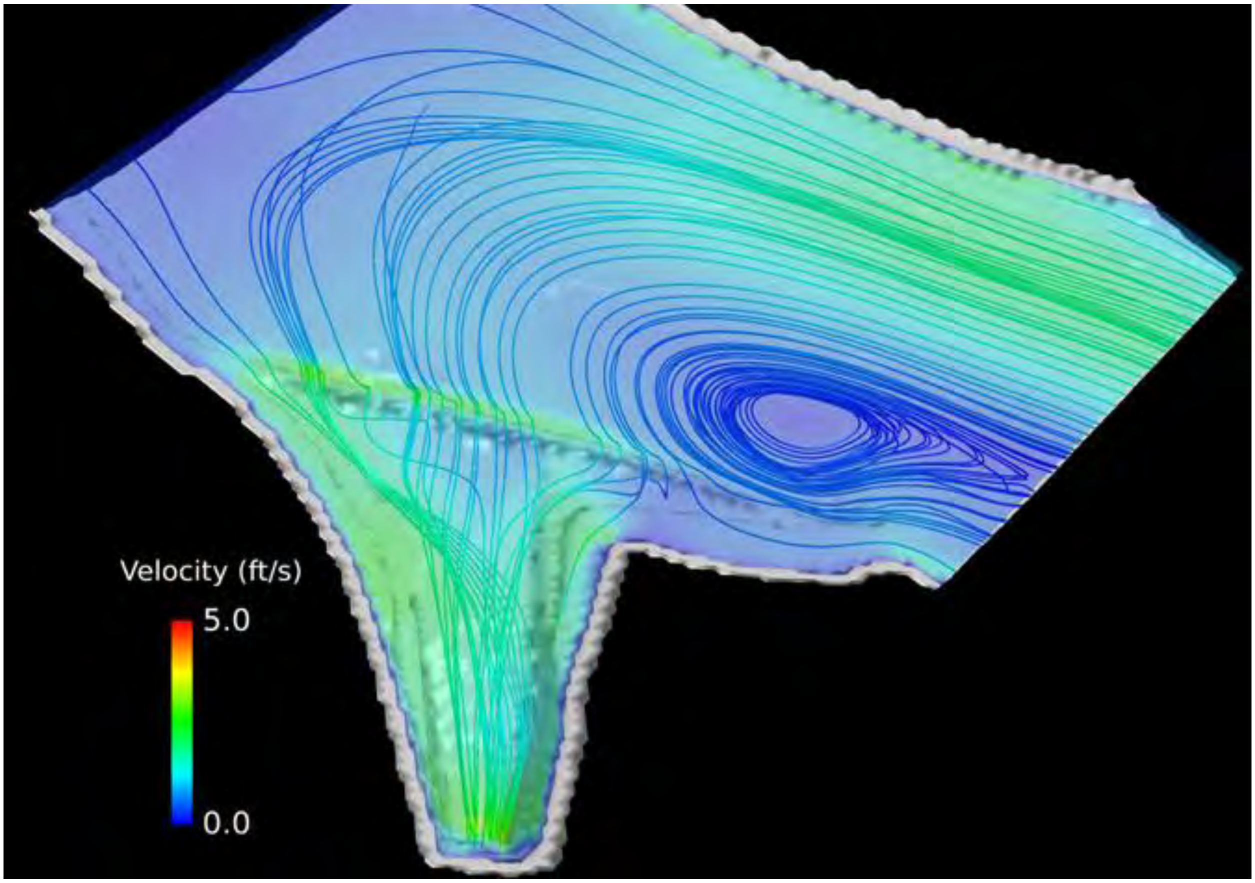

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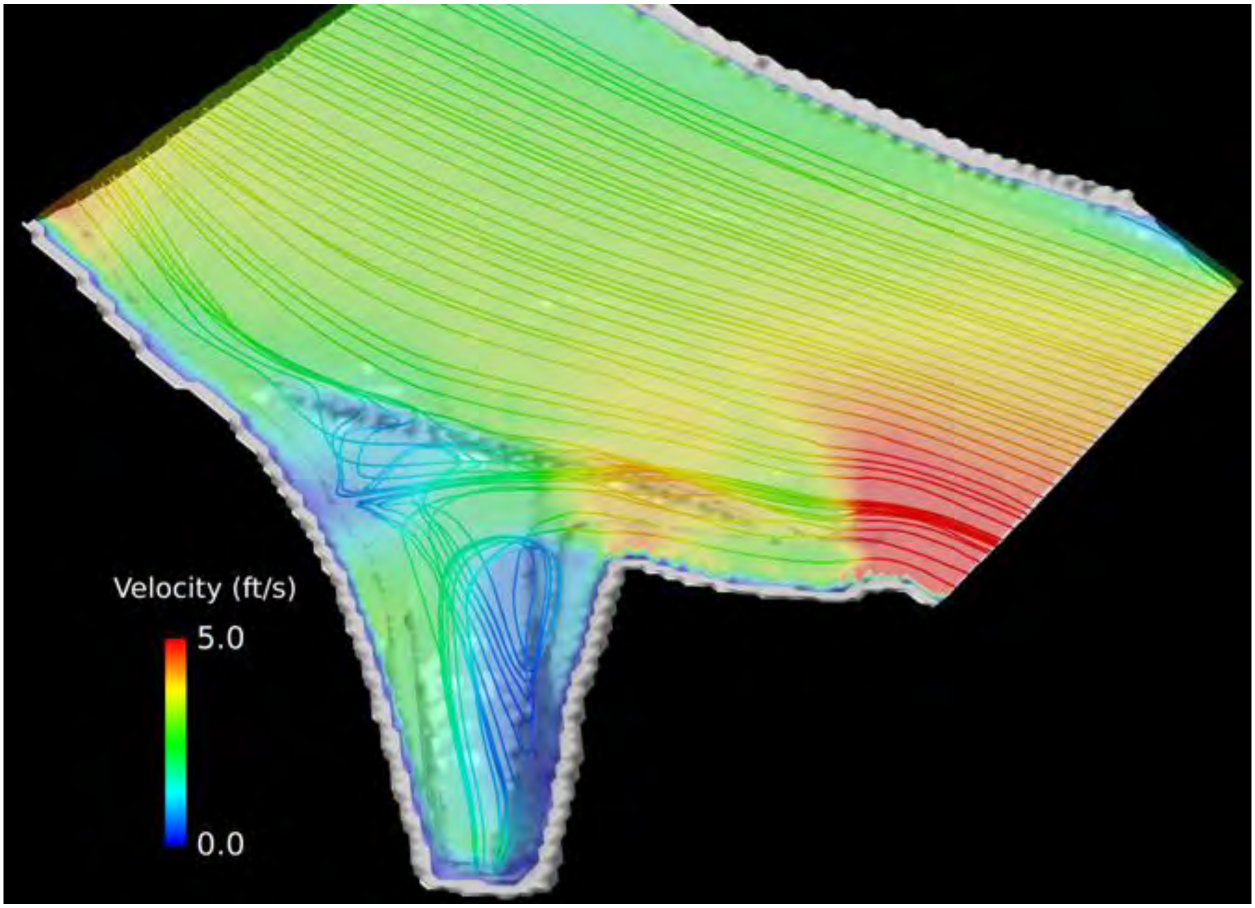

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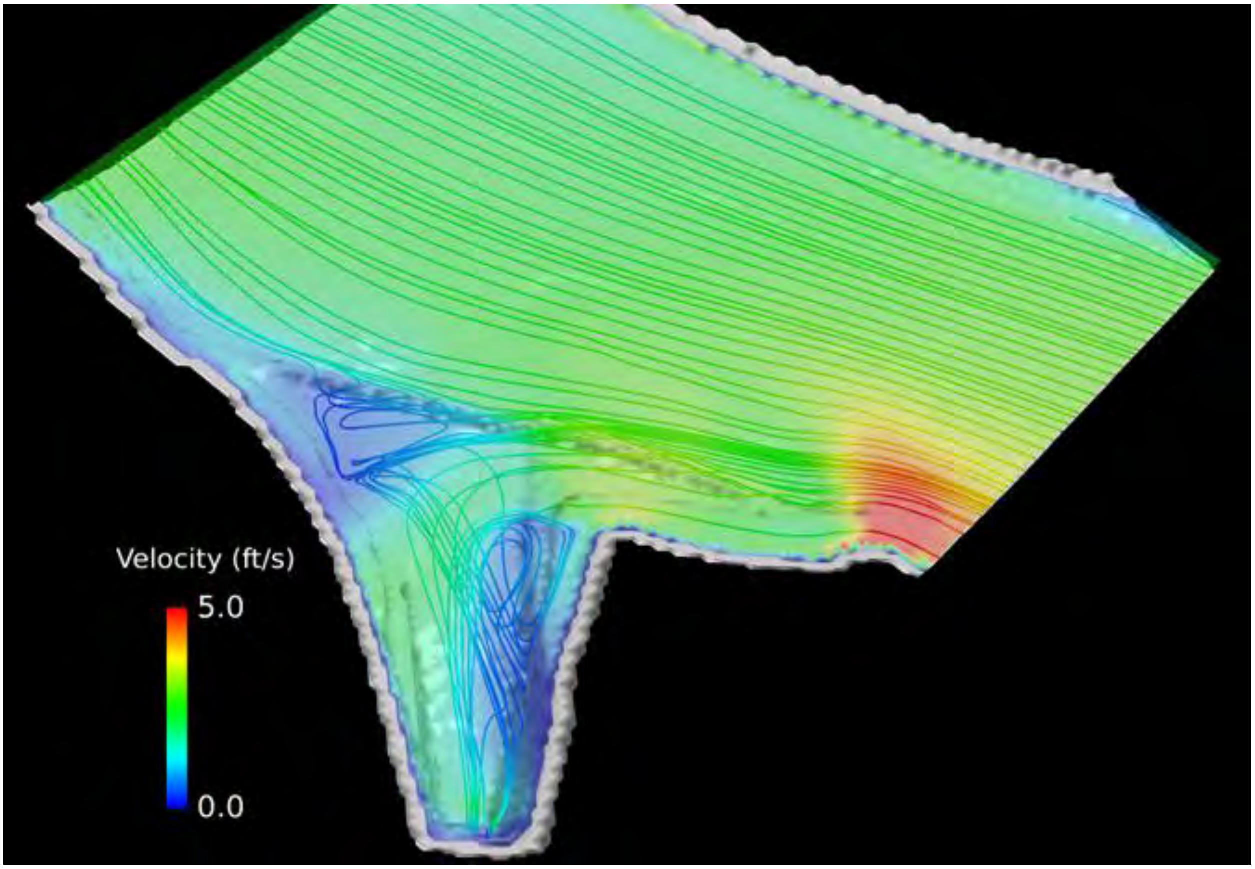

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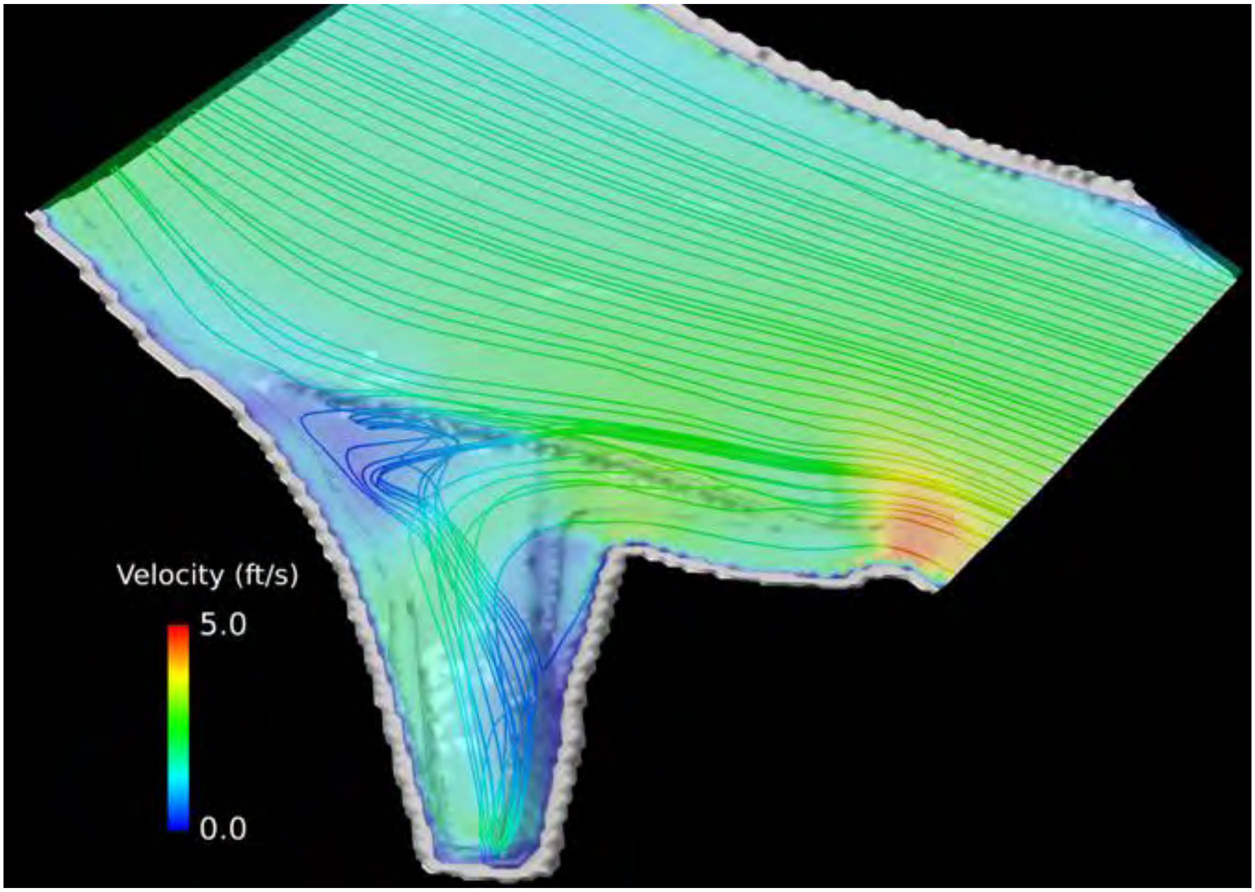

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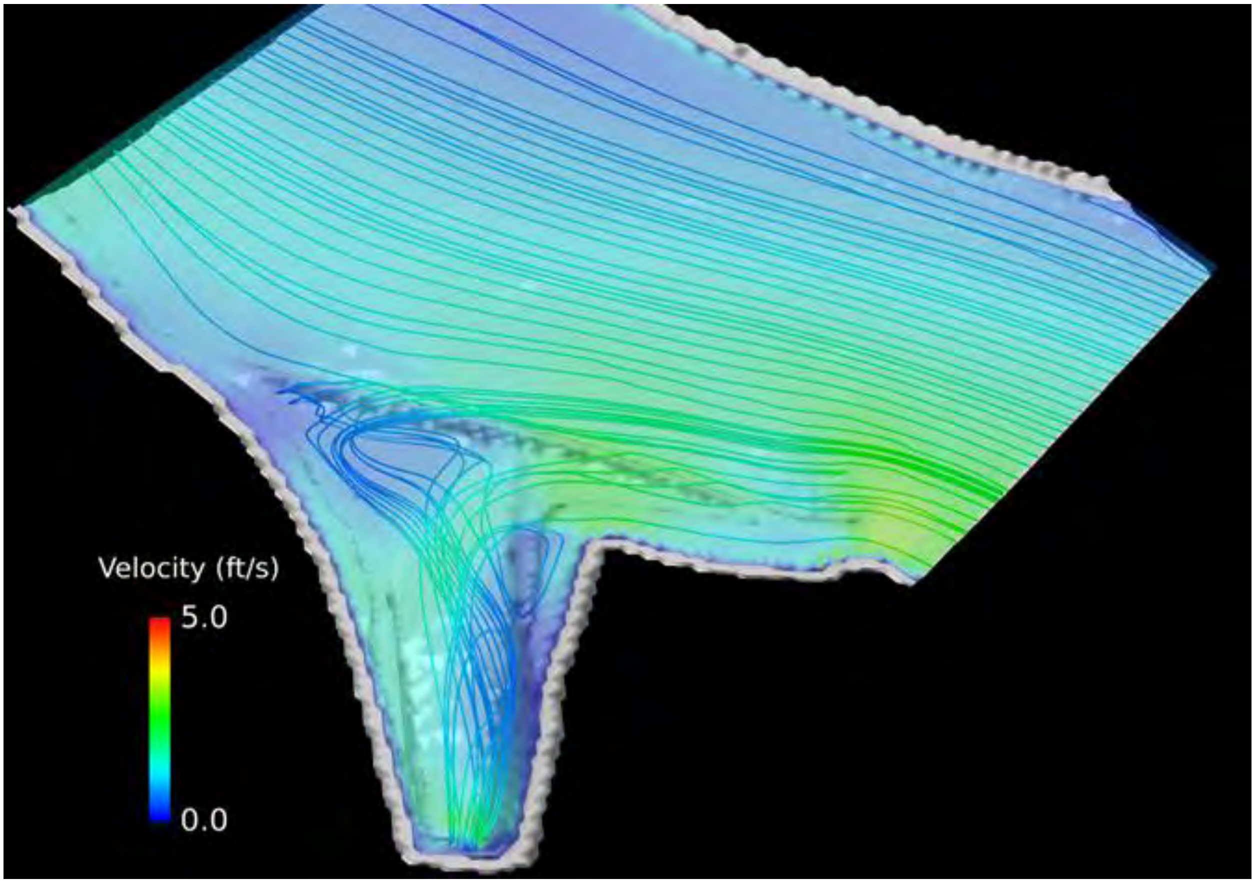

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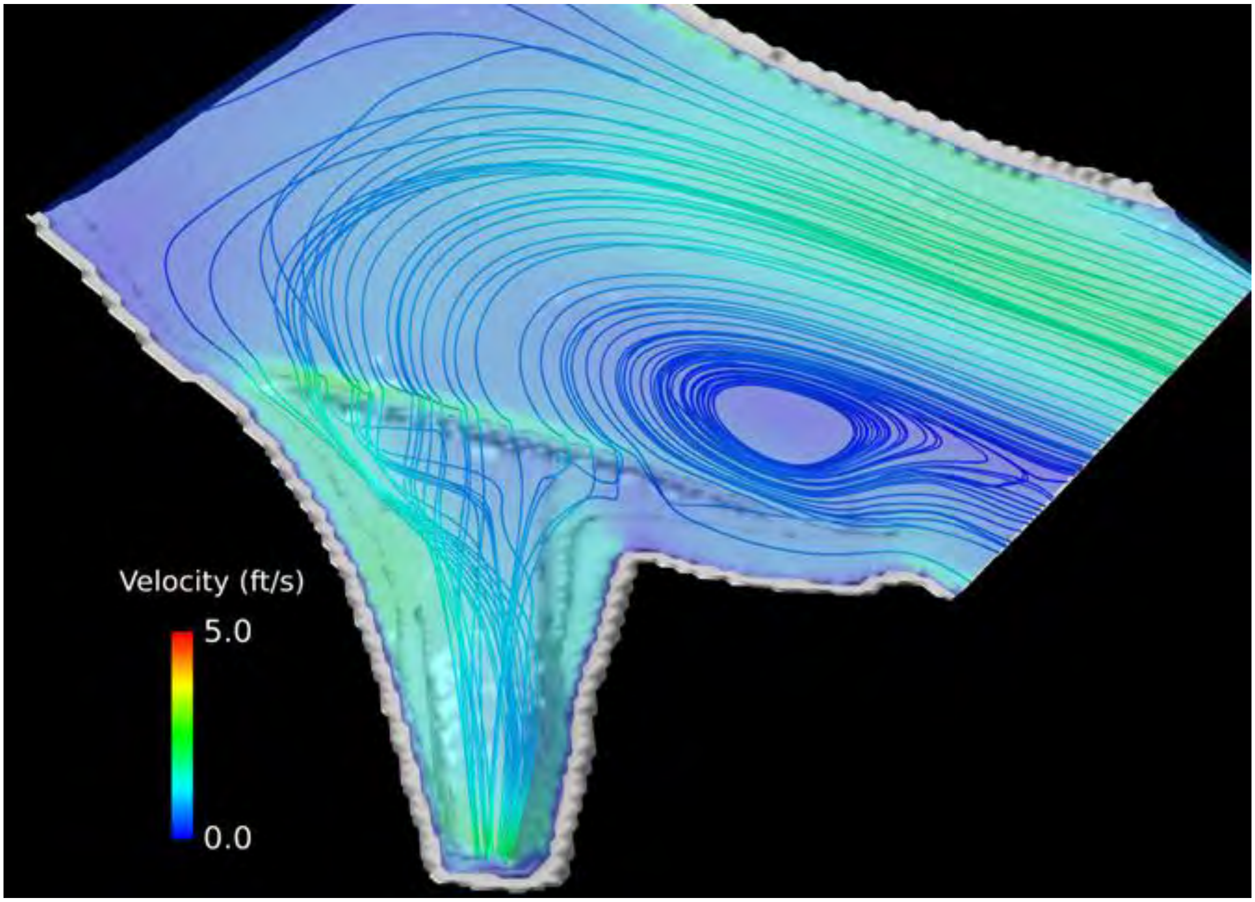

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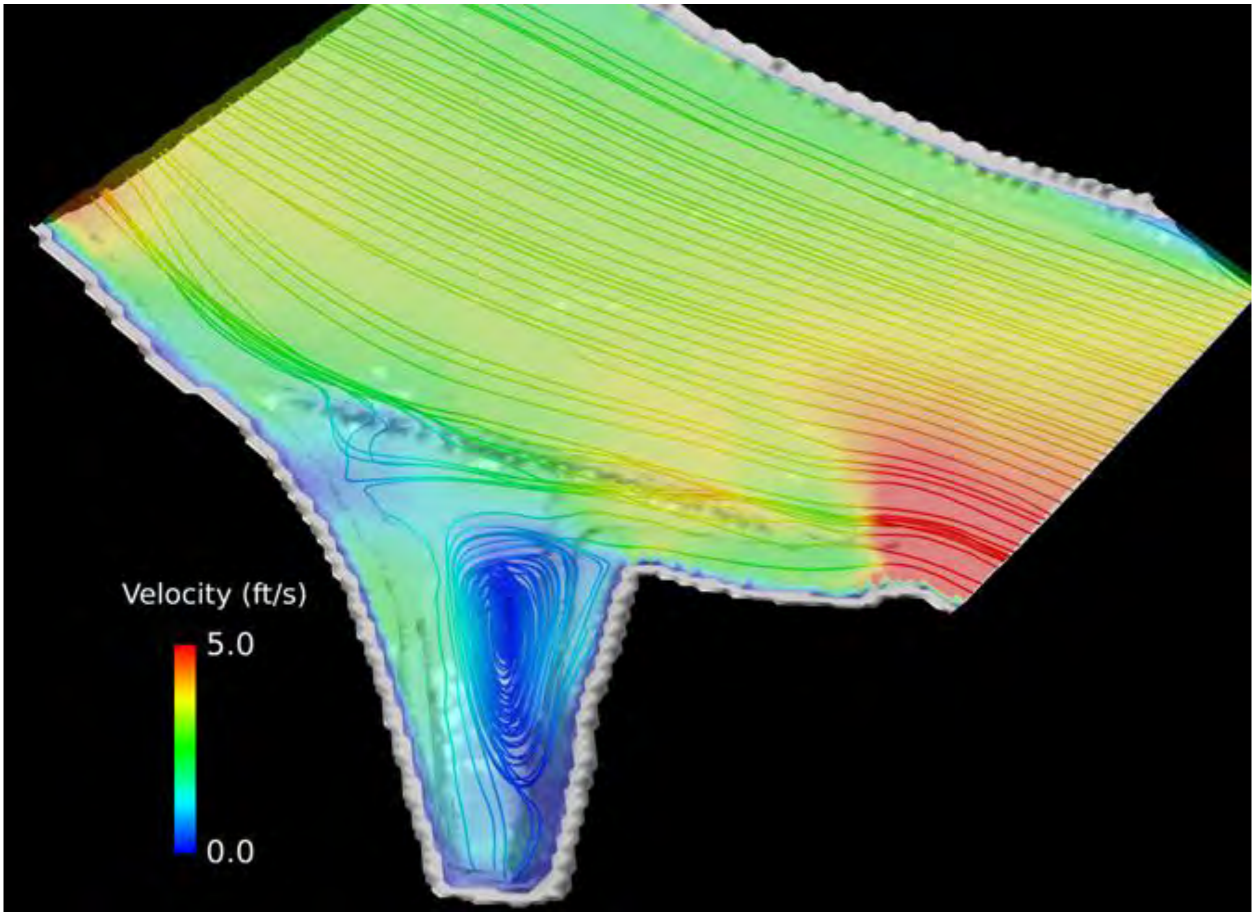

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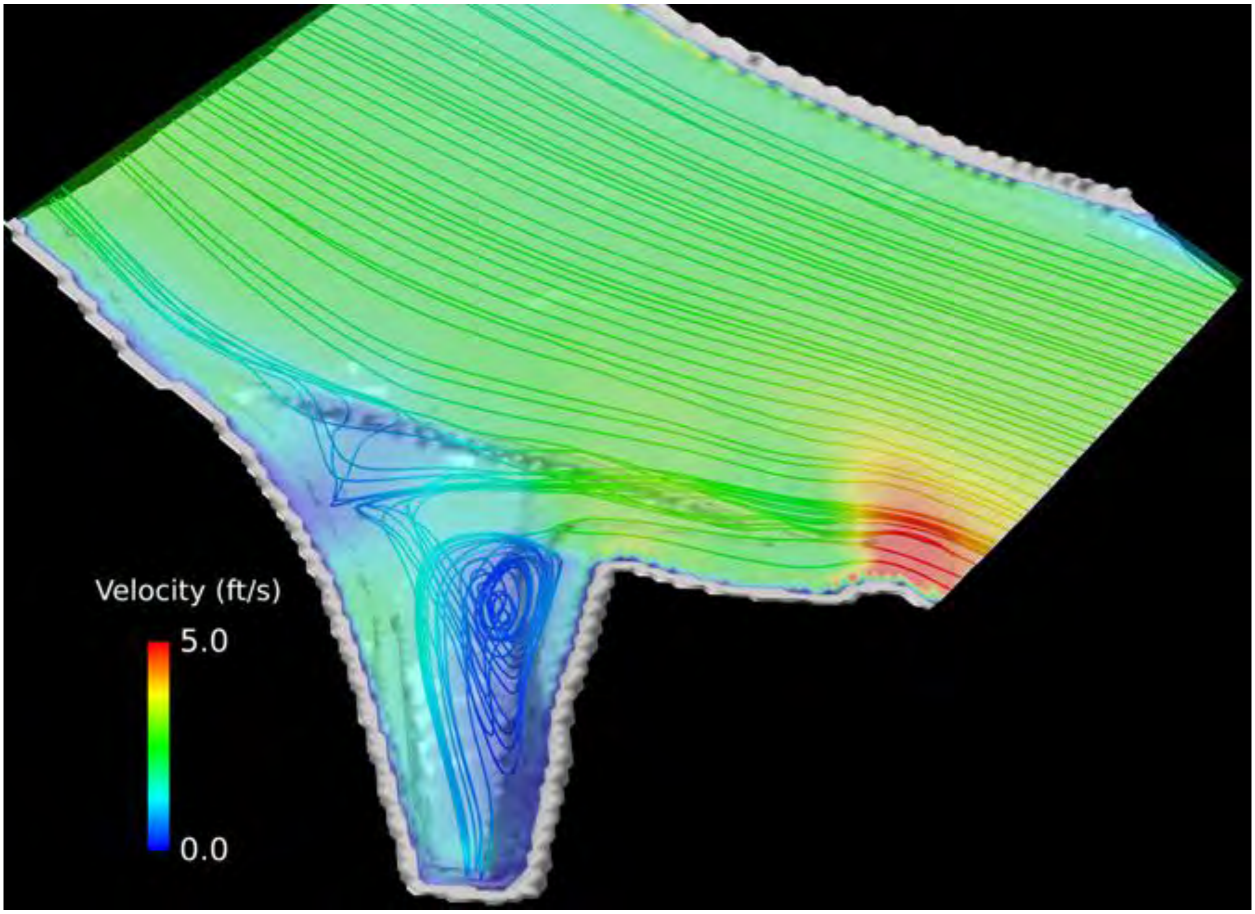

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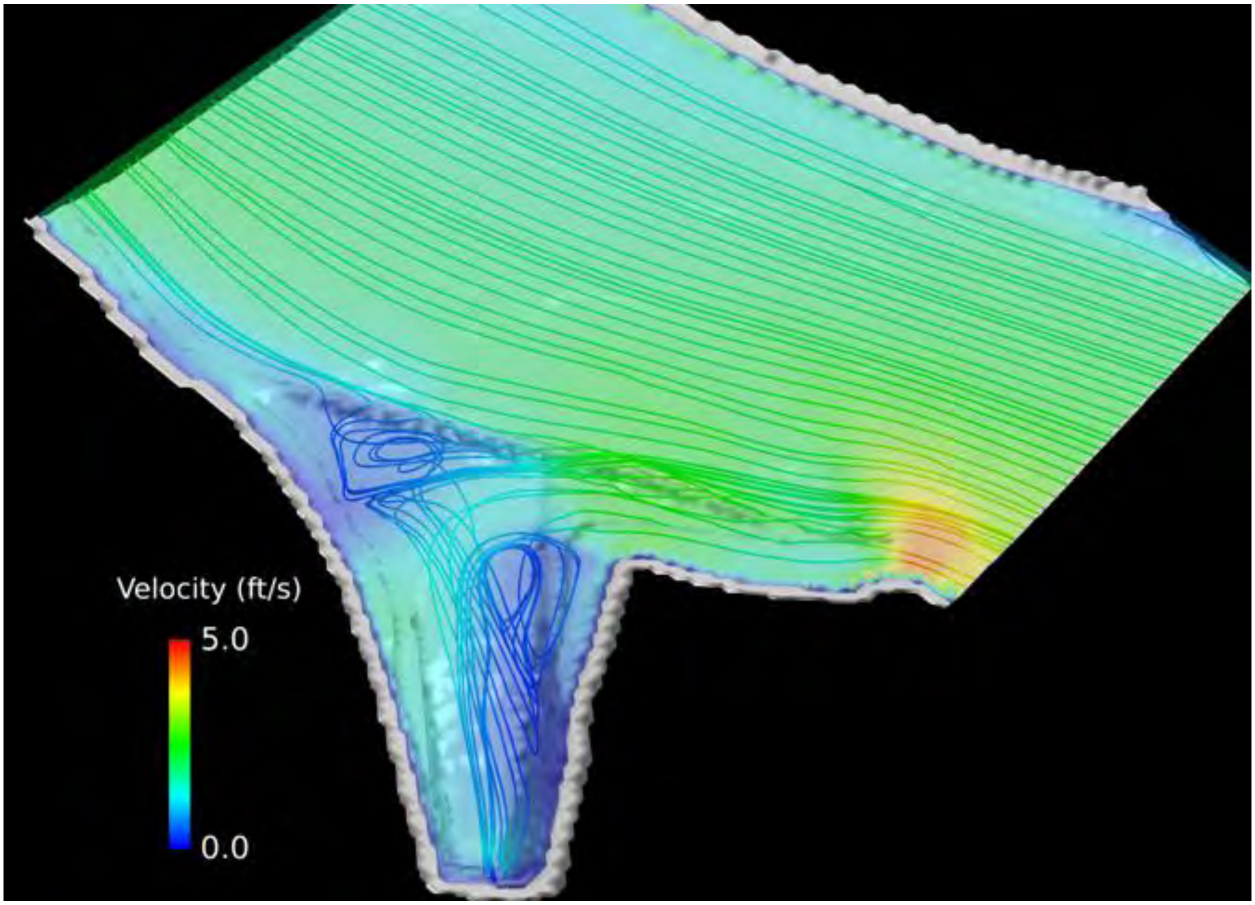

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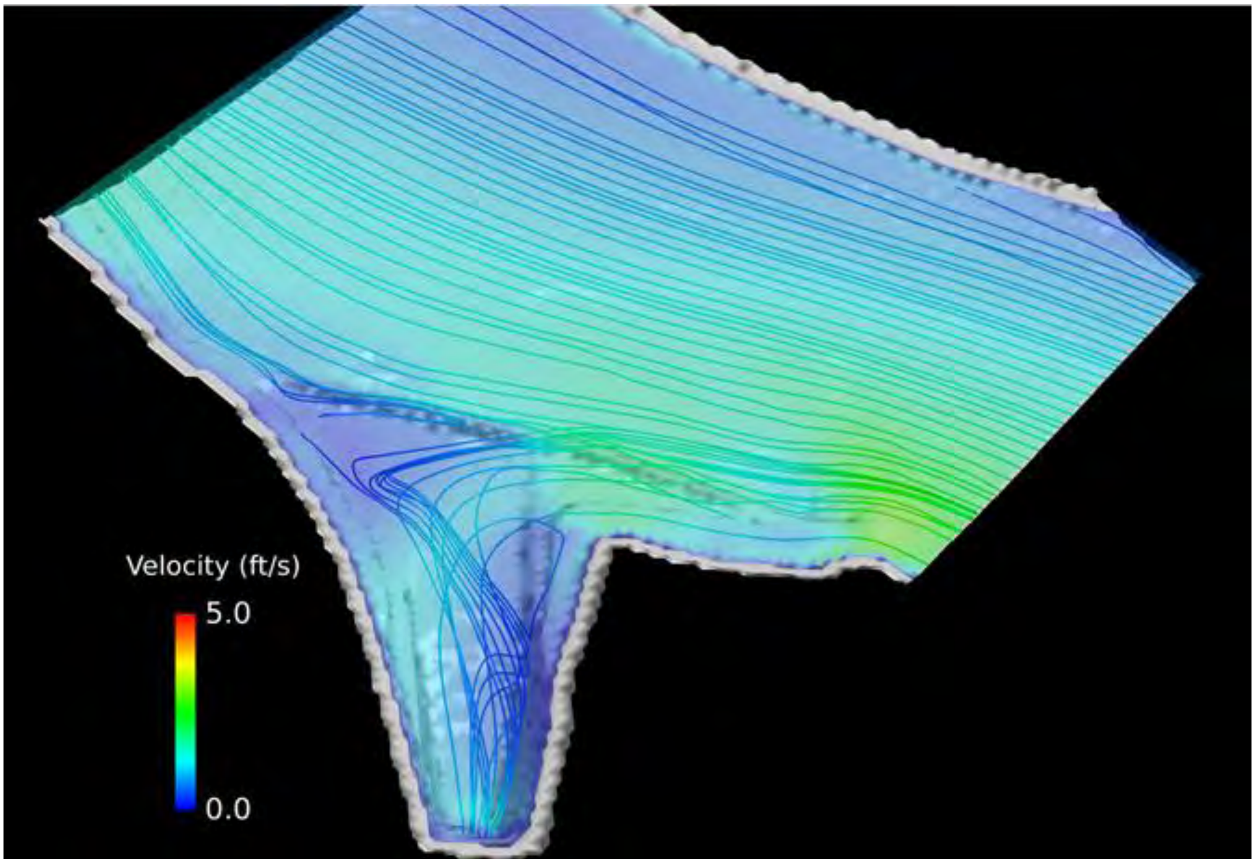

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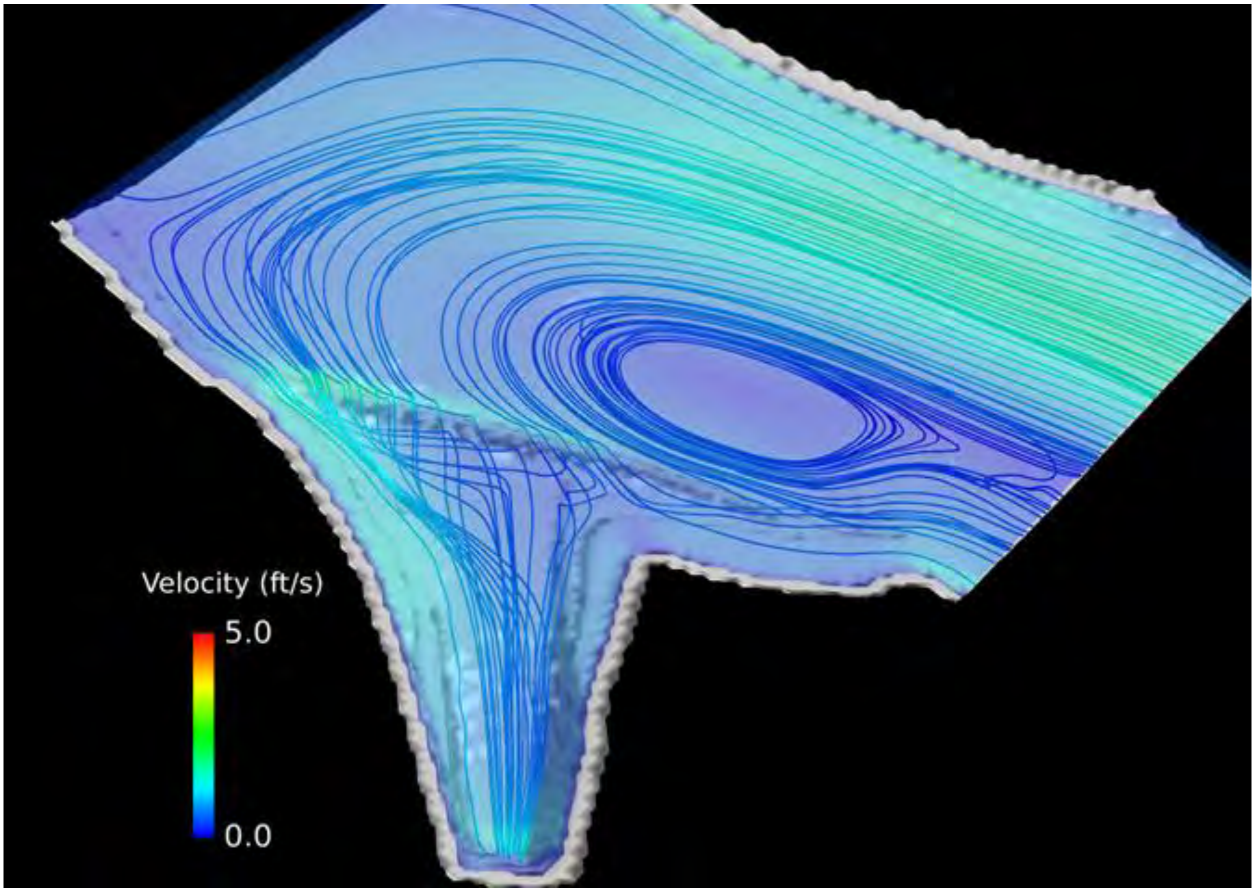

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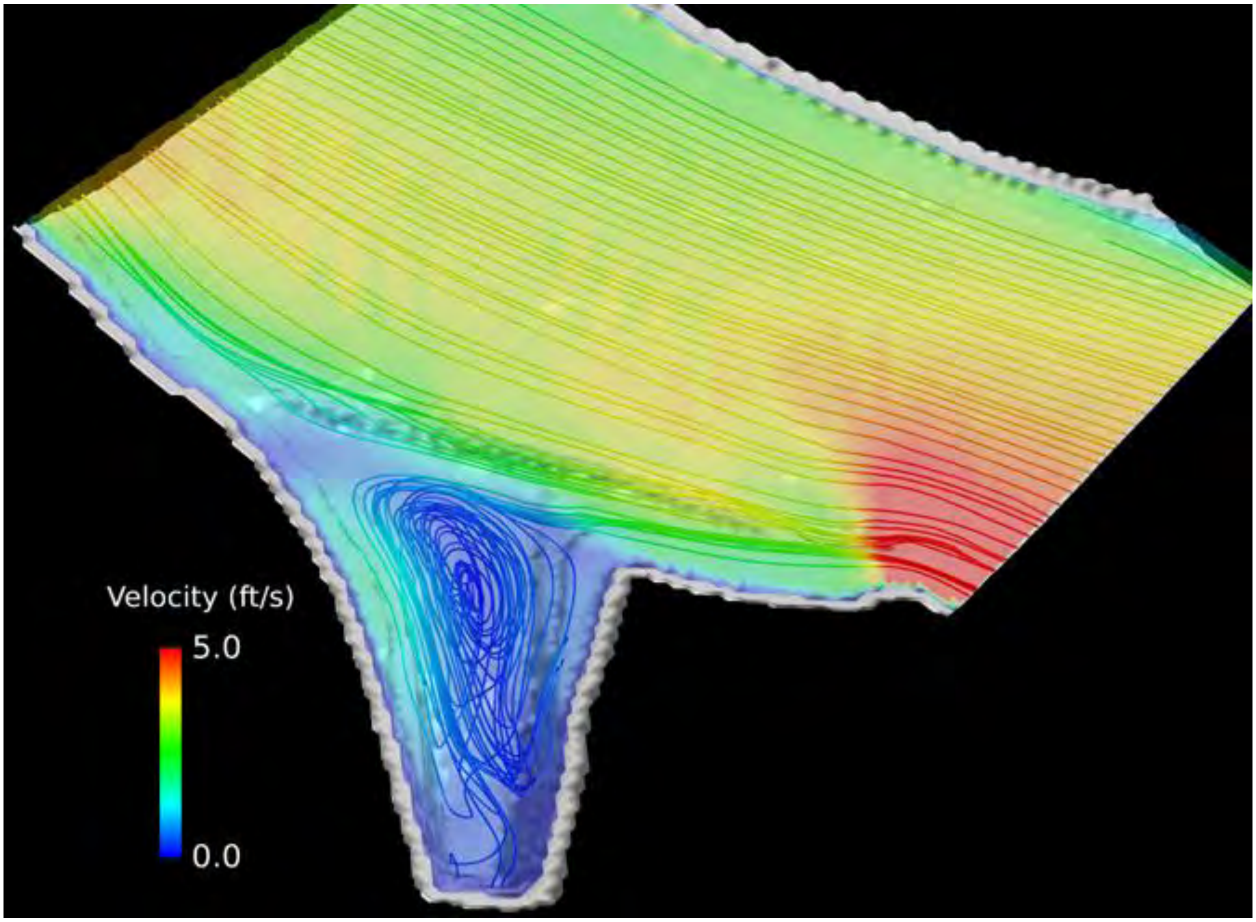

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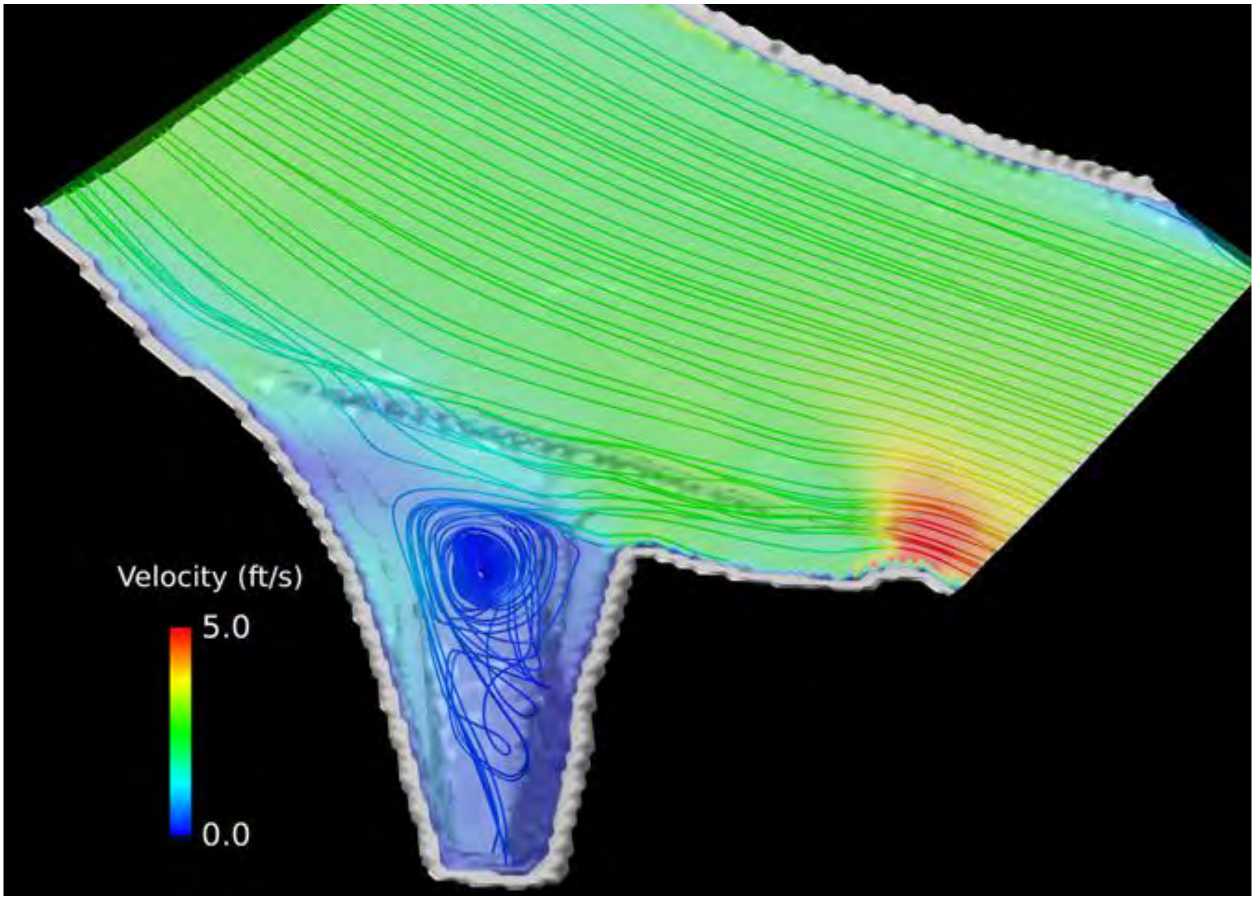

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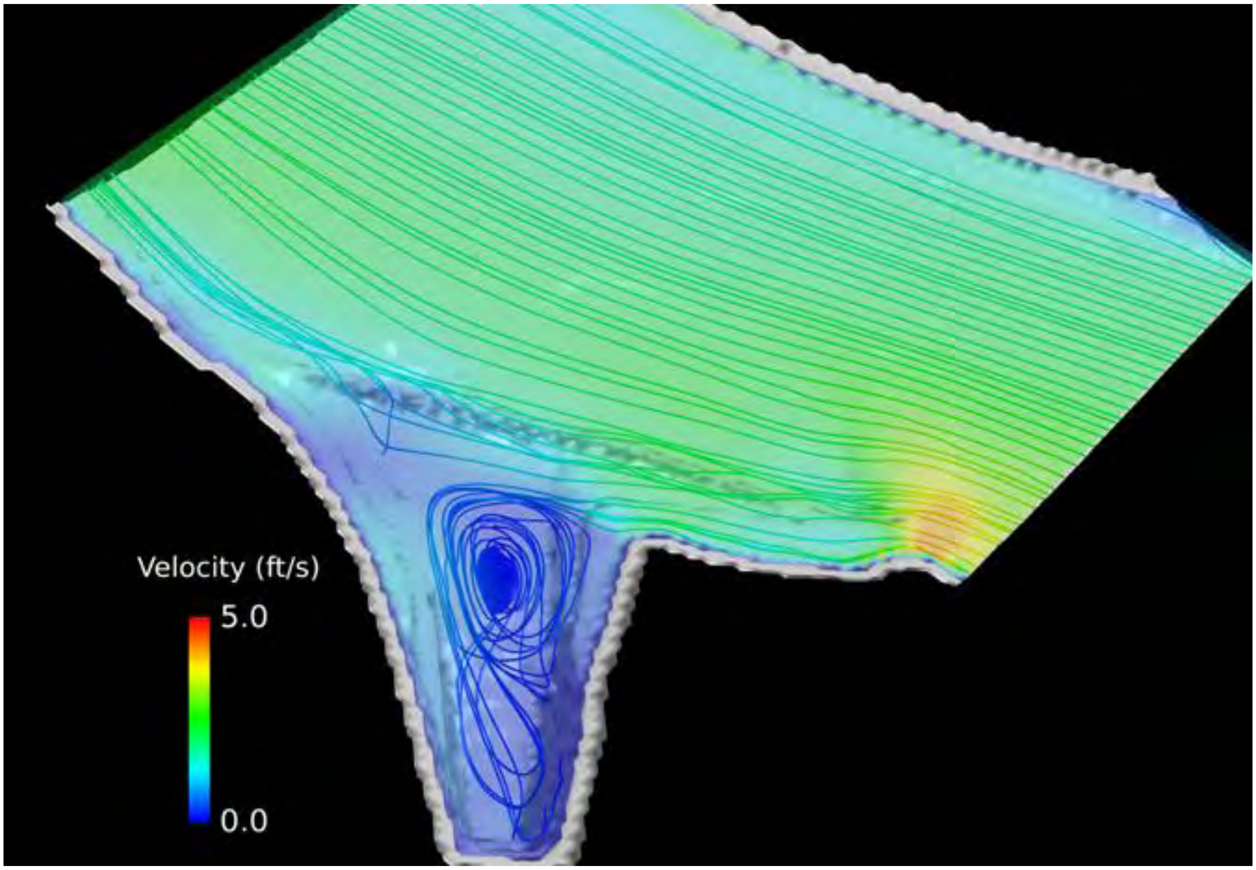

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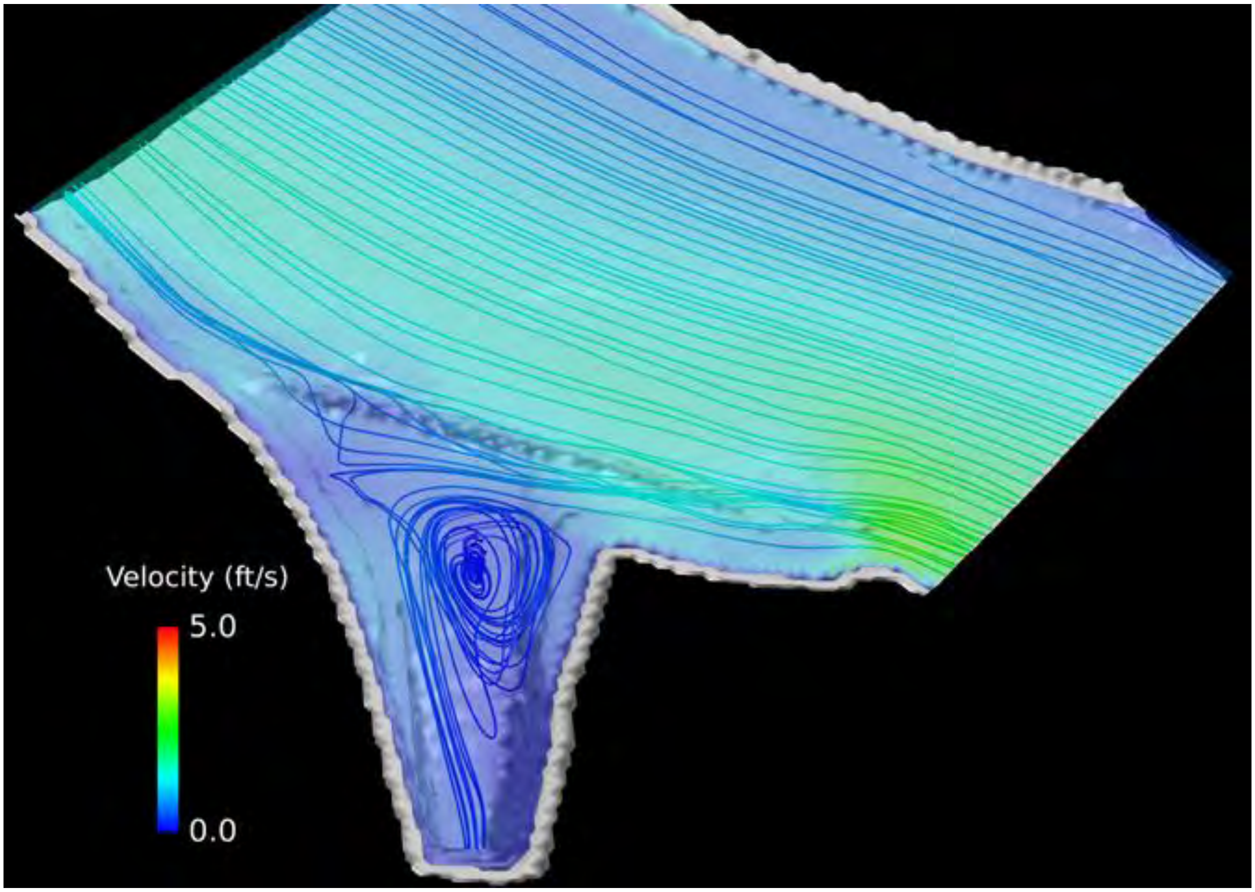

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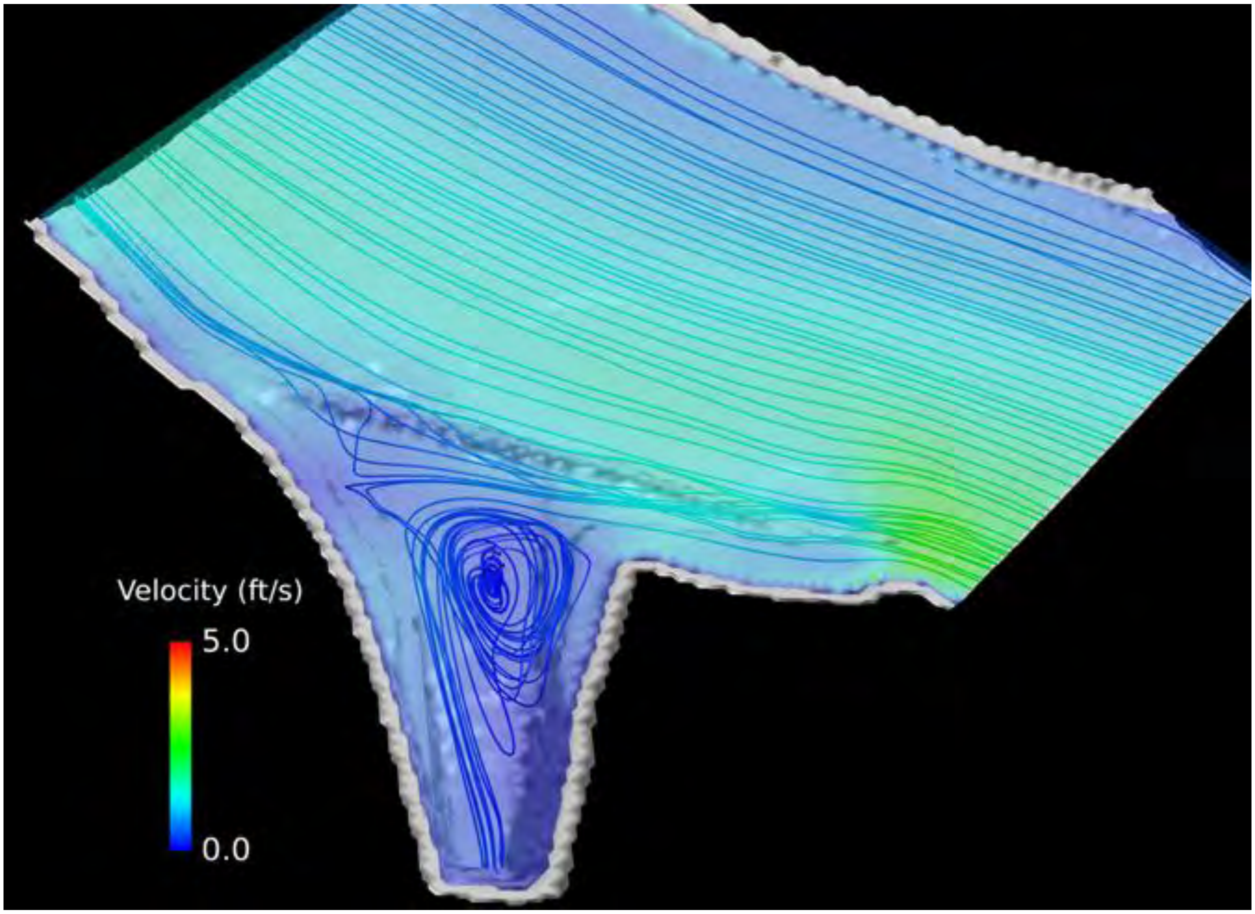

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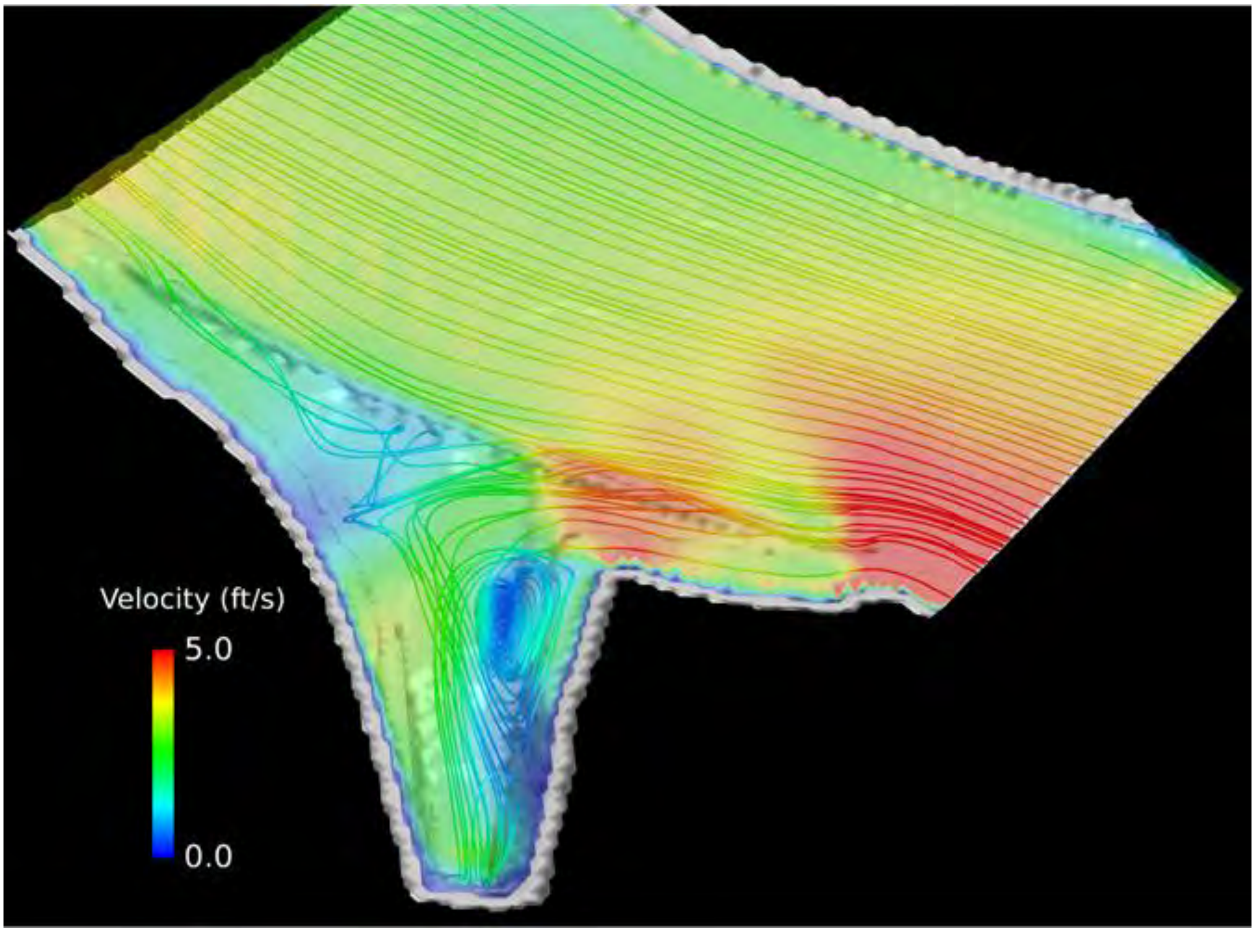

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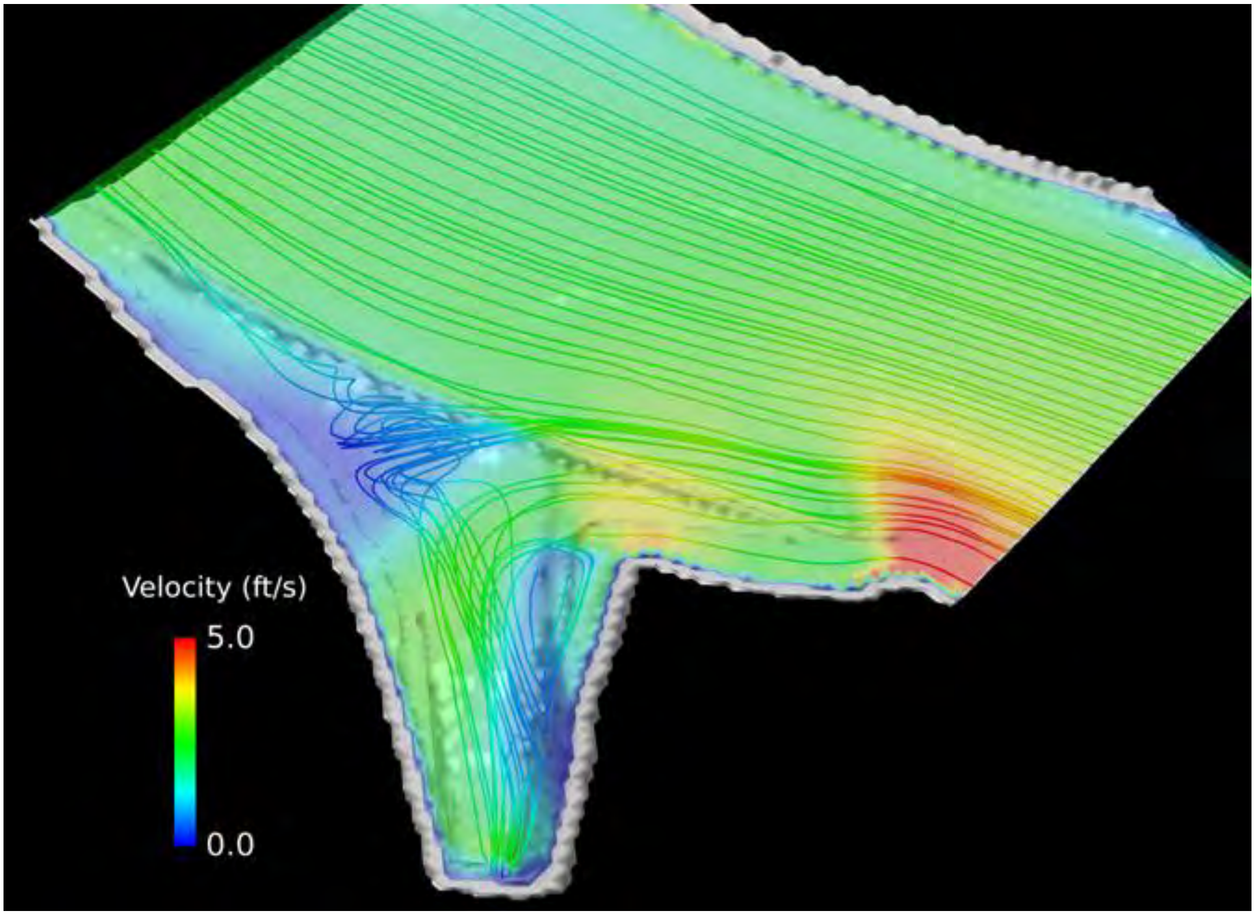

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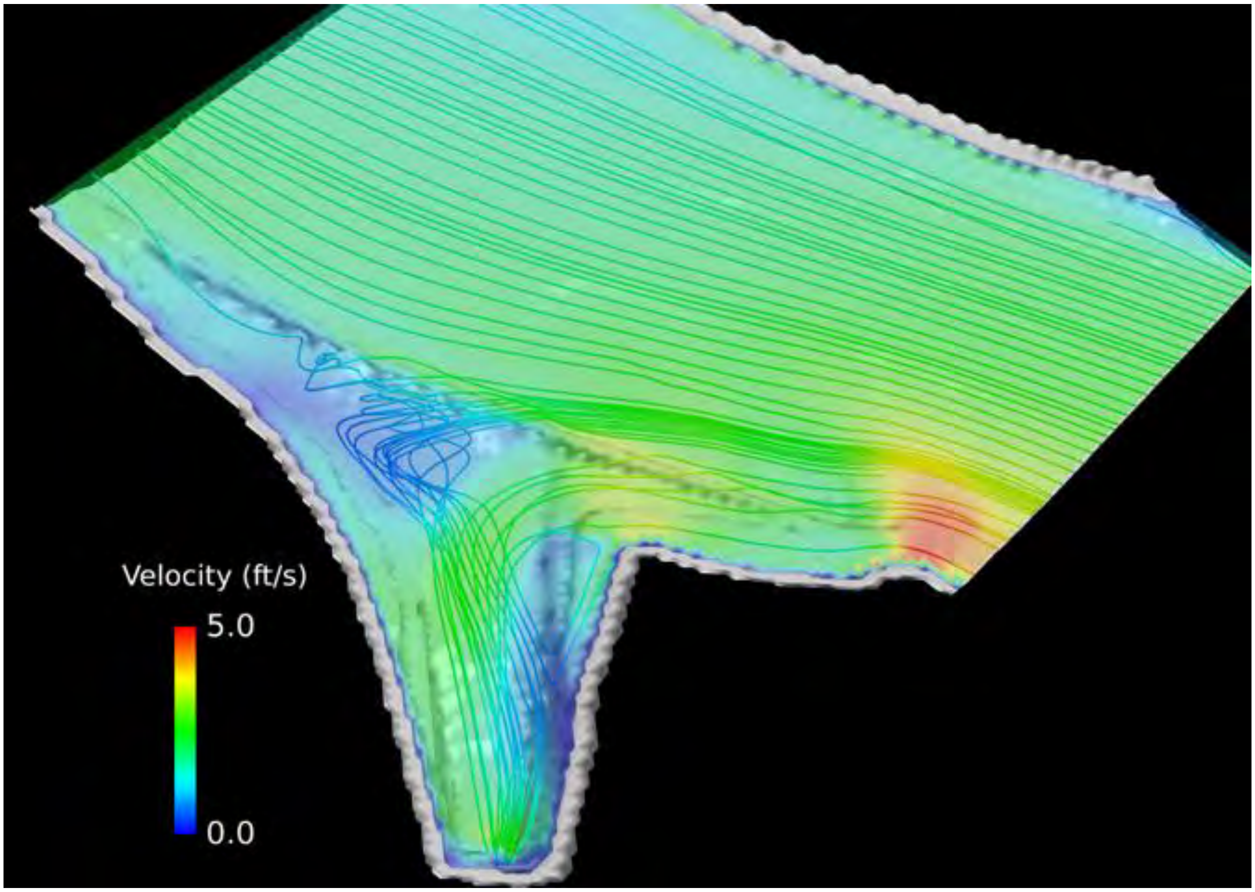

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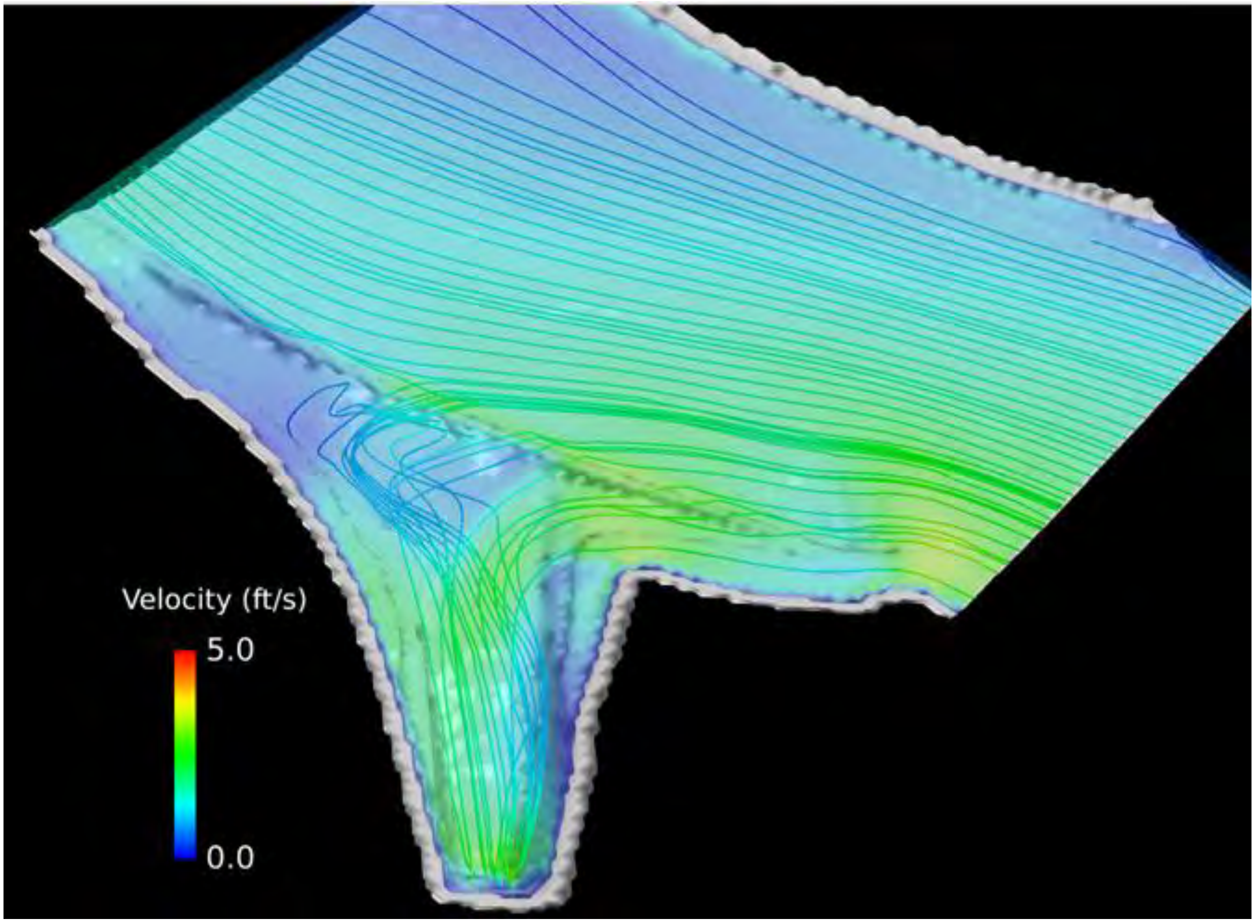

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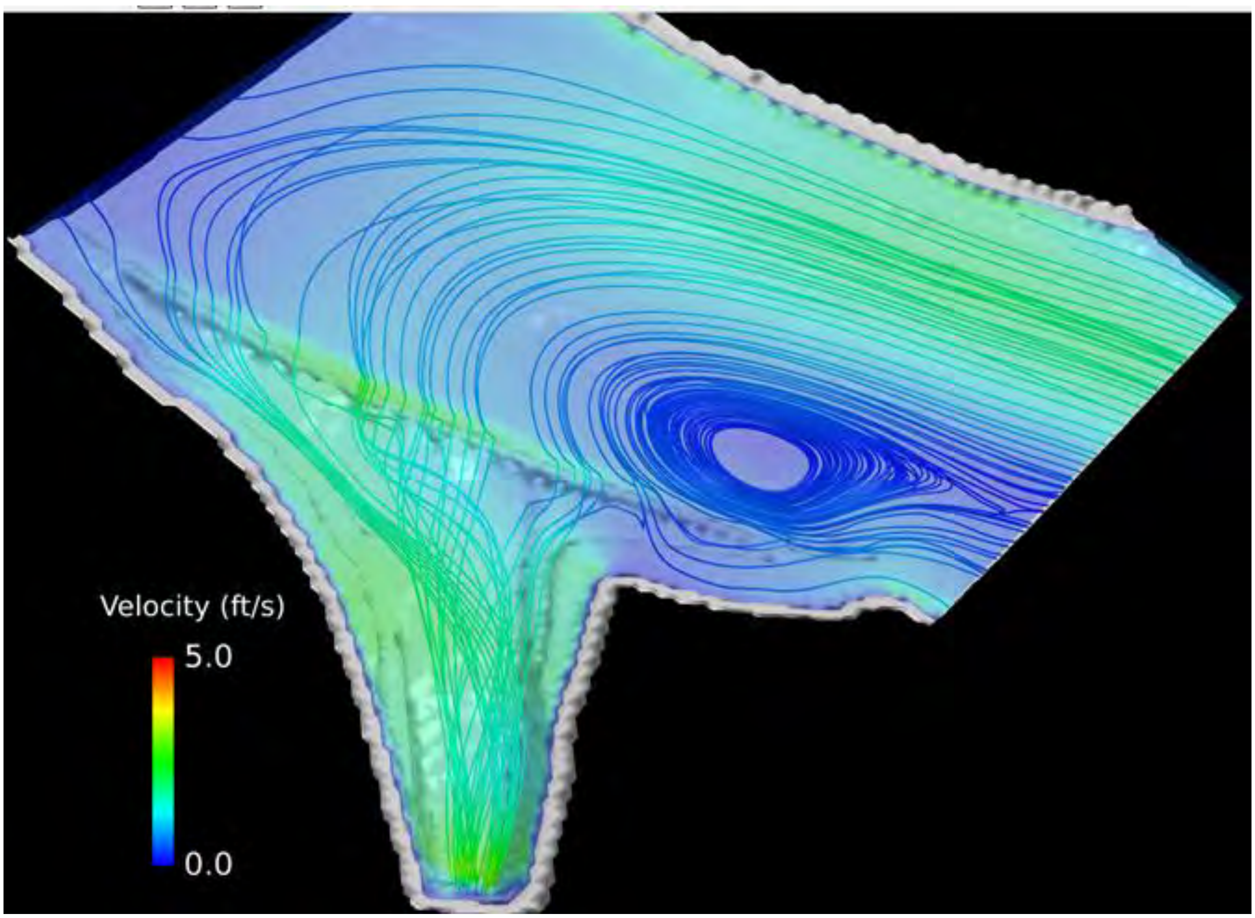

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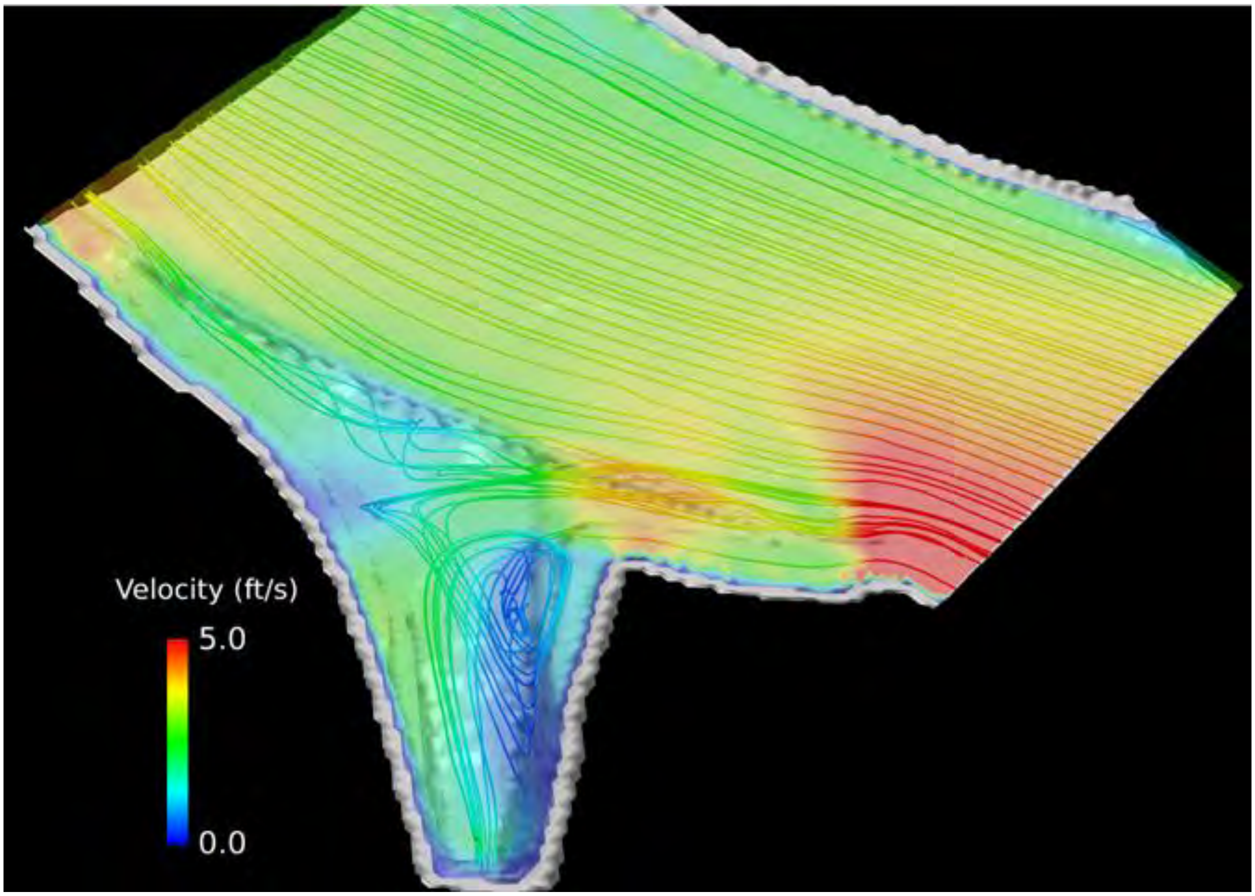

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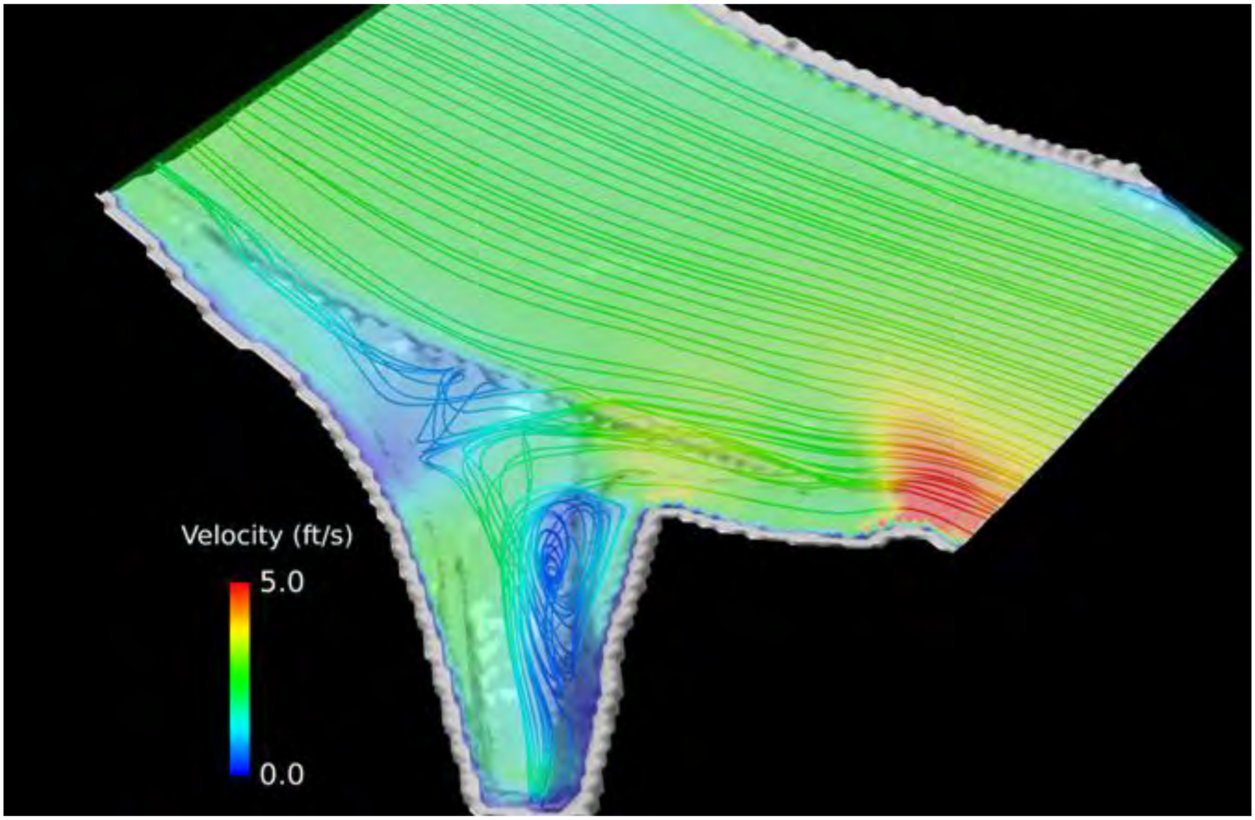

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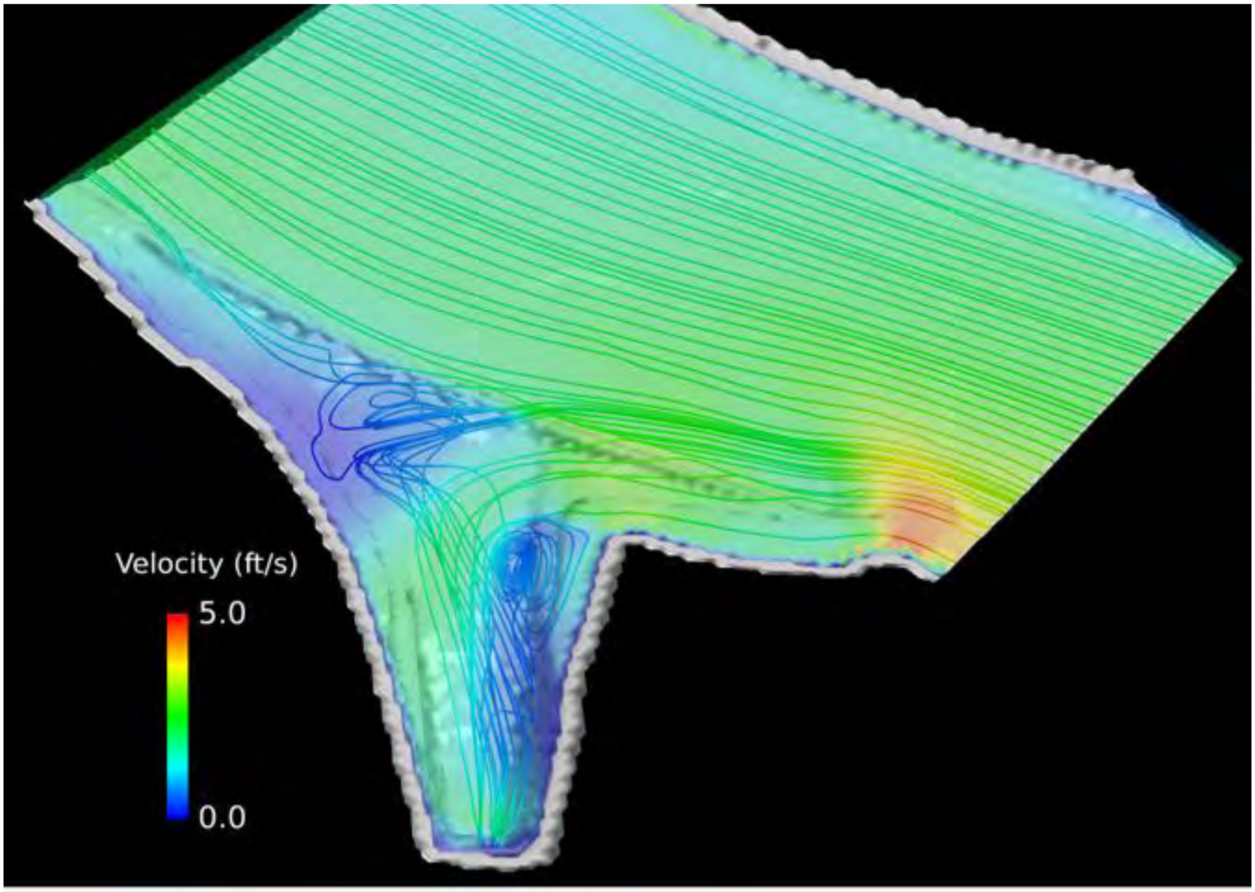

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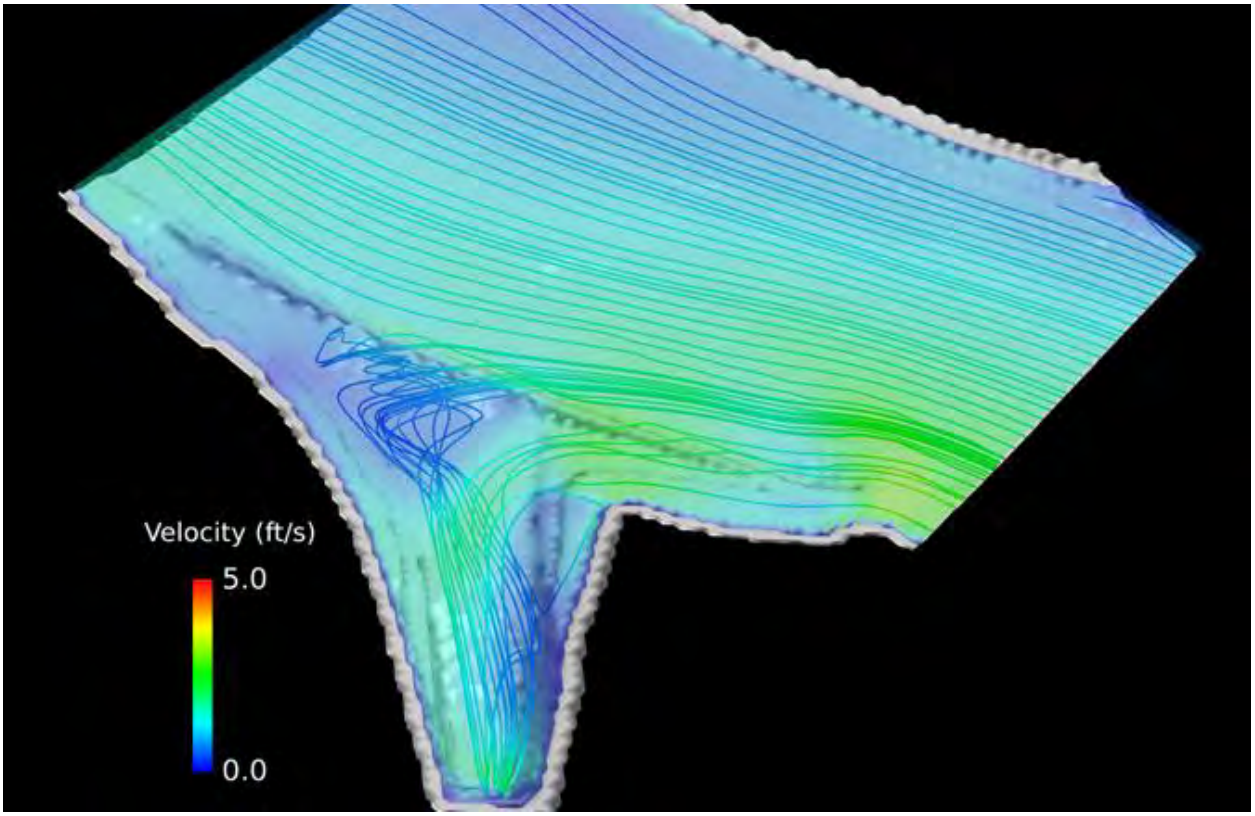

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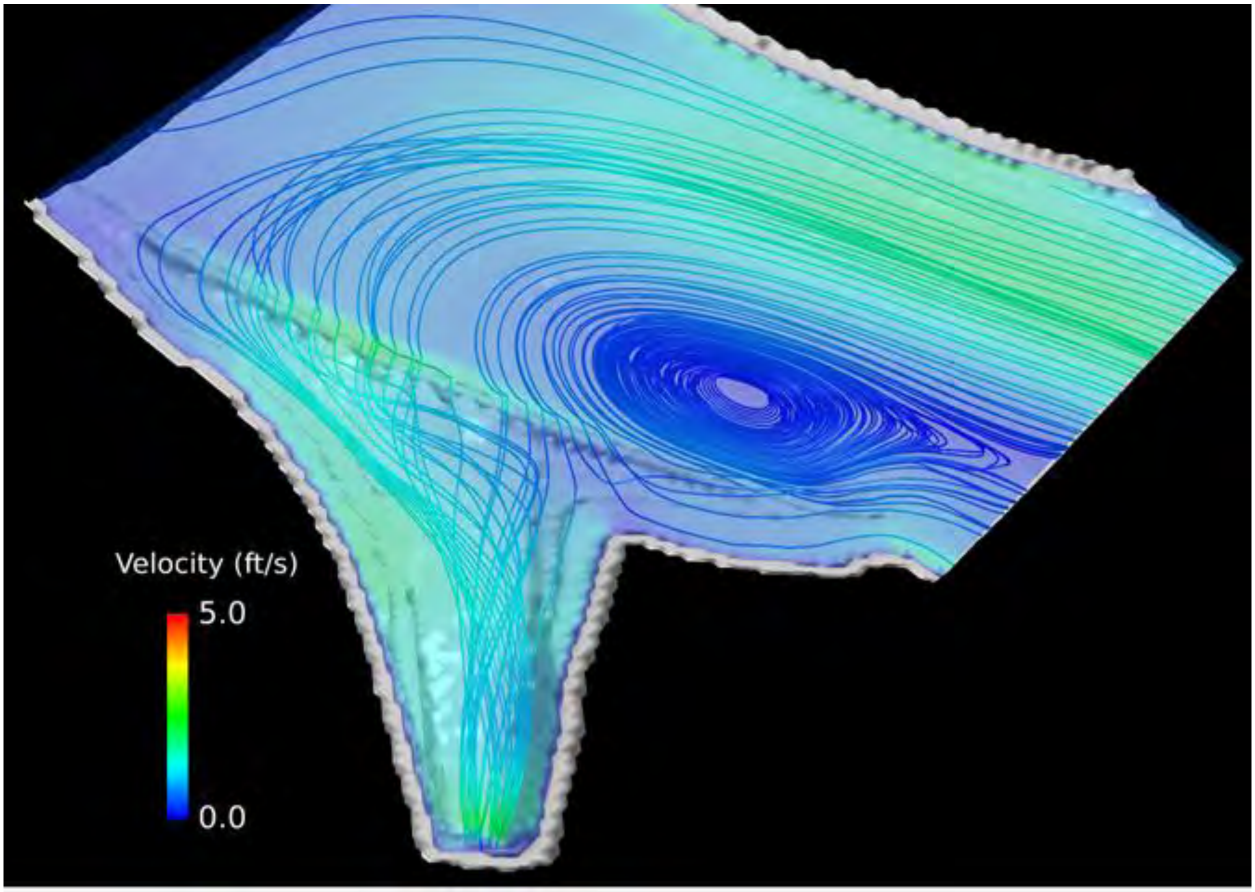

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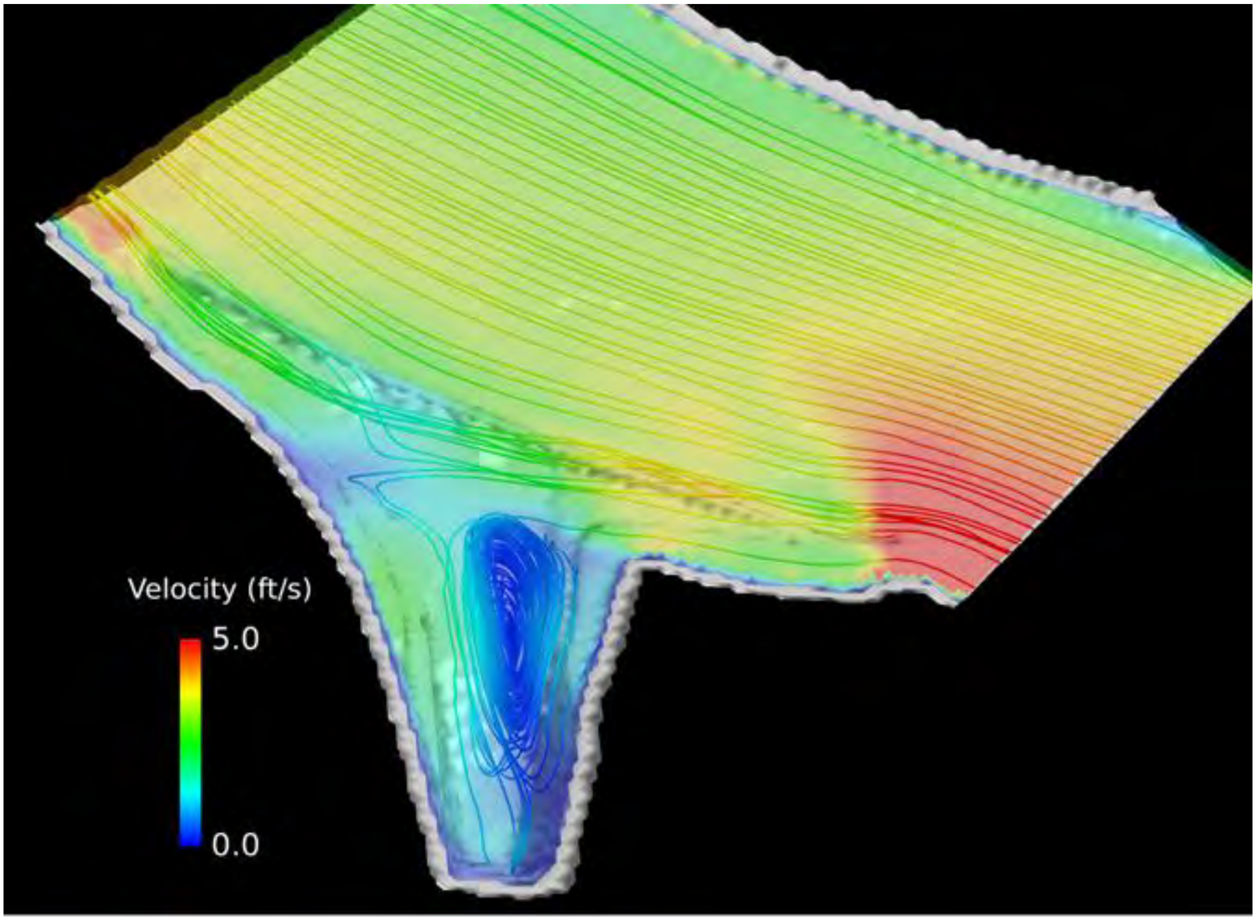

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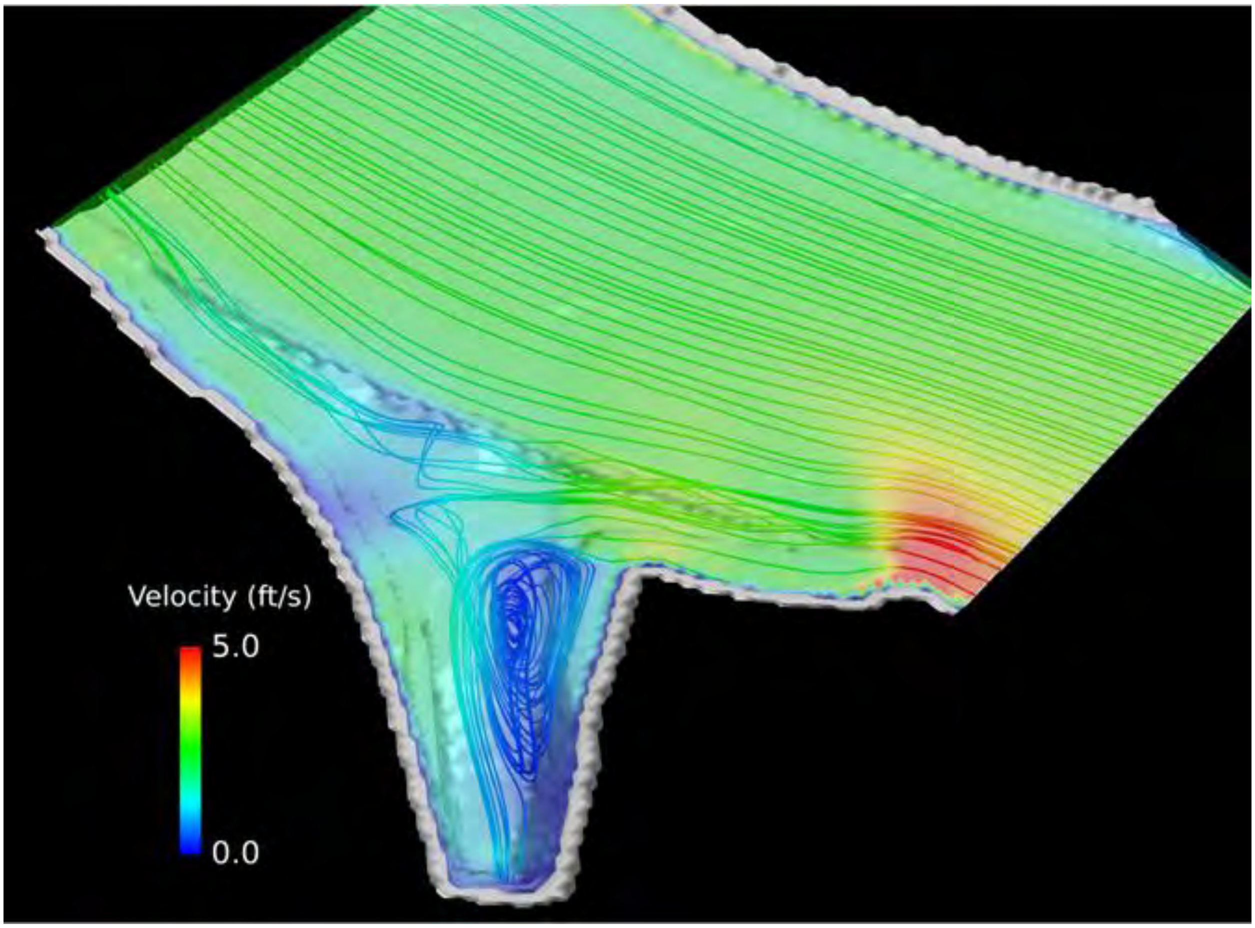

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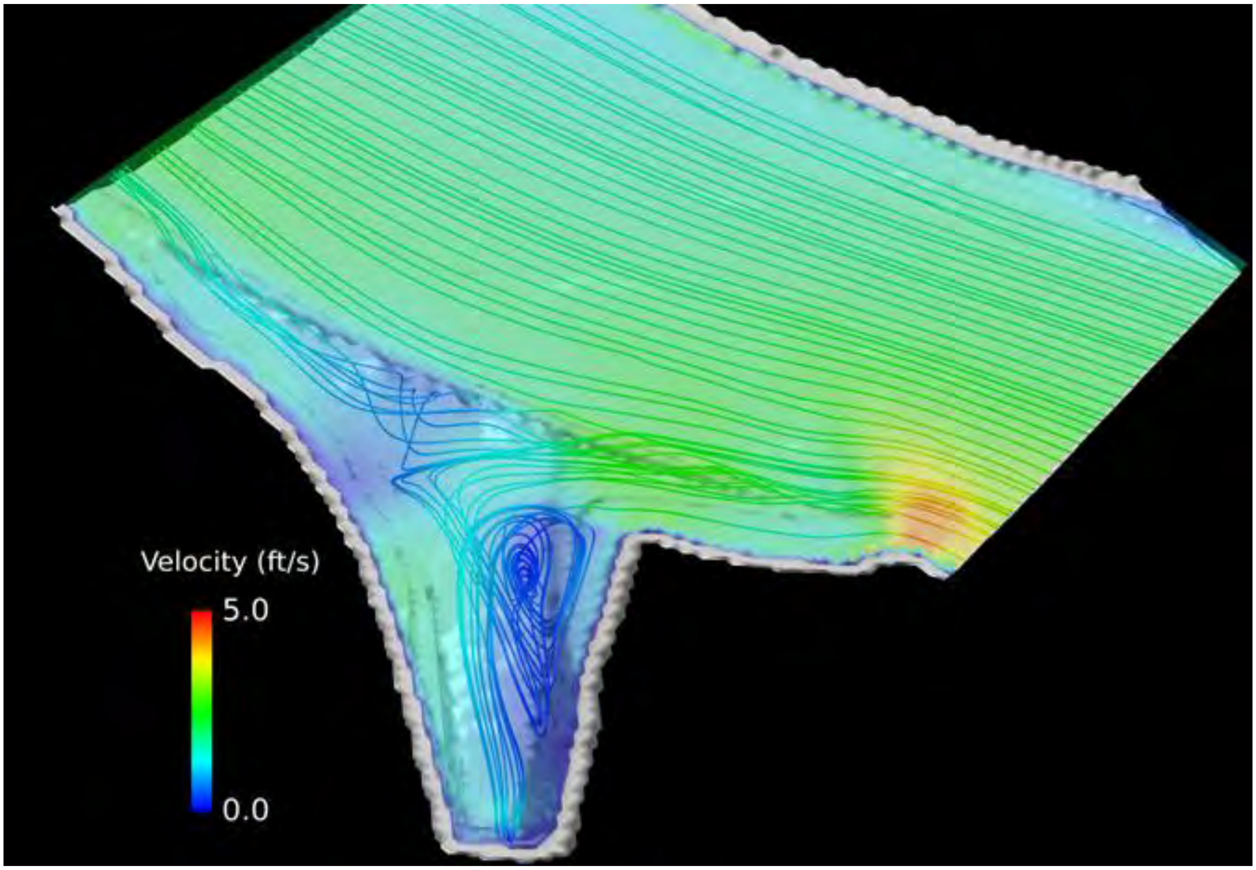

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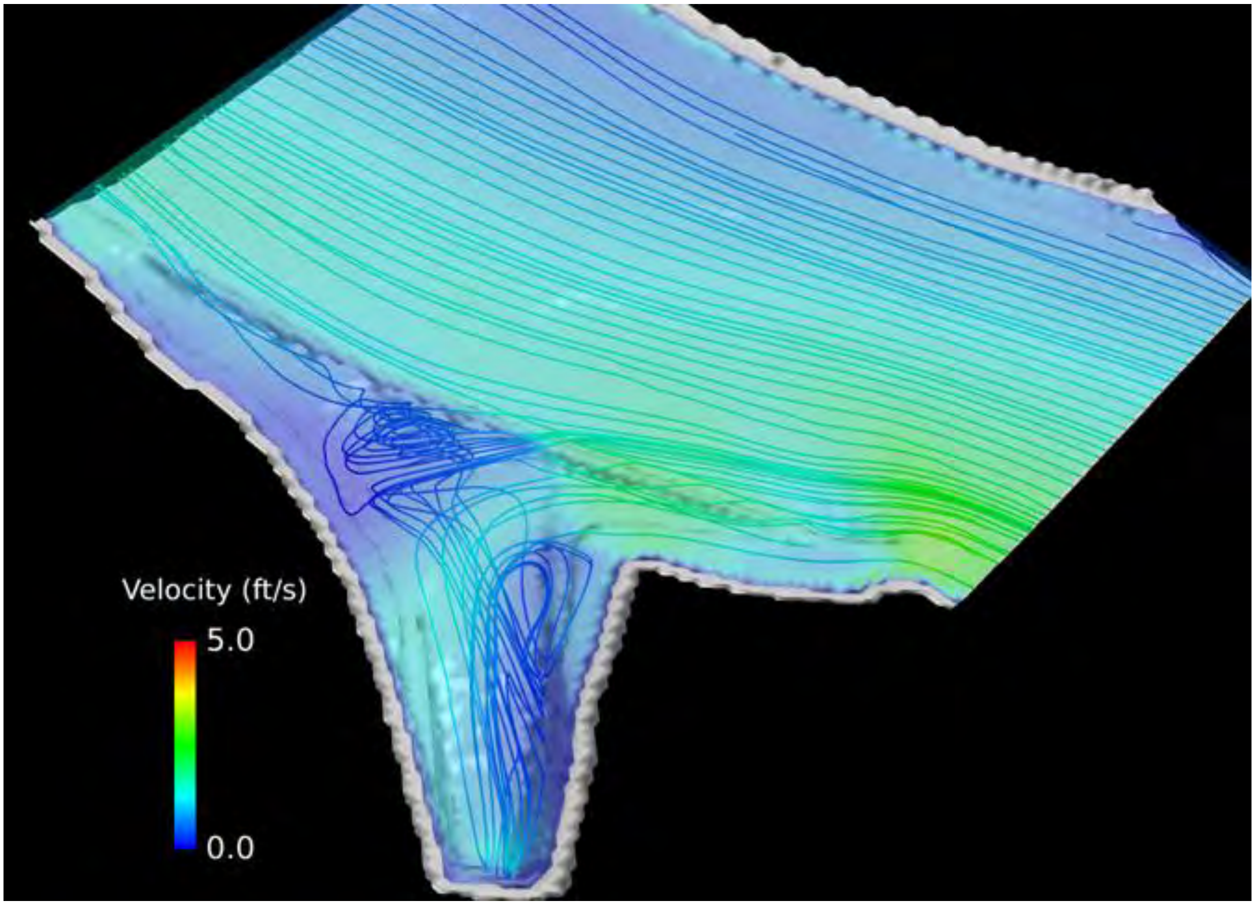

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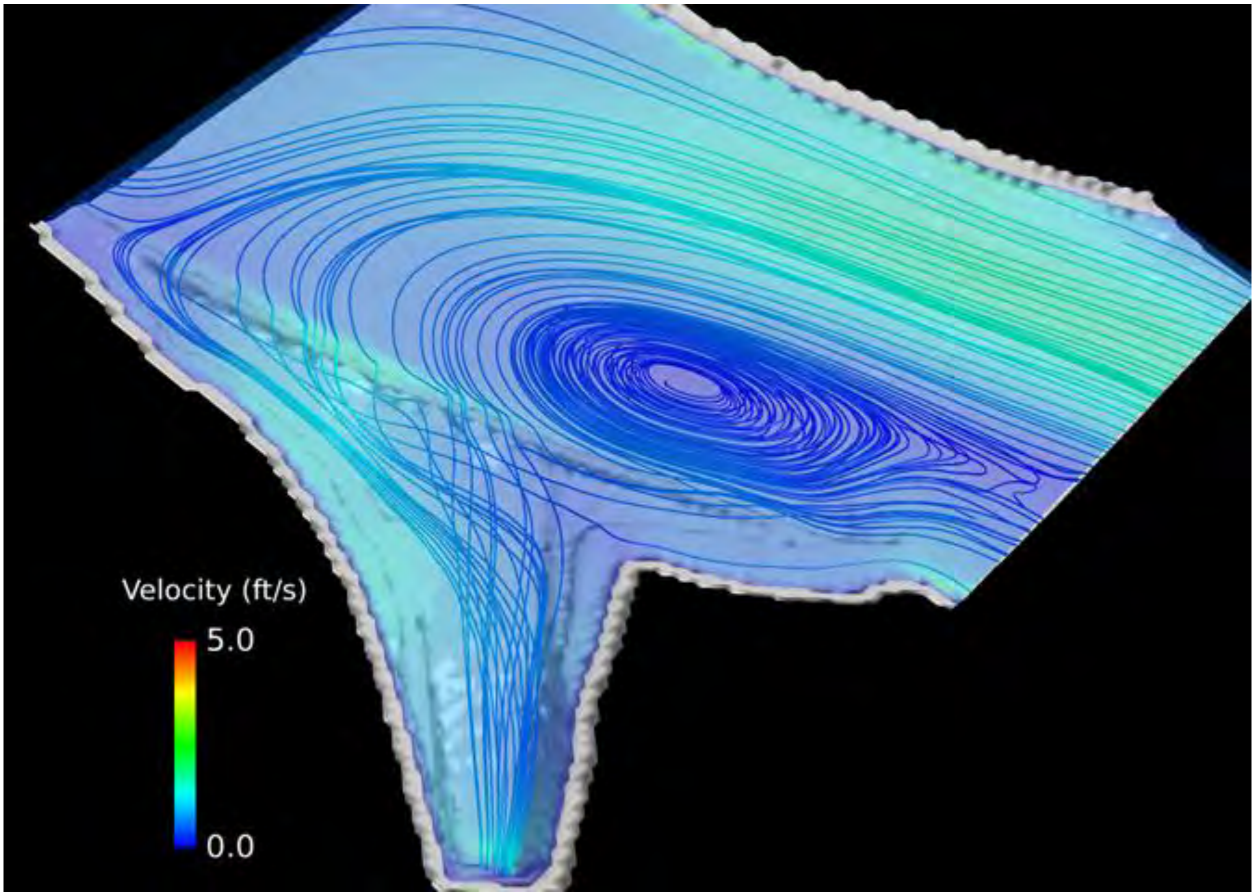

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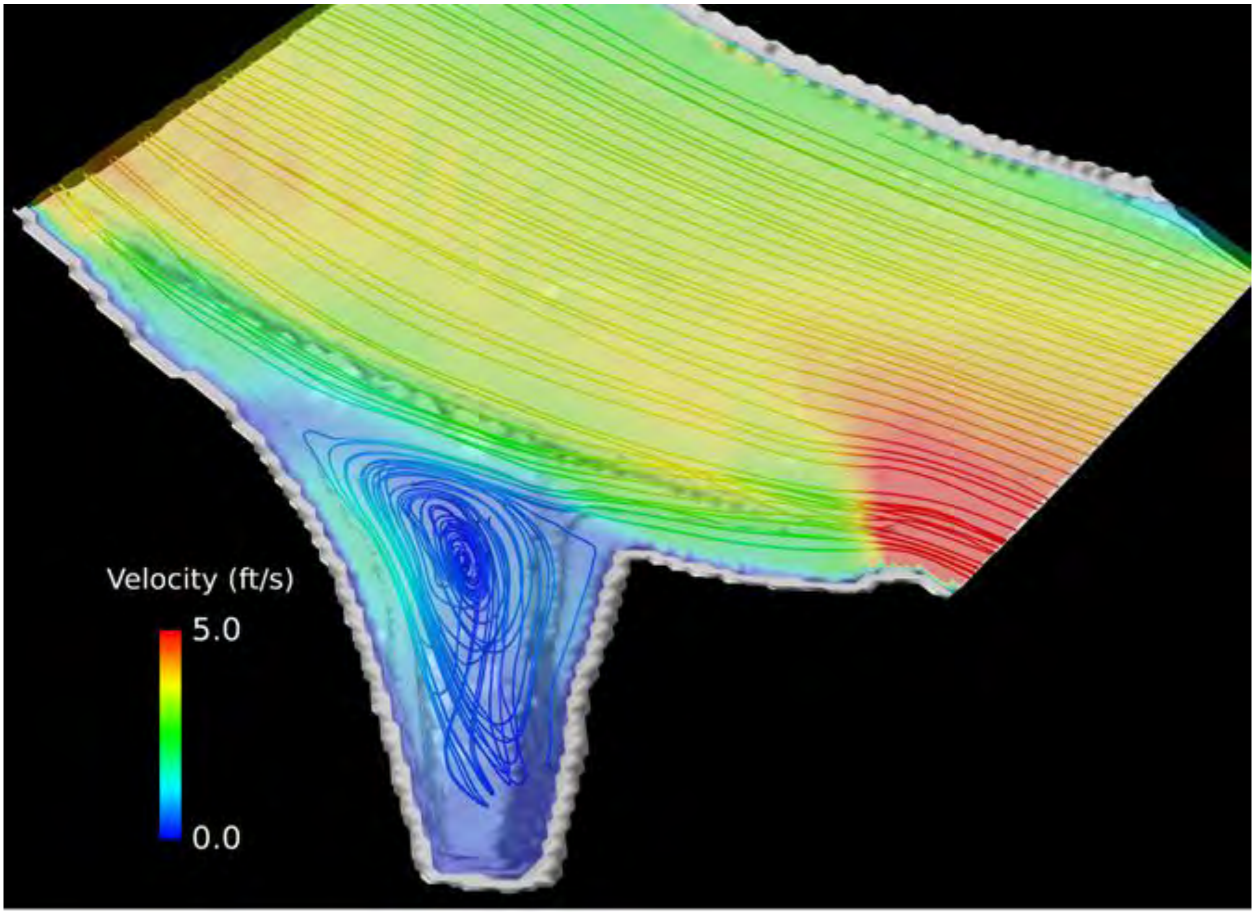

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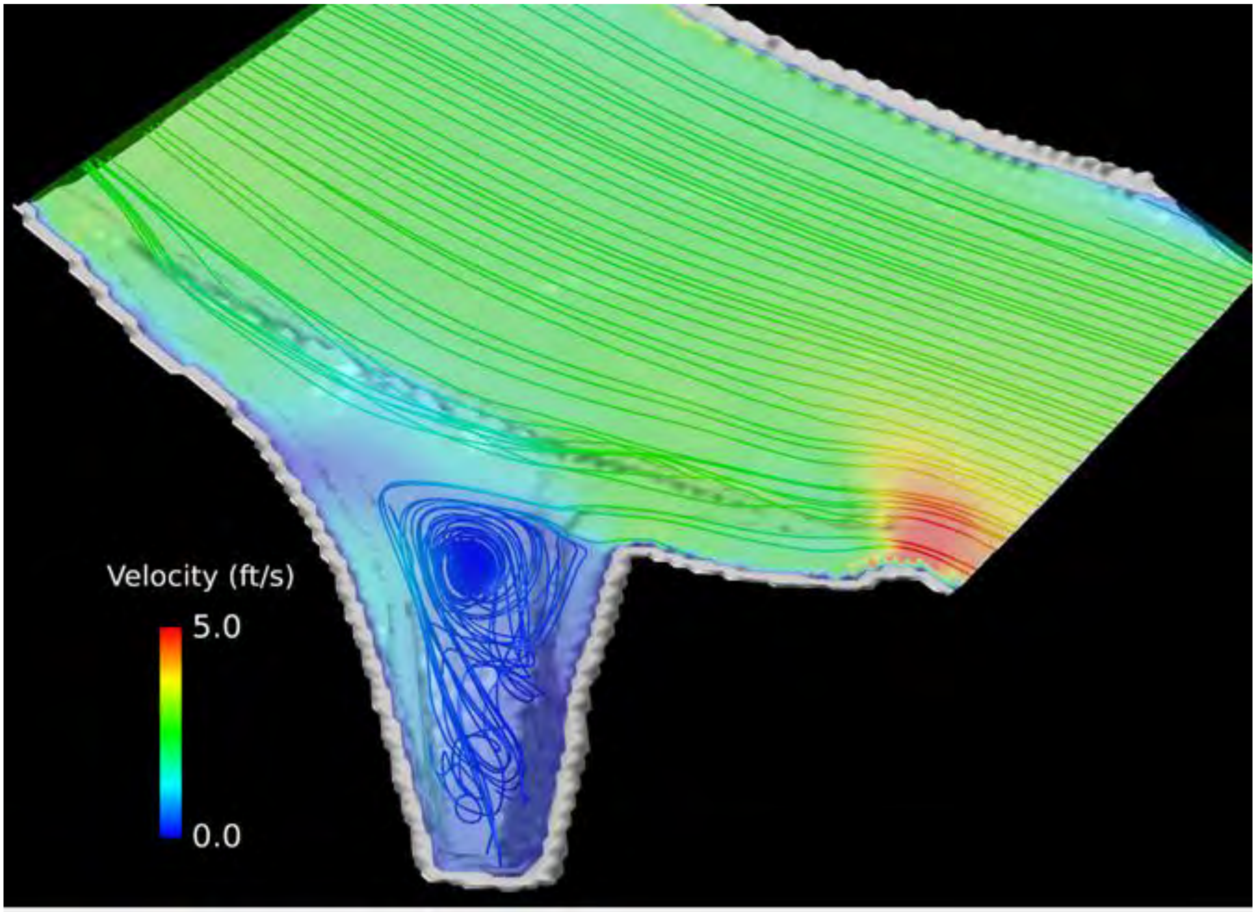

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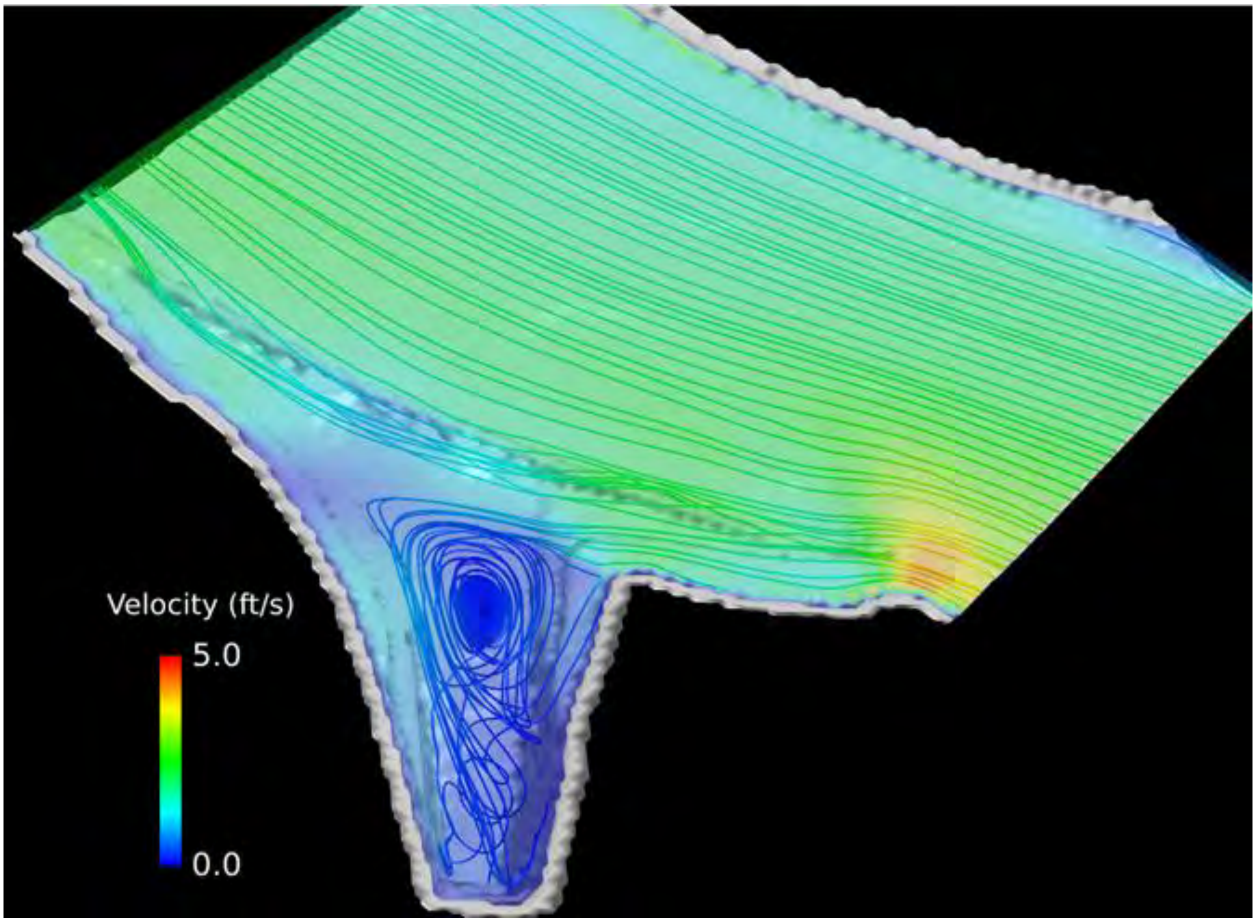

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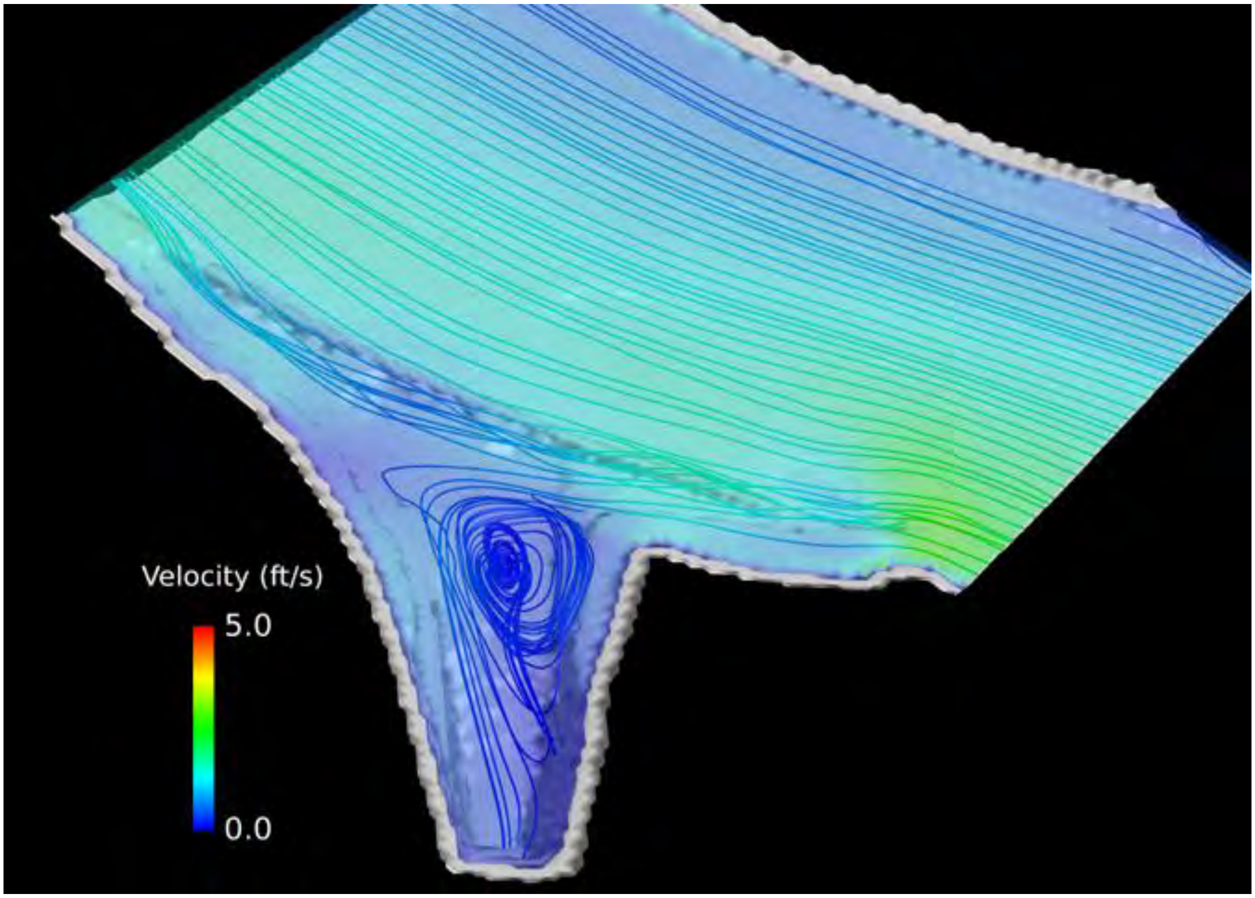

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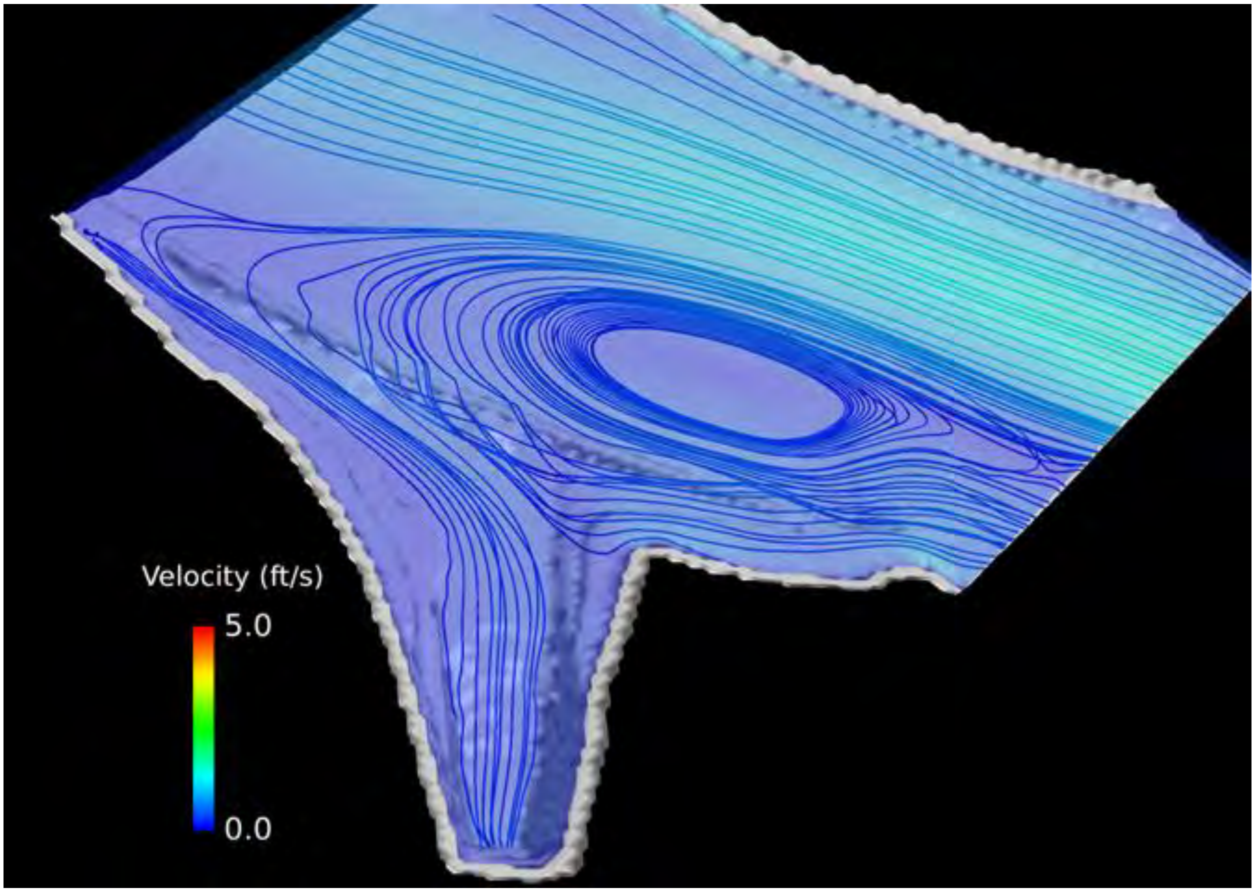


ALDEN

Solving flow problems since 1894

Connecticut River Physical Modeling Project

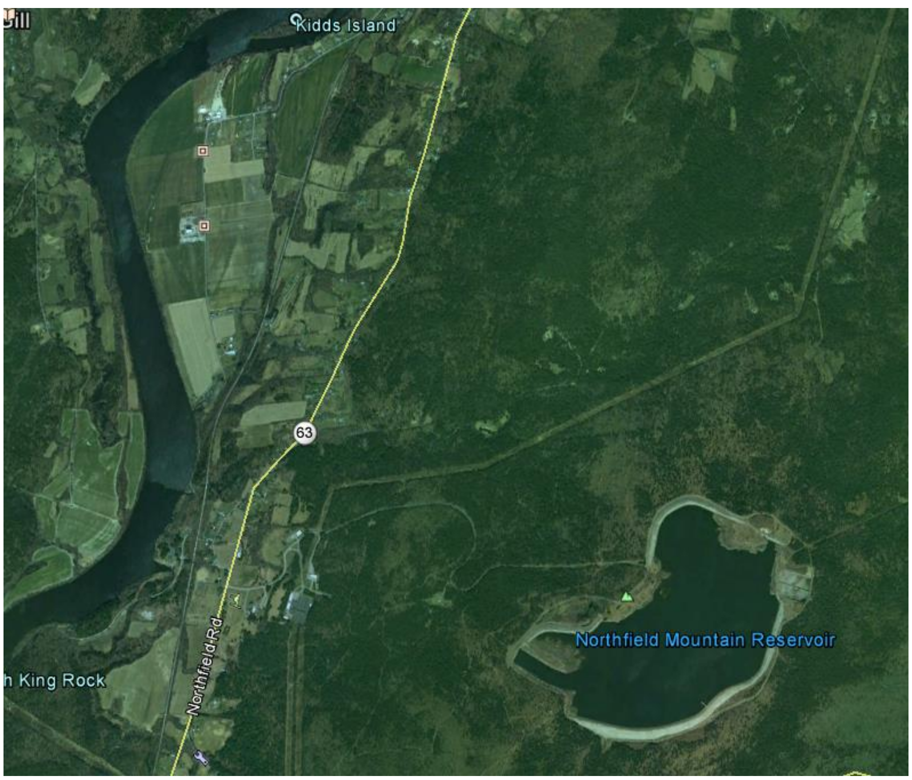
RFP 2015-02-27-NOR
Report – Revision 00

Alden Report No. : 1150NfldPhy

Prepared for:

FirstLight Power Resources

October 12, 2016



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Andy Johansson Director Hydraulic Modeling		P
Will Fay Associate Engineer		P
Tim Sassaman Engineer II		P
Stuart Cain, Ph.D. President		R

Record of Revisions

Revision No.	Revision Date	Change Description	Reason for Change
0			
1	10/12/2016	Changes in text	Address comments from FirstLight and Tractebel

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Executive Summary

In response to GDF Suez Energy Generation NA, Inc. (GDF Suez) request for proposal 2015-02-27-NOR dated March 3rd, 2015, Alden Research Laboratory, Inc. (Alden) conducted a field data collection program and a scaled physical model study with the main objective to design and test proposed new civil works to be constructed at the existing Connecticut River intake structure. The purpose of the new structure is to significantly reduce the intake of sediment during the pumping cycle at the plant.

Historic data from 2000 to 2010 was analyzed to determine the flood frequency, flow duration, and stage discharge relationship at the plant. Three years of historic sediment data (2012 to 2015) were analyzed to determine how suspended sediment concentration varies with river flow.

A field data collection program was conducted by Alden to survey the bathymetry in the forebay and the river near the plant discharge into the Connecticut river. Alden also collected bed sediment samples at the Route 10 bridge upstream of the plant and at the plant discharge. Suspended sediment samples were collected for 5 consecutive days in the Connecticut river at the plant discharge. Sediment samples were collected from the reservoir bottom in 11 locations to determine the grain size distribution of the material accumulating in the reservoir. The reservoir samples were also the basis for selecting the appropriate grain size in the live bed physical model.

A 1:100 scale physical model of the Connecticut river was constructed to determine the efficacy of a proposed weir in reducing the sediment transport to the Northfield Reservoir. The model extended about 2 miles upstream of the plant intake and 0.5 miles downstream of the intake. The model was built with a live bed along the entire length of the model. Sediment and water were recirculated in a closed loop system to eliminate the need for a sediment feed system Twenty one tests were conducted to test both the reproducibility of the model tests and the benefits of the weir. The model used a lightweight sediment with a particle diameter of 0.17 mm and a specific gravity of 1.18.

Most of the testing focused on a river flow of 70,000 cfs and three units pumping. Multiple weir alignments and crest elevations were tested. A weir alignment with a length of 700 feet provided suitable flow patterns. Based on fisheries requirements, the maximum velocity over the weir crest is 2 ft/s. With four pumps in operation, the velocity limit can be satisfied with a weir at elevation 170 feet when the water level is greater than 181.00 ft. Water levels greater than 181.00 ft occur about 90 % of the time. With three pumps in operation and a weir crest elevation of 170 feet, the velocity limit is satisfied when the water level is greater than 178.00 ft, which occurs about 99 percent of time. Alternatively, a moving weir can be constructed that remains at least 11 feet below the water surface.

Based on the physical model tests, a fixed weir at elevation 170 feet will result in a reduction of sediment transported to the reservoir of 10 to 20 percent for a river flow of 70,000 cfs. Model results at lower flows were inconclusive but the weir performance should not be worse at low flows than high flows. The physical model also showed that a moving weir could reduce the sediment load to the reservoir by 30 to 50 percent. The constructability of a moving weir was not investigated in depth by Alden.

The following considerations for further study are offered if the concept of a weir is further advanced:

1) Use field data from bathymetric surveys of the reservoir and river flow data to better estimate the amount of sediment transported to the reservoir during periods of low river flow relative to periods of high river flow.

2) Fully investigate the feasibility of constructing a moving weir. The higher weir crest preforms significantly better than the lower weir crest but requires a moving weir to satisfy velocity requirement.

3) Evaluate the effects of the weir during generation.

4) Consider using the physical model to determine if rock dikes upstream of the weir could improve performance.

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1.0 Introduction

In response to GDF Suez Energy Generation NA, Inc. (GDF Suez) request for proposal 2015-02-27-NOR dated March 3rd, 2015, Alden Research Laboratory, Inc. (Alden) conducted a field data collection program and a scaled physical model study with the main objective to design and test proposed new civil works to be constructed at the existing Connecticut River intake structure. The purpose of the new structure is to significantly reduce the intake of sediment during the pumping cycle at the plant.

The Northfield Mountain Project (NMP) is located on the east bank of the Connecticut River in the towns of Northfield and Erving, MA about five and one half river miles upstream of Turners Falls Dam. The NMP is a 1,166 megawatt pump storage project which uses the Connecticut River between Turners Falls Dam and Vernon Dam as the lower reservoir and Northfield Reservoir as the upper reservoir. River flows range from a few thousand cfs to about 77,000 cfs. During pumping the plant can withdraw up to 15,200 cfs from the river and during generation the plant can release up to 20,000 cfs. Figure 1-1 shows the location of the project in north western Massachusetts, about a 1 hour drive from the Alden office in Holden.

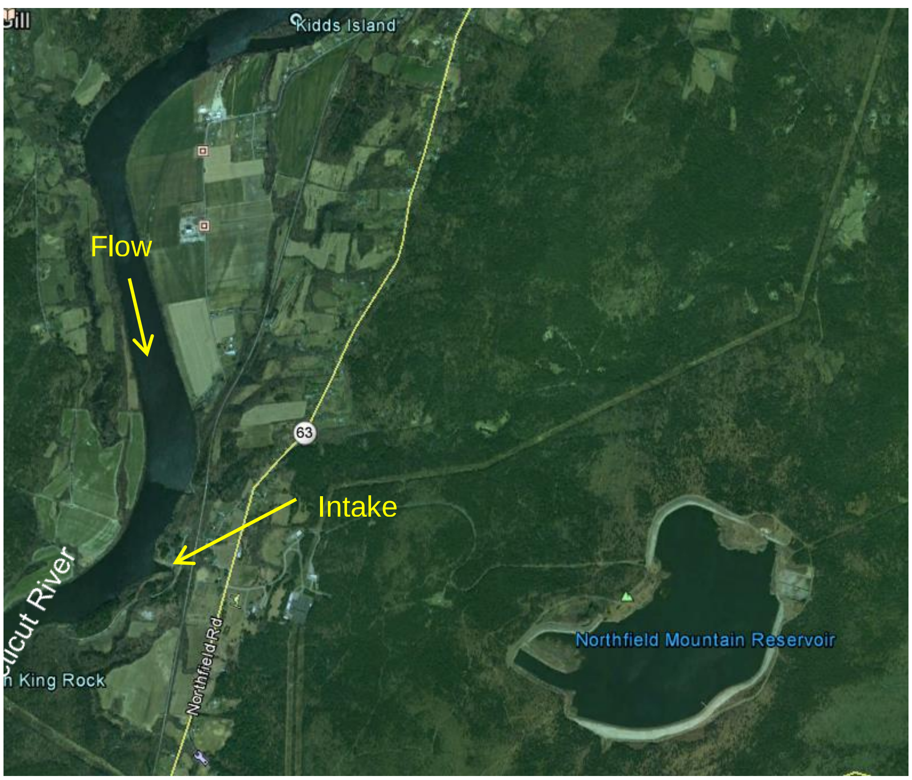

Figure 1-1: Northfield Mountain project location.

1.1 Background

The upper reservoir has experienced chronic sediment accumulation; however, the rate of accumulation appears to have increased in part due to an operational change in reservoir management. Figure 1-2 shows sediment accumulation in the reservoir after dewatering. Historically the reservoir level varied between a high of about 1,000 feet and a low of about 920 feet. More recently the reservoir low water level was increased to 938 feet. The reduced drawdown decreased the maximum reservoir velocity during generation, reducing the amount of sediment which is flushed from the reservoir and increasing the rate of sediment accumulation. In 2013 Alden was contracted to perform a root cause analysis of the sediment accumulation in the upper reservoir. The analysis included the development of a two dimensional numeric model of the upper reservoir which showed that the change in operating envelope for the project contributed significantly to the increase in sediment accumulation. The model was used to show that a change in the operations of the upper reservoir could reduce the sediment accumulation (Alden, 2014a). The report also indicates that it is not possible to flush 100% of the sediment which is pumped into the upper reservoir. With each pumping and generating cycle, a percentage of the sediment pumped into the upper reservoir becomes trapped, gradually filling the reservoir with sediment. Therefore, it is important to minimize the amount of sediment which is pumped to the upper reservoir.

In 2014 Alden conducted a CFD modeling study of the Connecticut River to evaluate potential options for reducing the sediment entrainment (Alden, 2014b). The CFD analysis showed that a sill near the intake could reduce the amount of sediment pumped to the upper reservoir. However, the CFD model had significant limitations and uncertainty. This resulted in the need to conduct a physical model study.

Figure 1-2: Sediment accumulation in the Northfield Mountain Reservoir.

The RFP was fairly prescriptive in the model design and required the following physical boundaries and scale:

- Upstream end is to be located approximately 3.2 km from the intake along the river centerline.
- The downstream model boundary is to be located about 0.8 km from the intake along the river centerline.
- The total river length requested to be modeled is approximately 4.0 km along the river centerline, which corresponds to an approximate overall model length of 3.7 km and a width of about 1.2 km.
- The physical model must be undistorted with a maximum scale of 1:100.
- Figure 1-3 shows the physical model domain required by the RFP.

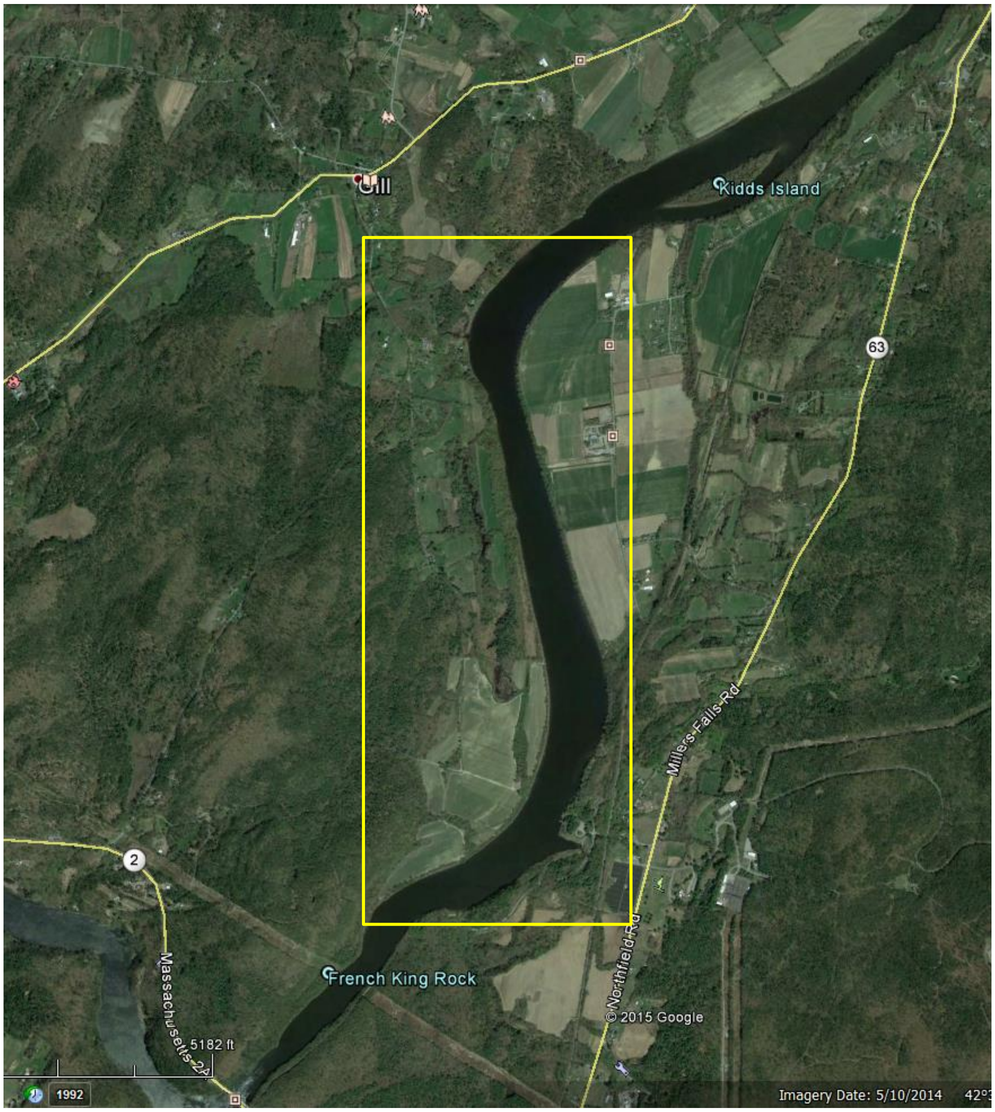

Figure 1-3: Required physical model domain.

1.2 Project Objectives

The objective physical modeling effort was to determine if a proposed modification of the intake can reduce the amount of sediment entering the intake structure. The proposed modifications took advantage of secondary currents in the vicinity of the intake structure. The purpose of the field work was to support the physical modeling effort.

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2.0 Historic Data

Historical stage, flow and sediment data was used as the basis for designing and operating the physical model.

2.1 Historic Flow Data

A ten year period of Connecticut River flow records is shown in Figure 2-1. Gomez and Sullivan provided the flow data to Alden. Peak flows in the Connecticut River during this period reached almost 80,000 cfs but most of the time the river flows at much lower levels. The average discharge for this period is just over 13,000 cfs.

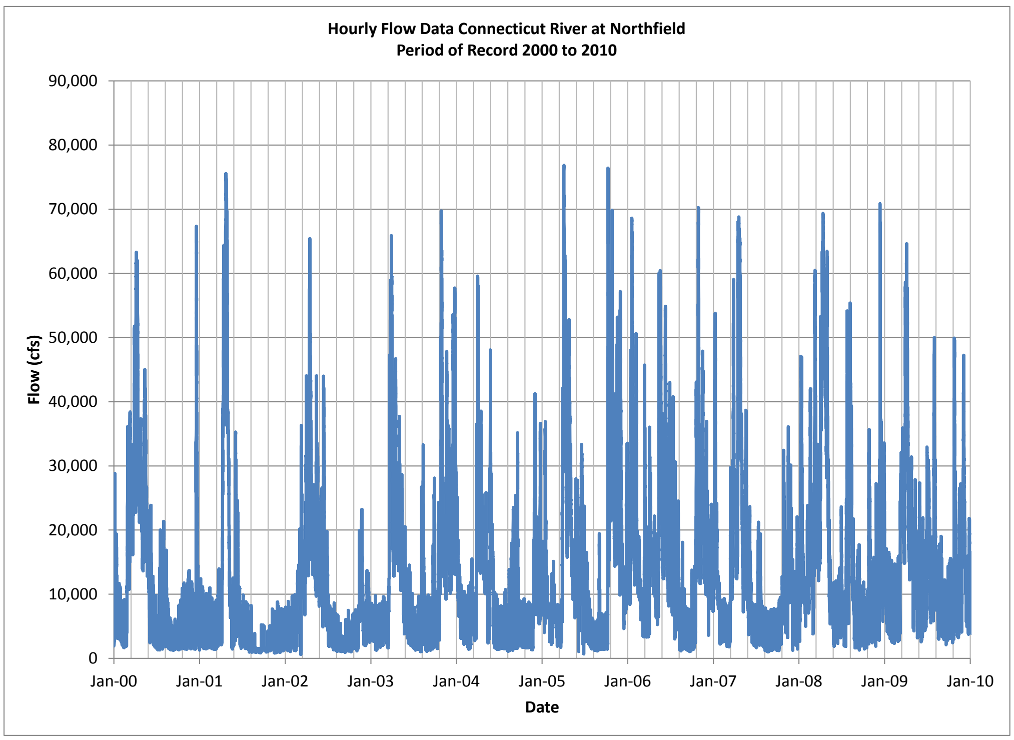

Figure 2-1: Connecticut River flow record January 2000 to December 2010.

2.2 Flood Frequency Analysis

The purpose of the flood frequency analysis is to estimate the recurrence interval of annual peak flows near the plant. Recurrence interval has units of years and is a statistical measure of how frequently a flow will occur. A 10 year flood (recurrence interval of 10 years) will statistically occur every ten years, or has a 1 in 10 probability of occurring in any given year. The flood frequency is estimated from flow data provided by Gomez and Sullivan.

The 11 year record is comprised of hourly flows. For each day the mean daily flow was computed and for each year, the peak mean daily flow was determined, yielding 11 peak flows. A log-Pearson Type III analysis was used to determine recurrence intervals for the data set.

The annual peak flow from 2000 to 2010 is shown in Table 2-1.

Table 2-1: Annual Peak Flow (cfs) for Connecticut River at Northfield

Year	Annual Peak
2000	58,897
2001	73,776
2002	58,484
2003	62,638
2004	66,198
2005	71,392
2006	66,460
2007	67,246
2008	67,032
2009	62,082
2010	62,934

The Log-Pearson Type III analysis is the standard technique used by most federal agencies in the United States for determining flood recurrence intervals. The model can be used to extrapolate results to flows higher than the observed flood events. The following equation is used to calculate the distribution:

$$\log x = \overline{\log x} + K\sigma$$

Where:

x = Flood discharge value with specific probability
$\overline{log\ x}$ = Average of the $log\ x$ values
K = Frequency factor (function of the skewness coefficient and return period) Determined from the frequency factor table (Appendix A).
σ = Standard deviation of the $log\ x$ values

The average of the log x values can be computed from the following equation:

$$\overline{\log x} = \frac{\sum_1^n \log x_i}{n}$$

Where:

x_i = annual peak flow during year i
n = number of records in data set

The standard deviation is computed from the following equation:

$$\sigma = \sqrt{\frac{\sum_1^n \left(\log x - \overline{\log x}\right)^2}{n-1}}$$

All variables are as defined previously. The skewness coefficient, C_s, is computed from the following equation:

$$C_s = \frac{n\sum_1^n\left(\log x - \overline{\log x}\right)^3}{(n-1)(n-2)(\sigma)^3}$$

The coefficient K is found using tabulated values according the skewness coefficient and the recurrence interval in years. Interpolation can be used to determine K values where necessary. The table of K factors is shown in Appendix A.

Results of the analysis are shown in Figure 2-2. Based on the analysis the average annual flood is about 59,000 cfs. A flow of 70,000 cfs has a recurrence interval of 5 to 10 years. In considering the results of the flow frequency analysis it is important to recognize that it is based on a short period of record (2000 to 2014).

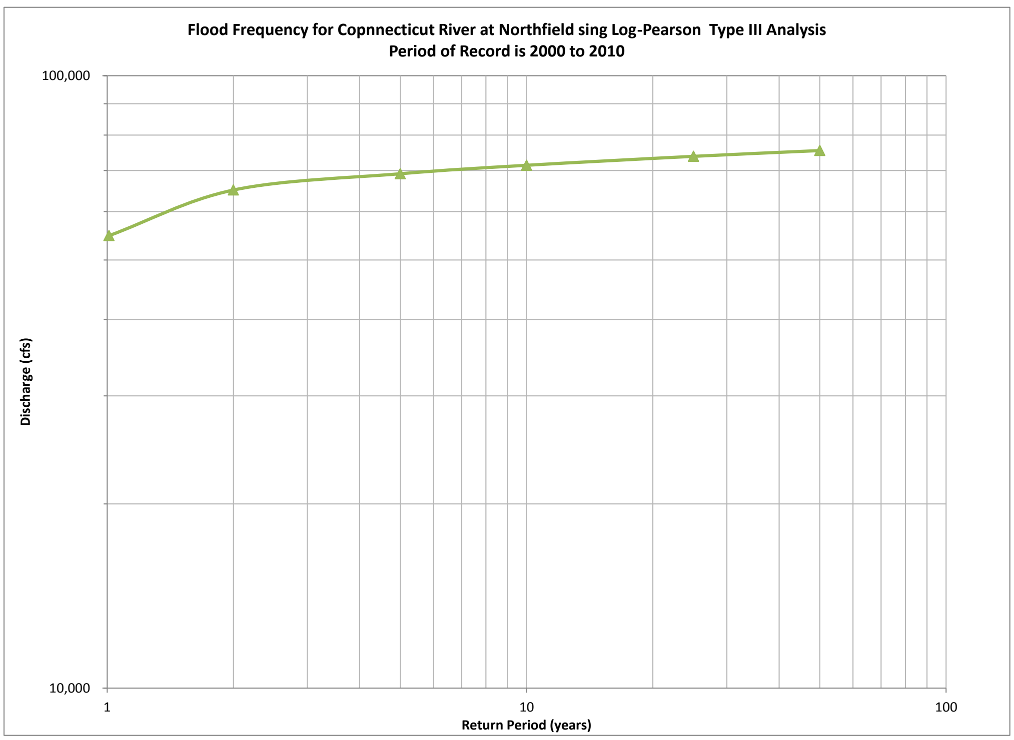

Figure 2-2: Results of flood frequency analysis.

Note: Return Period is the statistical recurrence interval of an annual peak flow in years, also referred to as the x year flow (e.g. 10 year flood) in the popular press.

2.3 Flow Duration Analysis

A flow duration curve of the Gomez and Sullivan discharge data is shown in Figure 2-2. The flow duration curve is useful in determining representative Connecticut River discharges for the sedimentation modeling. High discharge levels in the River are likely to correlate with times of high sediment concentration in the river. Periods when the Connecticut River flow exceeded 50,000 cfs are relatively uncommon and of short duration. During this period of record, the Connecticut River flow was greater than 70,000 cfs about 0.1 percent of the mean daily measurements (5 days) and greater than 50,000 cfs for about 2.5% of the mean daily discharge measurements. Connecticut River flow exceeded 30,000 cfs only 10% of the time. Most of the time when Connecticut River flow exceeded 30,000 cfs was between March and May (springtime freshets). Figure 2-4 shows the monthly association of high Connecticut River flow periods.

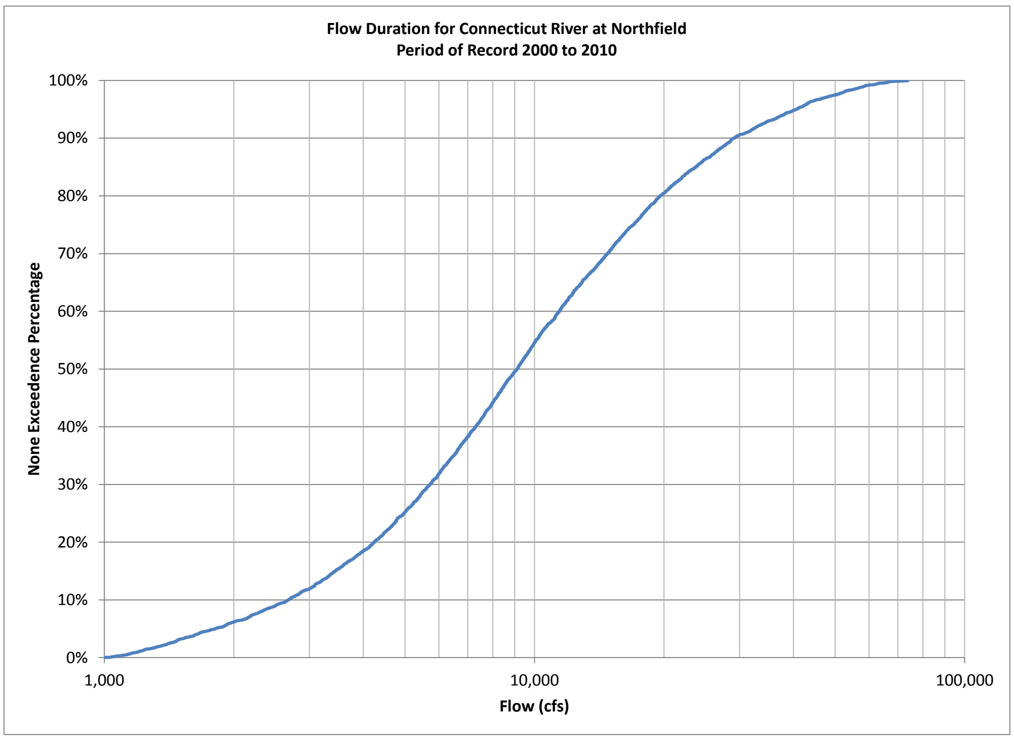

Figure 2-3: Flow duration curve for Connecticut River at Northfield

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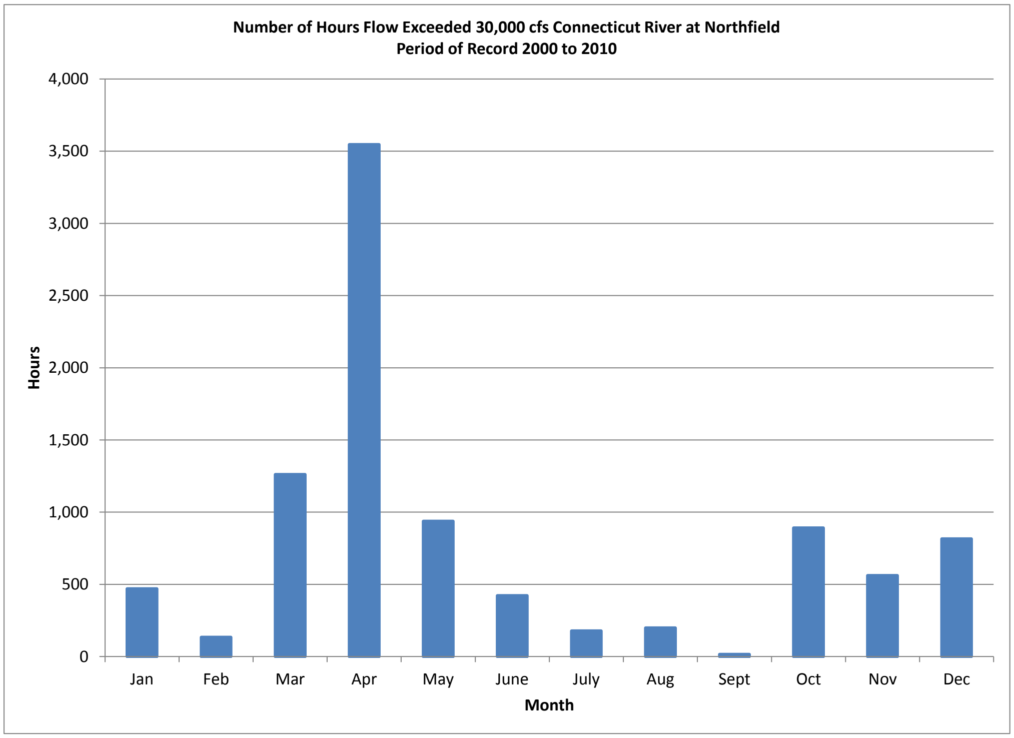

Figure 2-4: Monthly association of flows in excess of 30,000 cfs.

2.4 Stage Discharge Analysis

Analysis of the 2000 to 2010 water levels and discharge at Turners Falls yields the stage discharge rating curve at the Northfield intake/outlet shown in Figure 2-5. It is interesting to note the five foot fluctuation in water level that is observed at lower flows. Addendum 1 to the RFP indicates that the fluctuation is not an artifact of operations at Northfield but results from downstream control of the river. The black line shows a best fit curve that Alden used for the downstream boundary (Alden, 2014b).

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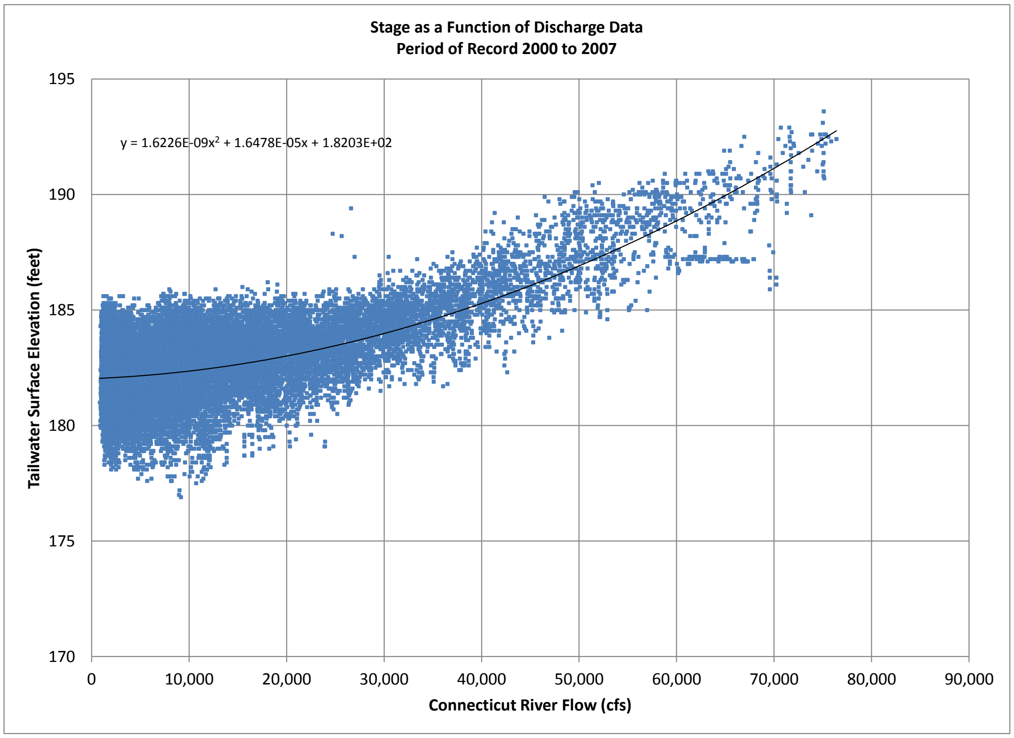

Figure 2-5: Stage Discharge Curve 2000 to 2010 (Alden, 2014b)

2.5 Suspended Sediment Data

Suspended sediment data was available for 2012 through 2015 at multiple locations near the site:

2.5.1 Route 10 Bridge

GDF Suez operated a continuous suspended sediment monitor just upstream of the Route 10 bridge in Northfield, MA. The continuous suspended sediment monitoring equipment used was a Laser In-situ Scattering Transmissometry (LISST) StreamSide unit. Samples were collected from September 21, 2012 through July 20, 2015 at an interval of approximately 30 minutes. The units did not operate during the winter period and freezing temperatures (Gomez and Sullivan, 2015). Figure 2-6 shows the approximate location of the sampler relative to the plant. The Route 10 bridge is approximately 5.7 miles upstream of the tailrace.

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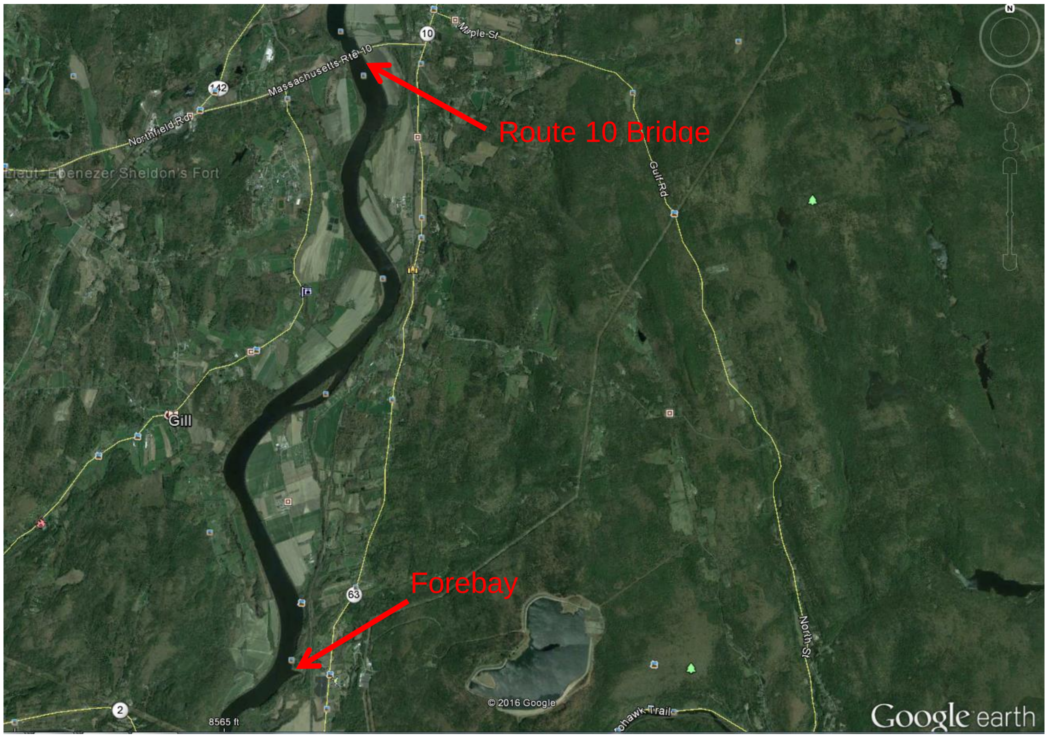

Figure 2-6: Location of Route 10 Bridge LISST StreamSide Sampler.

2.5.2 Northfield Mountain Tailrace

GDF Suez operated two continuous suspended sediment monitors in the Northfield tailrace as shown in Figure 2-7. The continuous suspended sediment monitoring equipment used was a pair of LISST-HYDRO units. Samples were collected from August 1, 2013 through June 11, 2015 at an interval of approximately 15 minutes. The units did not operate during the winter period and freezing temperatures (Gomez and Sullivan, 2015).

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Figure 2-7: Location of streamside samplers in forebay (Gomez and Sullivan, 2015).

2.5.3 Suspended Sediment Data Analysis

Figure 2-8 shows the suspended sediment concentration data at the Route 10 bridge as a function of discharge for all of the samples collected. A second order polynomial has been fit to the data. The suspended sediment data in the forebay is plotted as a function of time for each sampler in Figure 2-9. The forebay data shows an increasing concentration trend with increasing flow, however, the data shows significant variability. The variability may in part be attributable to the fact that some of the data is collected during generation and some of the data is collected during pumping. The forebay data was reduced to include only data collected between midnight and 8 am. This eliminates most of the data collected during generation. In addition, all data points with a concentration less than 2 mg/l were eliminated on the basis that they are likely to be erroneous, especially at higher flows. The resulting plot is shown in Figure 2-10.

The data in Figures 2-8 and Figure 2-10 were combined to create Figure 2-11. All of the fit lines are second order polynomials. Based on discussions with GDF Suez the target model sediment concentrations shown in Figure 2-12 were identified. At a river flow of 70,000 cfs, a suspended sediment concentration of about 400 mg/l was targeted and at 50,000 cfs a concentration of about 200 mg/l was targeted. The concentrations are significantly higher than observed values in the river.

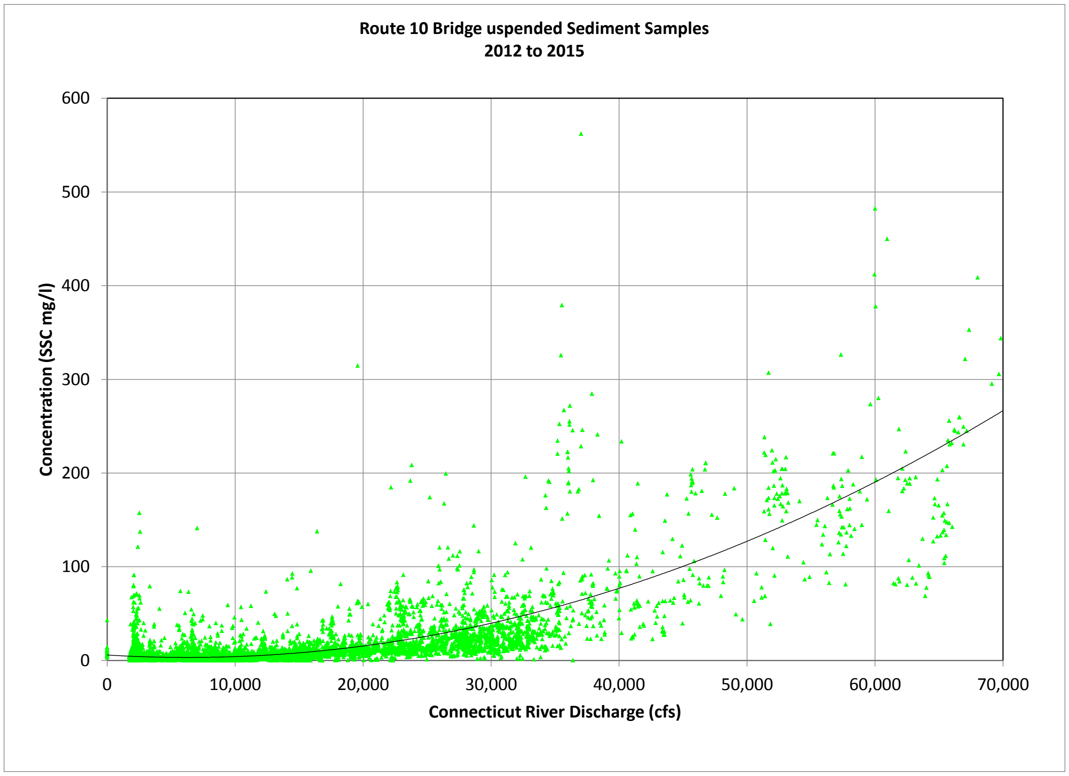

Figure 2-8: 2012 to 2015 suspended sediment concentrations at Route 10 bridge.

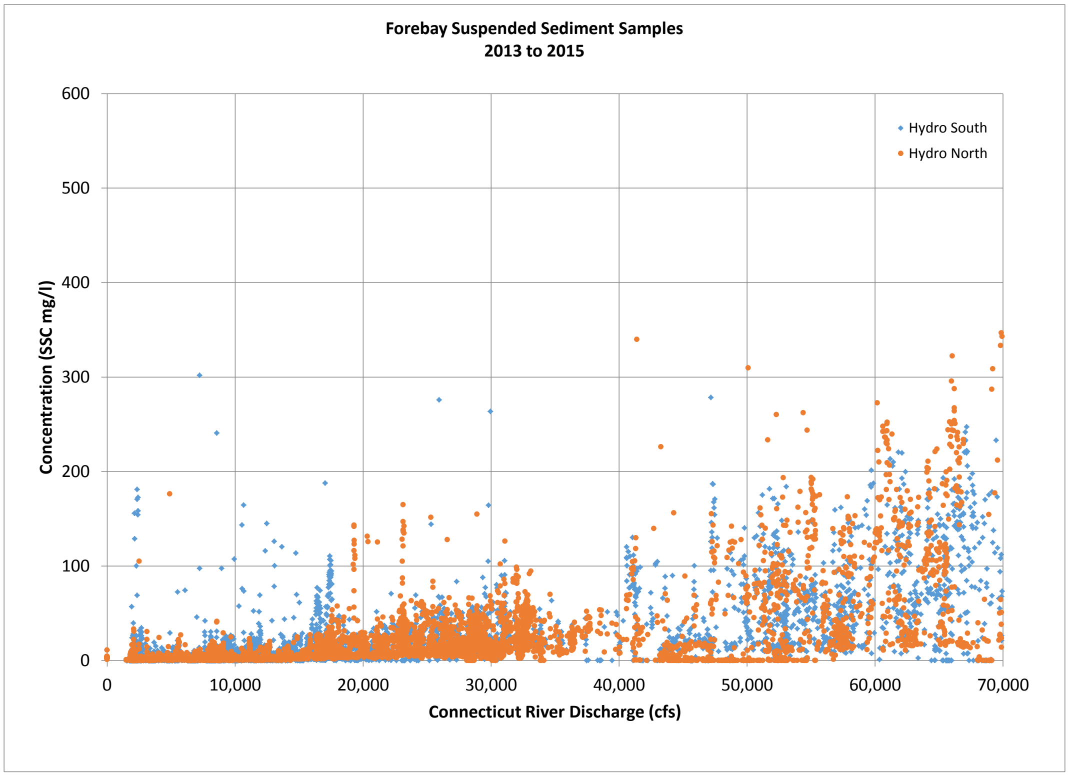

Figure 2-9: 2013 to 2015 suspended sediment samples in forebay.

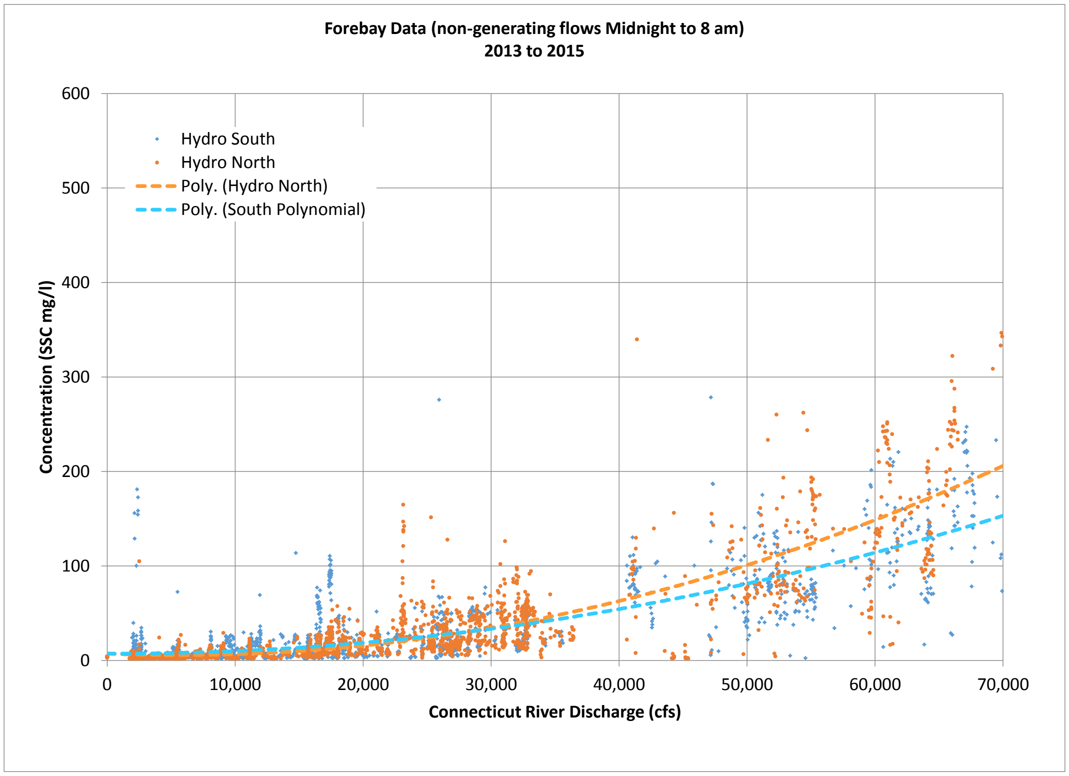

Figure 2-10: Suspended sediment concentration in forebay during non-generating times.

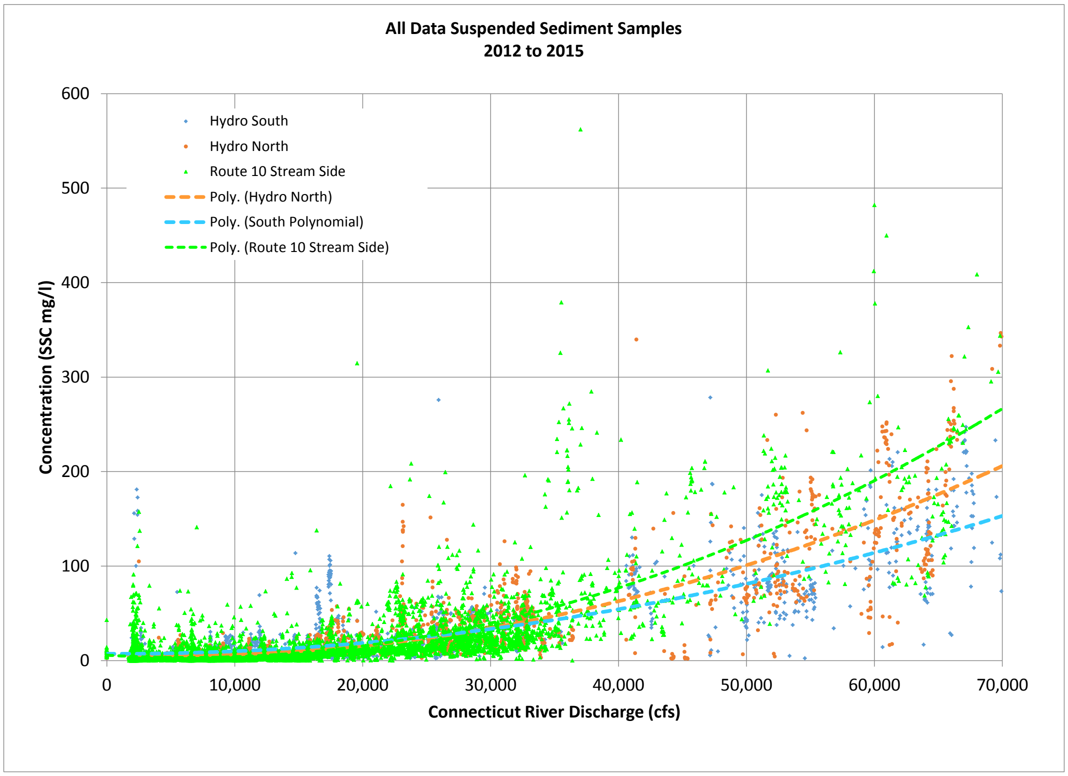

Figure 2-11: All suspended sediment data 2012 to 2015.

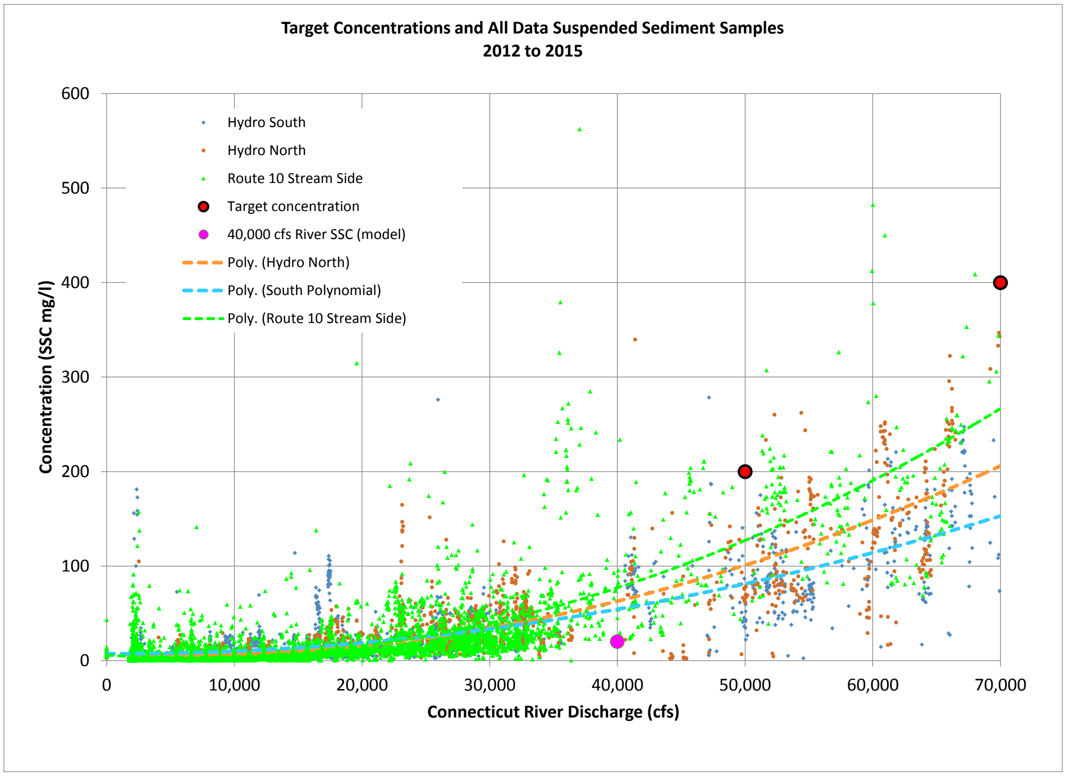

Figure 2-12: Target suspended sediment concentrations in model (red dots).

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3.0 Field Data Collection

To support the construction and calibration of the physical model, it was necessary to collect field data. Most of the required data was collected by Alden; however, some of the required data was previously collected by Gomez and Sullivan under a separate contract and provided to Alden. Bathymetric data was provided by Gomez and Sullivan and then augmented by Alden as described in Section 3.3 to define the river geometry in the physical model up to the highest water level of interest. Sediment samples were collected by Alden to characterize the river bed and the sediment size fraction which is accumulating in the reservoir. The data were augmented by suspended sediment data collected by Gomez and Sullivan. The sediment size fractions were used to determine the sediment size which was used in the physical model. Water velocity measurements previously made by Gomez and Sullivan were used to validate the velocity distribution in the physical model.

3.1 Alden Field Data Collection Objectives

The objectives of the field data collection program were as follows:

- Collect detailed bathymetric (underwater sounding) data in the vicinity of the intake structure to allow Alden to produce a detailed contoured elevation drawing at the intake. The data collected by Alden was combined with bathymetric data of the river to create a complete bathymetric map of the area included in the physical model. The bathymetric drawing was used as the base map to create topographic cross sections of the river to support construction of the physical model.

- Collect topographic data (above water) to supplement the bathymetric data in the development of the 3D surface used to construct both the physical model.

- Collect riverbed sediment samples at 10 locations to determine the river bed gradation. Each sediment sample underwent grain size analysis. These data were used to support the physical and numerical sediment transport modeling.

- Collect reservoir sediment samples at 11 locations to determine the grain size distribution of the material being trapped in the upper reservoir.

- Collect suspended sediment samples at nine locations in the water column on five days to determine the grain size distribution of the suspended sediment material and the suspended sediment concentration for one flow rate in the river.

3.2 Schedule of Field Operations

Survey operations at the Northfield Mountain Project were conducted during two deployments. The first deployment lasted five days from Monday June 1, 2015 to Friday June 5, 2015. The Alden field team deployed from the public boat launch near the Northfield visitors center. The field team staged equipment near the plant intake. This provided a safe, secure and efficient location from which to work. All of the field work on the Connecticut River was completed in publically accessible areas. Collection of sediment samples in the reservoir was coordinated with John Howard of GDF Suez.

A second deployment occurred on Saturday July 11, 2015 to collect bathymetric data in the Connecticut River forebay area. Northfield was in an outage condition during the data collection, making it possible to safely collect bathymetric data inside the exclusion zone. The data collection effort was an addition to the scope of work when it was found that the existing data did not include bathymetry in the exclusion zone.

Prior to launching the survey vessel and starting work, the Alden field team conducted a safety brief with John Howard of GDF Suez. The Alden field survey plan, safety plan, communication expectations, and survey operating procedures were reviewed and discussed.

Below is a short summary of the field tasks which took place each day during the field investigation:

Table 3-1: On Site Field Data Collection Activities

Deployment 1		
Day 1: 6/1/2015	Monday	Arrived at site and started preparing equipment for deployment
		Deploy water level logger
		Collect water for 9 suspended sediment samples
Day 2:	Tuesday	Collect water for 9 suspended sediment samples
6/2/2015		Collect 10 river sediment samples
Day 3:	Wednesday	Collect water for 9 suspended sediment samples
6/3/2015		Collect 11 reservoir sediment samples
Day 4:	Thursday	Collect water for 9 suspended sediment samples
6/4/2015		
Day 5:	Friday	Collect water for 9 suspended sediment samples
6/5/2015		Recover water level loggers
Deployment 2		
Day 2	Saturday	Deployed water level loggers
7/11/2015		Collect approximately 12 bathymetric transects
		Use GPS to measure structure location
		Recover level loggers

3.3 Bathymetric Survey

The bathymetric survey was conducted to map the river bottom relative to the Northfield Mountain intake structure. River bathymetry was one of the necessary data sets to support the engineering design and analysis, and physical modeling. Accurate bathymetric data collection is comprised of the following four components:

- A single-beam echo-sounder which measures the vertical distance from the water's surface to the river bottom (water depth) using high frequency sound.
- A horizontal positioning system which determines the location where each echo-sounding measurement is collected relative to the project's horizontal datum.
- A vertical referencing system which monitors the elevation of the water surface during the survey so that the echo-sounding or water depth data can be referenced (via time) to the project vertical datum allowing the depth data to be converted to elevations.
- A trackline control, navigation and data logging system. This is typically a computer and software package which logs the water depth data with the position data and the time of the data collection for real-time vessel control and post survey data processing and presentation.

For this project Alden equipped the survey vessel with a Knudsen 200 kHz single frequency survey grade digital depth echo-sounder for collecting water depth data. A Hemisphere VS110 USCG/WAAS Differential Global Positioning System (DGPS) was used for geodetic positioning (the vessel's latitude and longitude), interfaced with the PC-based hydrographic software package HYPACK MAX for survey vessel trackline control, navigation and data logging. Vertical referencing of the survey vessel was obtained using *In-Situ* Onset Hobo U20 water level data loggers. The water level logger benchmarks were referenced to the construction drawing vertical datum during the upland survey. Calibration of the depth sounder for local water mass sound speed was accomplished by performing "bar checks" at the beginning and end of each survey day. The bar check procedure consists of lowering an acoustic target on a graduated sounding line to the target depth. The depth sounders speed of sound control is adjusted so that the target is printed precisely at the known depth. The target is then raised in 5 foot increments and the chart readings and displayed digital depths noted at each increment. Variations which exist in the indicated depths at these calibration points are subsequently incorporated into the bathymetric data analysis procedure to yield maximum accuracy in the resulting depth data. This calibration was also confirmed using the YSI CastAway CTD, an instrument used to collect water column profiles of conductivity, temperature and depth. The processed CastAway data can be used to create a depth profile of the local water mass speed of sound. This data profile can either be used in place of the bar check or to confirm its results. These instruments, when used together, constituted a single beam sounding system and supported the creation of Alden's contoured chart of the Connecticut riverbed and forebay area. The horizontal accuracy of the single beam sounding system is about +/- 0.5 inches (1cm). The vertical accuracy depends both on the accuracy of determining the vertical position of the boat and the accuracy of the depth sounder. Based on the combined uncertainty Alden estimates the vertical accuracy of the topographic survey to be +/- 0.16 ft.

The available bathymetric data did not include sufficient detail to create a model of the forebay area. Therefore, a bathymetric survey was conducted on July 11 between 9:45 am and 10:49 am to determine the forebay bathymetry. Figure 3-1 shows the location of the surveyed transects. In addition to surveying the forebay, Alden extended the survey a short distance into the river as shown in Figure 3-2. Twenty transects were surveyed in the forebay with a total length of about 4400 feet and five lines were surveyed outside the forebay with a total length of 4700 feet. The bathymetric survey completed by Alden was combined with bathymetric data provided to Alden by GDF Suez as part of the project. Alden also obtained LiDAR data from Gomez and Sullivan for the overbank area. The LiDAR data was combined with the two bathymetric surveys to create a single topographic map of the model domain.

Water levels were monitored throughout the one hour survey period. One level logger was installed at a rock outcrop on the on the north side of the forebay as shown in Figure 3-3. The sensor made readings at a six minute interval. The water level logger data showed that the water level in the reservoir increased by 0.17 ft throughout the data collection. The plant was in an outage at the time of the survey.

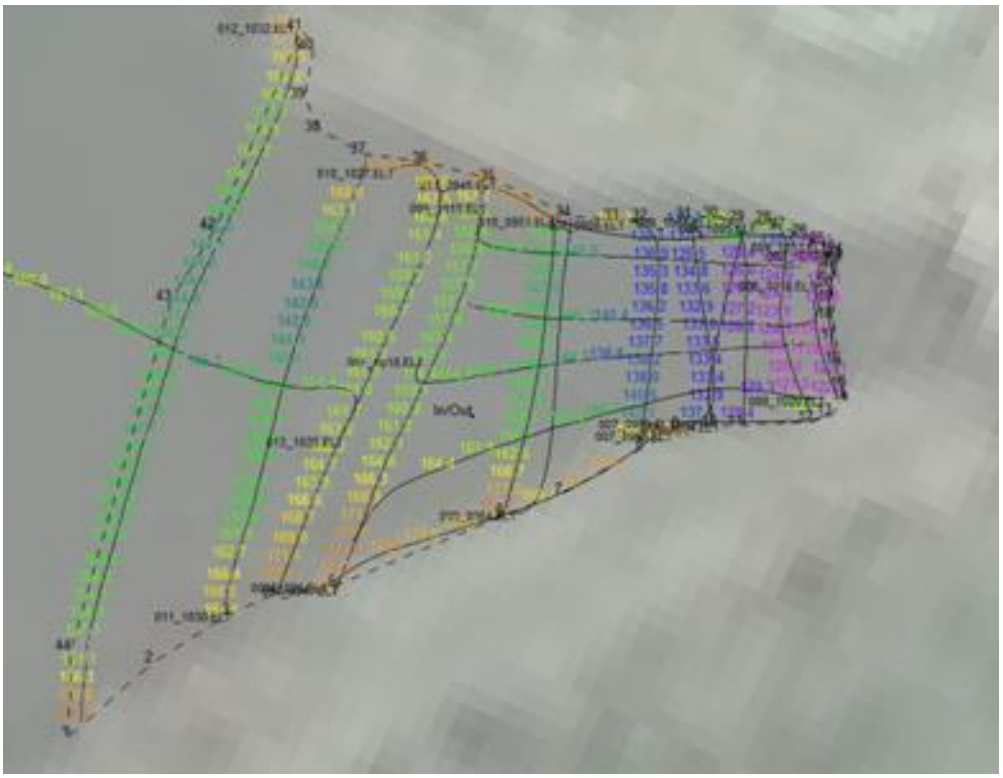

Figure 3-1: Bathymetric survey completed by Alden in forebay.

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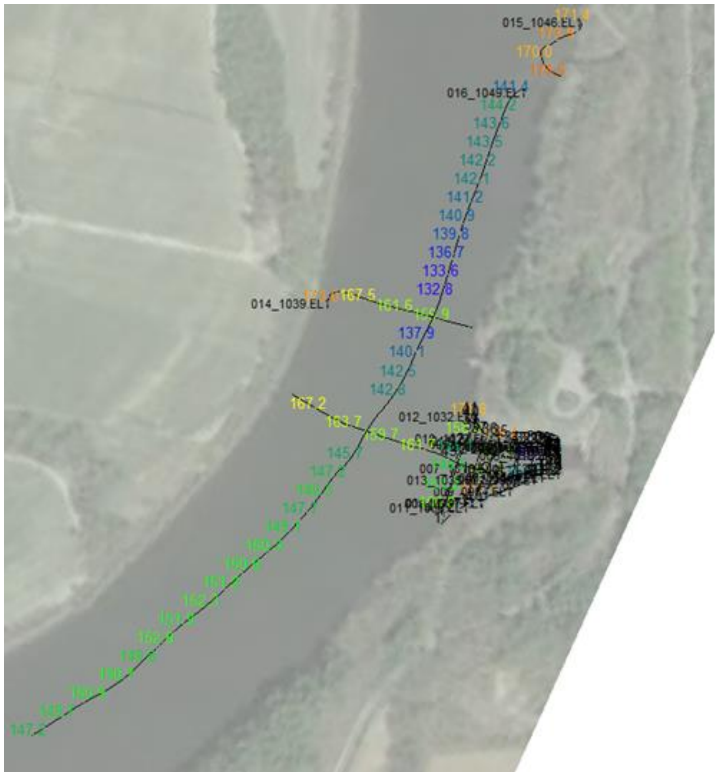

Figure 3-2: Bathymetric survey completed by Alden in river.

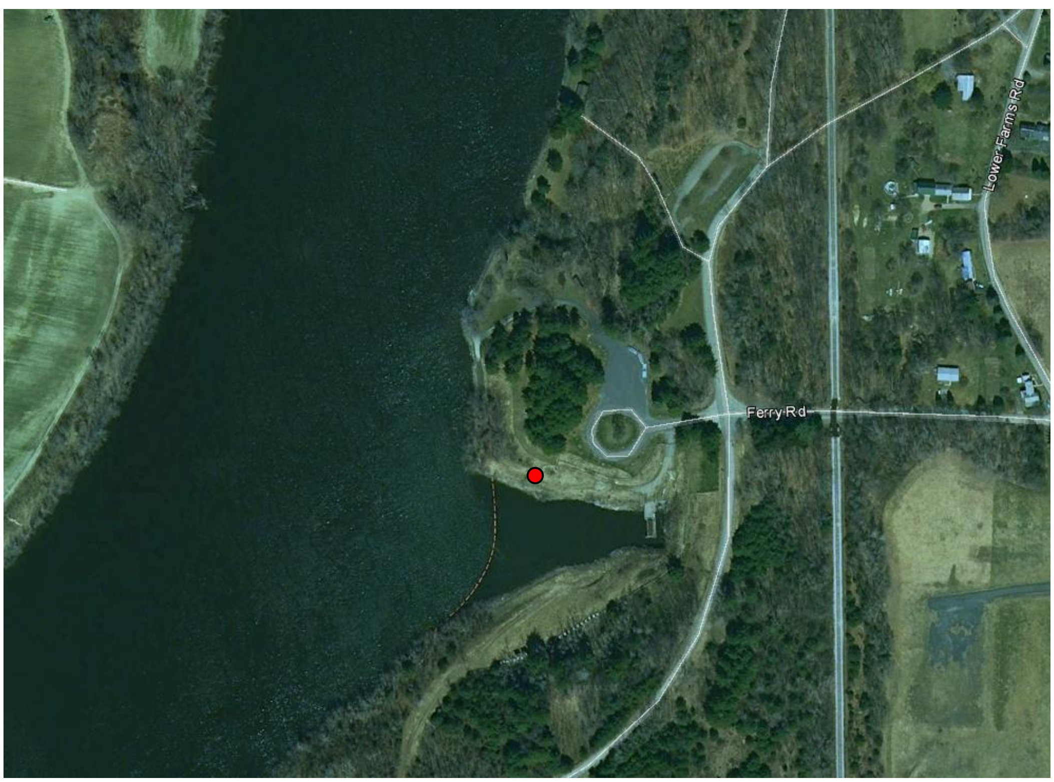

Figure 3-3: Location of level logger.

3.4 Upland Survey

For this project Alden deployed a survey team with an Ashtech Promark3 survey grade GPS system. This system achieves sub-centimeter accuracy by maintaining a link between two GPS antenna, the fixed position base station and the roving survey unit. The physical site conditions precluded the use of more traditional surveying methods using a total station and a prism pole. The accuracy of the upland surveying system is about 0.5 inches (1cm).

Upland survey data was collected to extend the bathymetric transects up the river banks above the water surface elevation at the time of the bathymetric survey. Alden also collected topographic data to locate the intake structure. The upland survey data was combined with the bathymetric data to create a single topographic data file.

The survey data collected by Alden was processed to create a contour map of the river bed throughout the study reach. Figure 3-4 shows a contour map of the model domain. The surveys are used to define the surface used in the physical model. Figure 3-5 shows a detailed view around the intake. The bathymetry and LiDAR data are in NGVD29 according to Dan Gonzales at Gomez and Sullivan (6/12/2015 12:10pm e-mail)

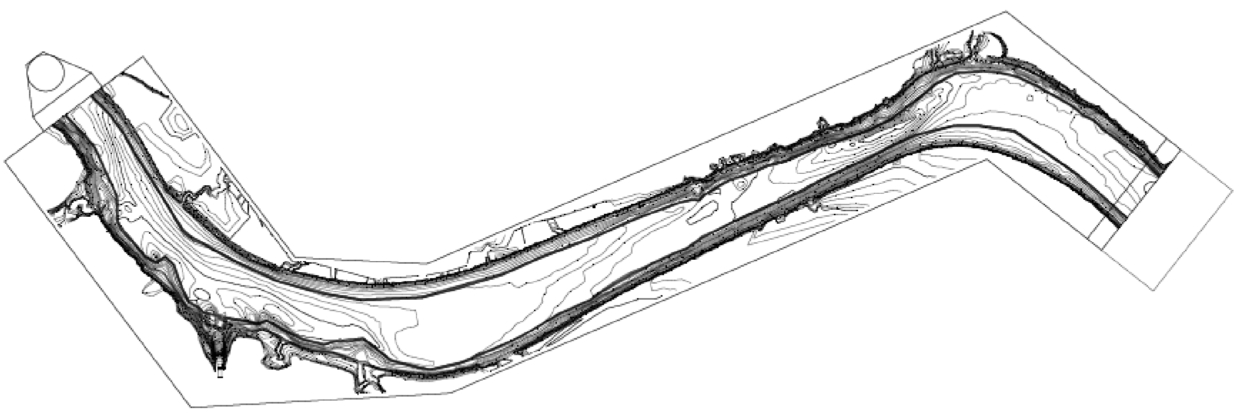

Figure 3-4: Contour map of river bed elevation.

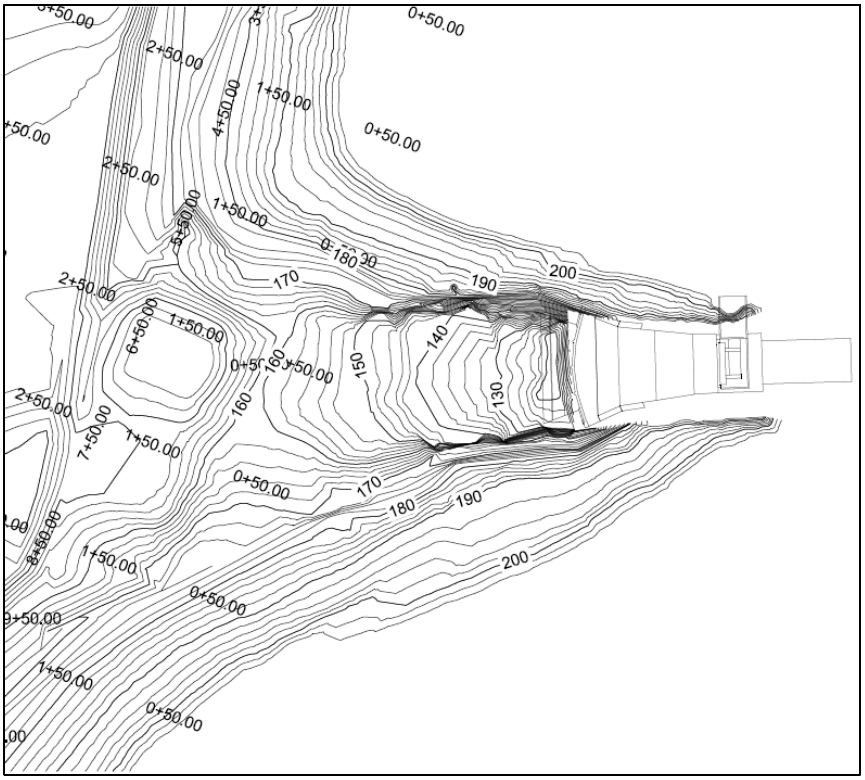

Figure 3-5: Detailed view of intake bathymetry.

3.5 Sediment Sampling Program

Surface sediment samples were collected at the planned locations along the Connecticut River and in the reservoir. A sieve analysis of the samples was performed to determine the sediment size distribution of the river material and the material which is transported to the reservoir. This data was necessary for the physical sediment transport modeling efforts. The grain size distribution was a significant component in determining the physical model scale. In total 10 samples were collected in the river and 11 samples were collected in the reservoir.

The sediment samples were mainly acquired using a Wildco Clamshell Ponar surface sediment grab sampler. The sediment samples were collected over a two day period. The location of the sediment samples is shown in Section 3.5.1. The nominal sediment sample size was approximately one liter; all samples were stored in durable plastic containers and returned to Alden for analysis at the completion of the field work.

The sediment is primarily sand with a specific gravity of 2.65 (specific gravity of quartz) and a density of 165 lbs/ft^3.

Alden staff determined the grain size distribution of each sediment sample using a set of mechanical sieves, a drying oven, a shaker, and a laboratory scale. The sieve analysis was completed in accordance with ASTM D422C.

3.5.1 Riverbed Sampling

River bed sediment sampling was conducted at the Route 10 bridge and near the intake as shown in Figure 3-6. At each location, five sediment samples were collected across the width of the river. Figure 3-7 shows the location and naming convention for the riverbed samples collected near the intake. Figure 3-8 shows the location and naming convention for the samples collected near the Route 10 bridge.

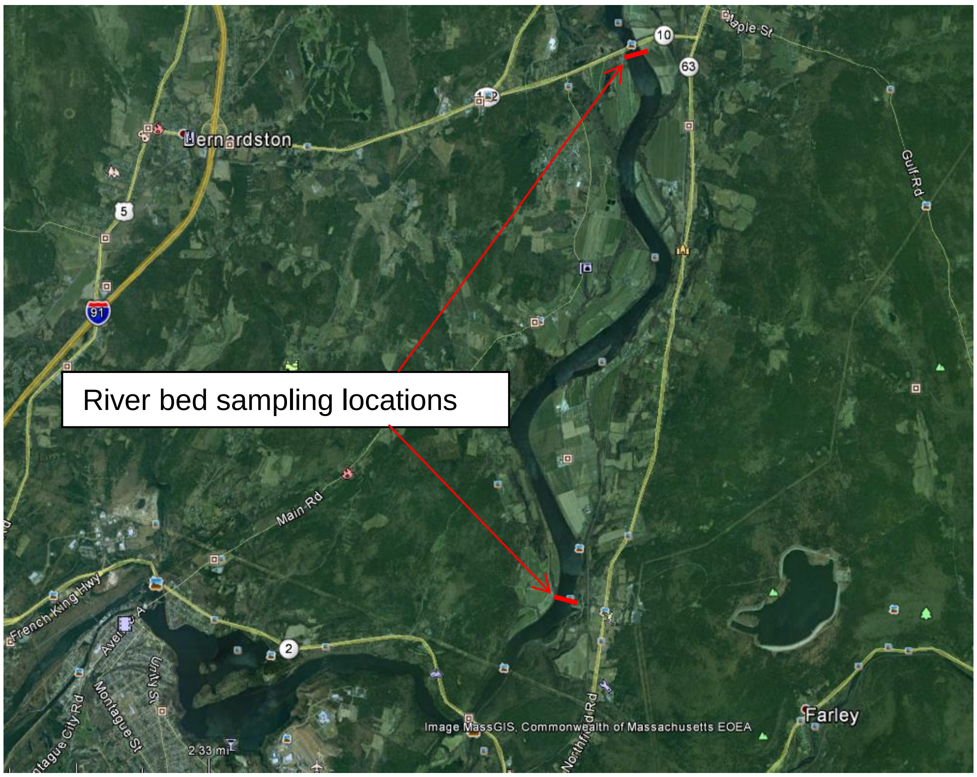

Figure 3-6: Location where sediment samples were collected.

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Figure 3-7: Location and D_{50} of riverbed sediment samples near intake.

Figure 3-8: Location and D50 of riverbed samples collected near Route 10 bridge.

Grain size distributions varied significantly, however some trends were identified. The river banks tend to be fine material with a D_{50} between 0.06 mm and 0.2 mm. The river banks are likely the ultimate source for the material found in the reservoir. Mid river samples have a D_{50} ranging from about 1mm to 25mm. Sieve analysis results are shown in Figure 3-9. The four finest samples were collected from the river banks and are samples 1 and 5. The three in river samples collected near the route 10 bridge are very coarse with a D_{50} greater than 10 mm. This material is not representative of the material being collected in the reservoir. Samples 3 and 4 appear to be the most representative characterization of the riverbed. Results for each individual sample are included in Appendix B.

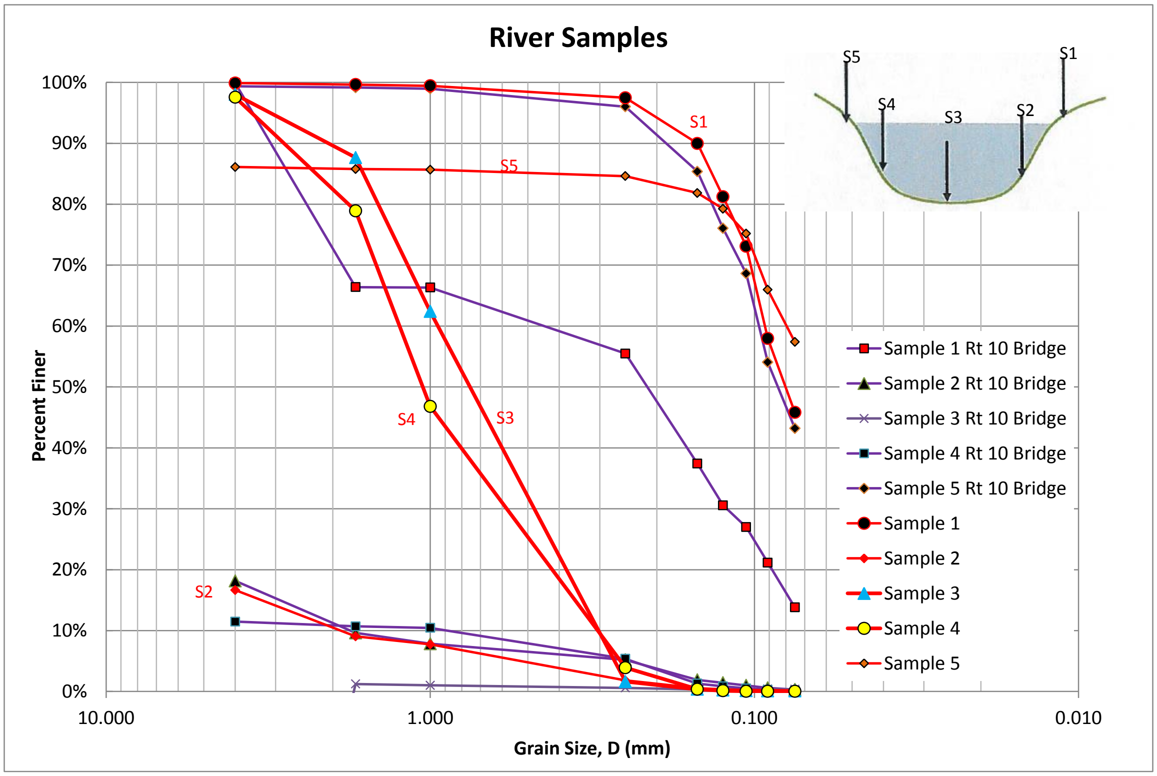

Figure 3-9: Sieve analysis results for riverbed samples.

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3.5.2 Suspended Sediment Sampling

Suspended sediment samples were collected daily for a period of five days from June 1, 2015 to June 5, 2015. The samples were collected at a river section directly upstream of the intake as shown in Figure 3-10. Nine samples were collected on every day for a total of 45 samples. The location of the samples is shown schematically in Figure 3-11. The samples were collected 25%, 50% and 75% of the distance across the river. Vertically, samples were collected about three feet below the water surface, at mid depth and about three feet from the river bed. A drop grab sampler was used for suspended sediment sampling. The sampler is comprised of an open tube with a spring loaded closure mechanism on each end. When the springs are triggered, the ends of the tube are rapidly close, collecting the water sample. A photo of the sampler is shown in Figure 3-12. Procedurally, the sampler is lowered to the river bottom to determine the water depth. Based on the measured depth, the sampler is then moved to the three locations in the water column for sample collection. Attached to the cylinder is a YSI CTD probe that continuously logs the depth of the sampler. This provides an independent verification that the sampler was at the correct depth. The water samples were sent to Tobin Labs for analysis of size distribution using laser granulometry.

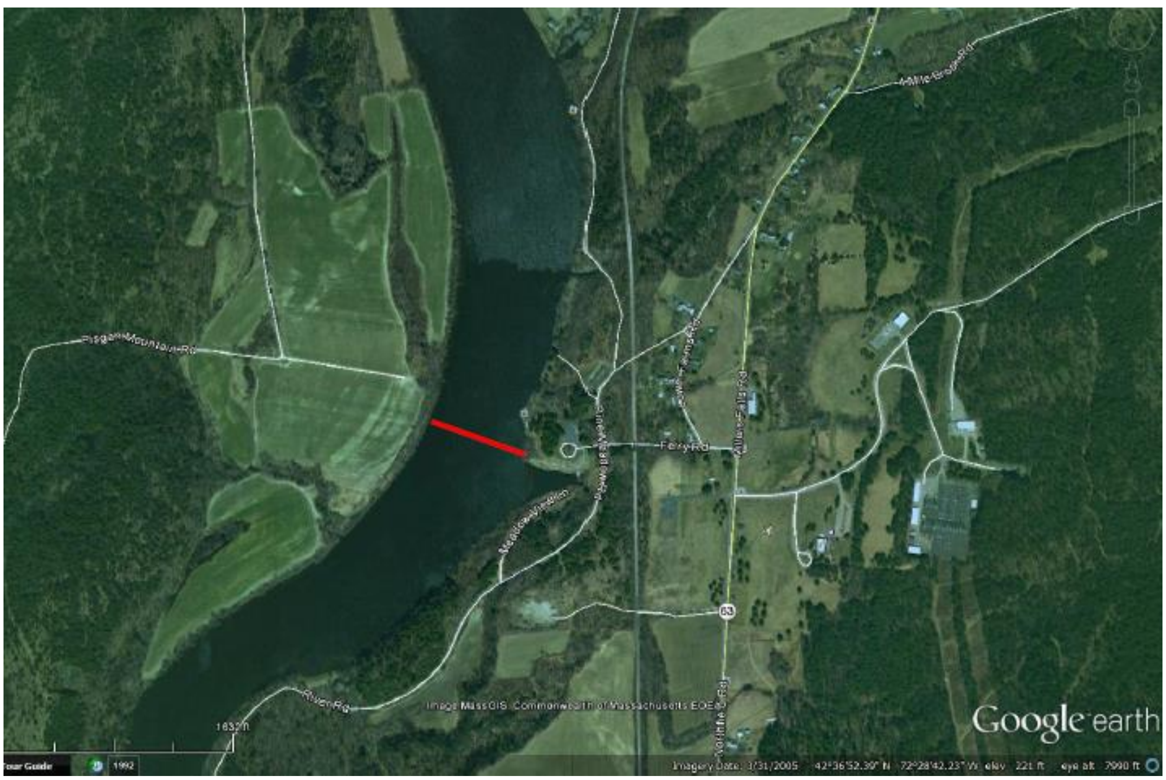

Figure 3-10: Suspended sediment sampling transect location.

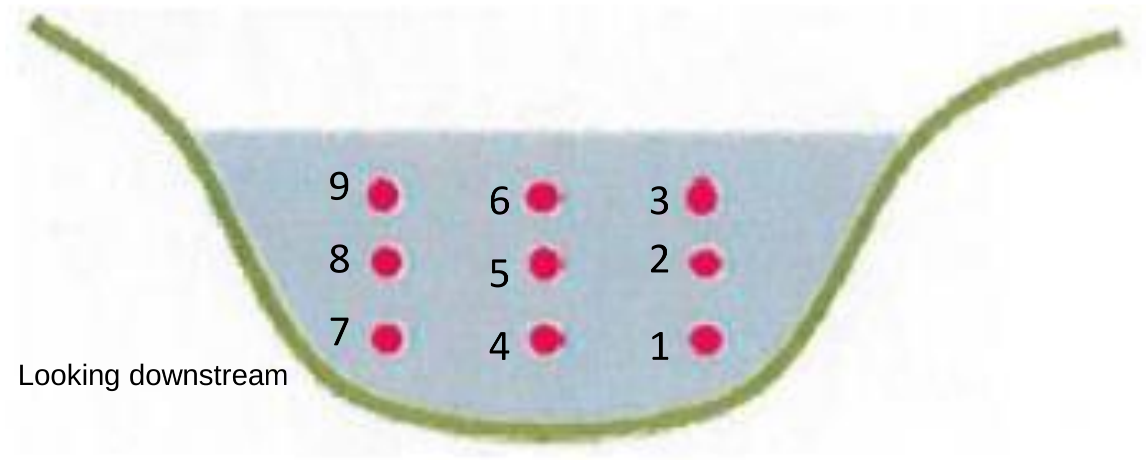

Figure 3-11: Schematic representation of suspended sediment sampling location.

Figure 3-12: Suspended sediment sampler.

Results of the analysis showed a very consistent grain size distribution. Figure 3-13 through Figure 3-17 show grain size distributions for nine samples on each day. Figure 3-18 shows all of the samples. River flow on the five days of data collection ranged from about 12,000 to 30,000 cfs.

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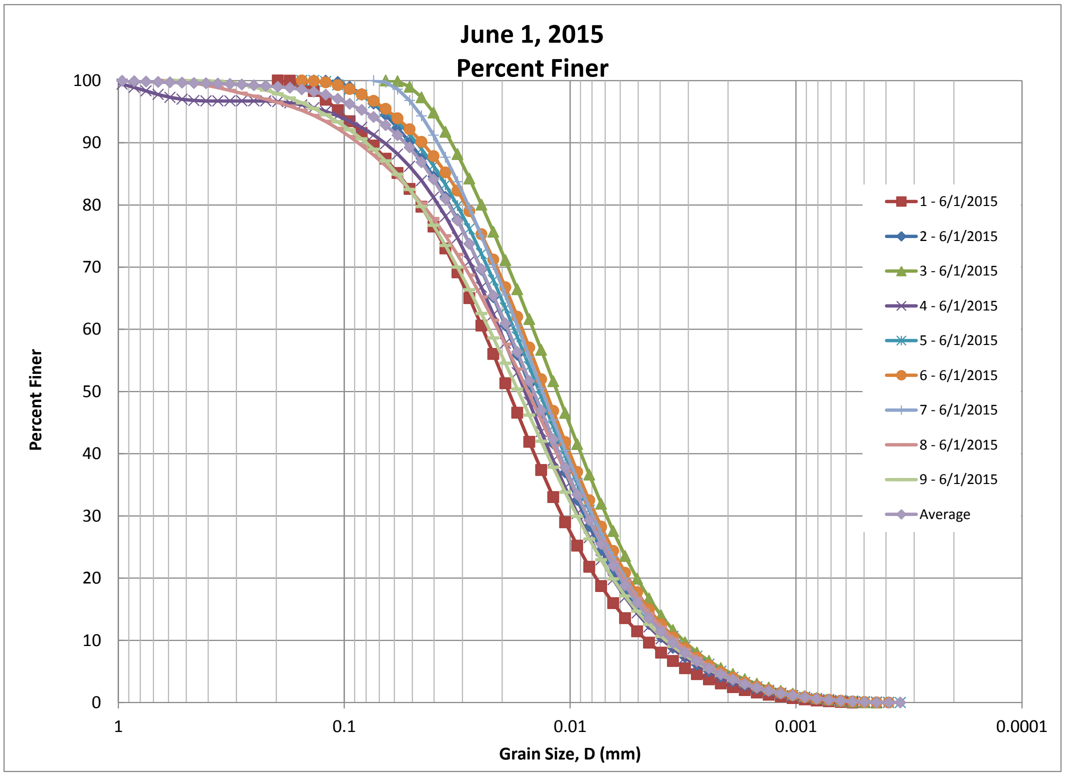

Figure 3-13: Suspended sediment samples, Monday June 1, 2015.

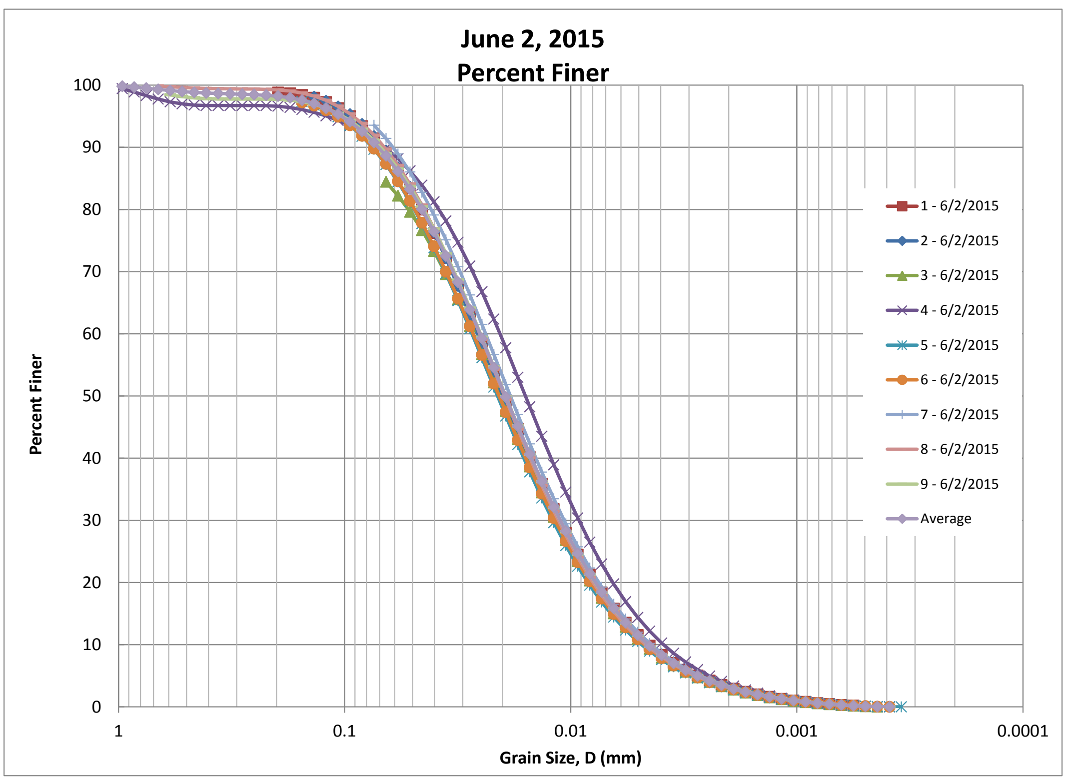

Figure 3-14: Suspended sediment samples, Tuesday June 2, 2015.

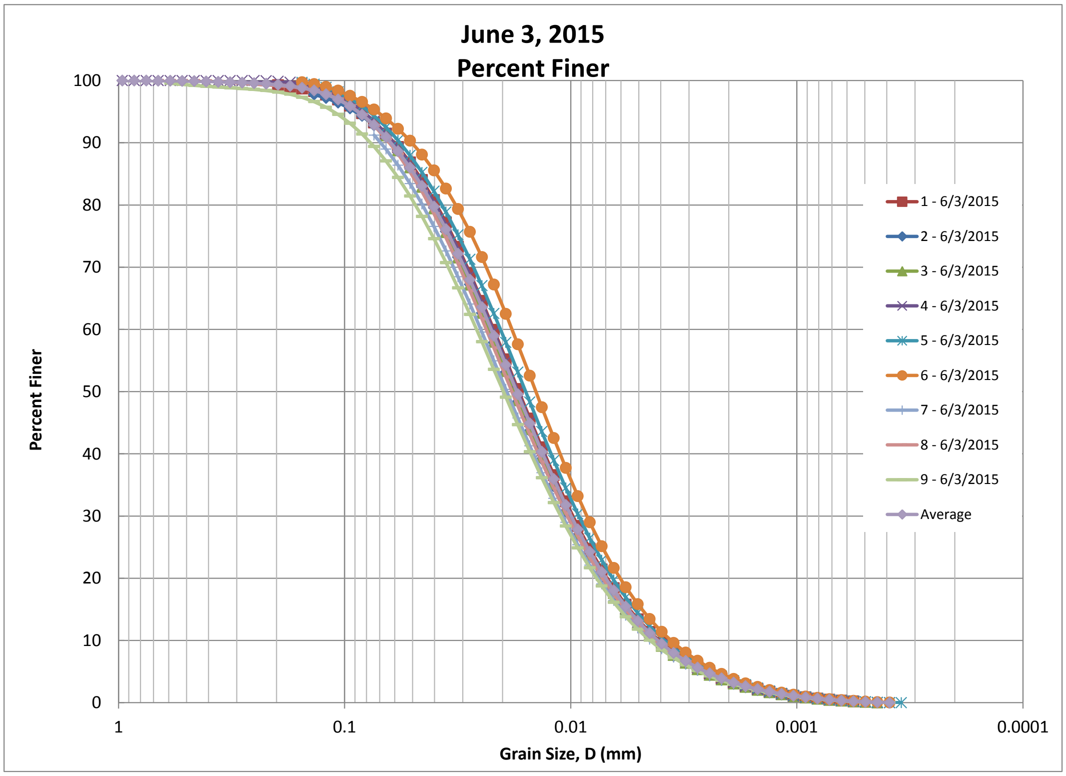

Figure 3-15: Suspended sediment samples, Wednesday June 3, 2015.

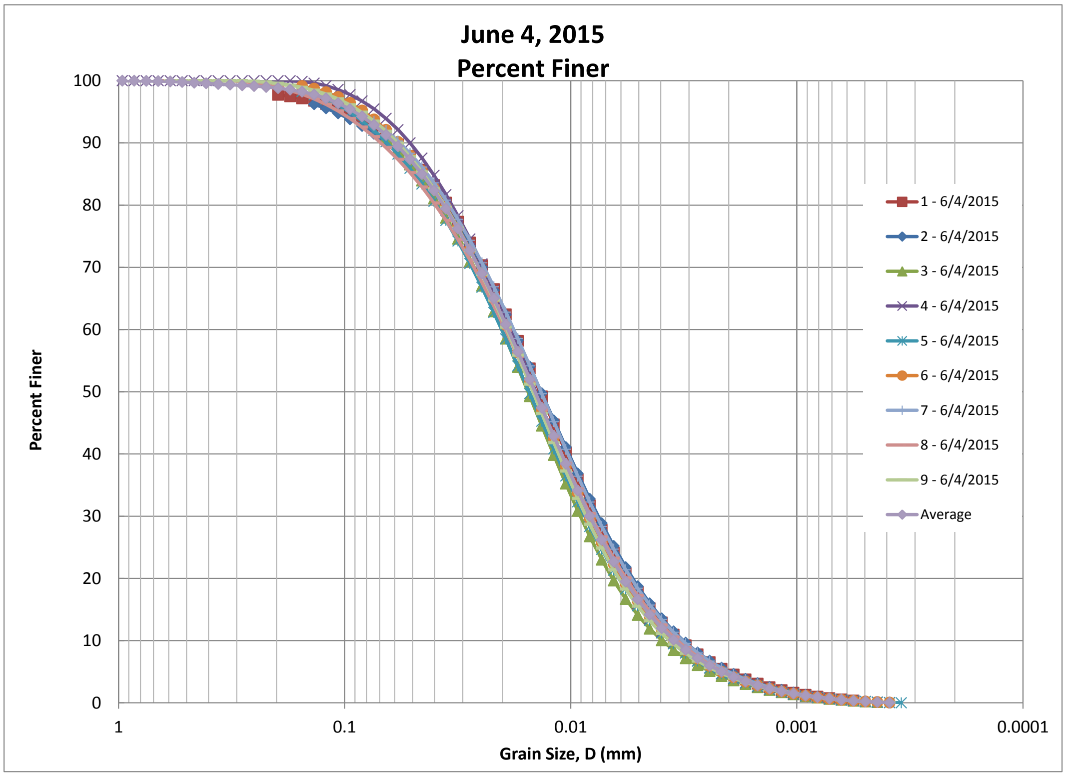

Figure 3-16: Suspended sediment samples, Thursday June 4, 2015.

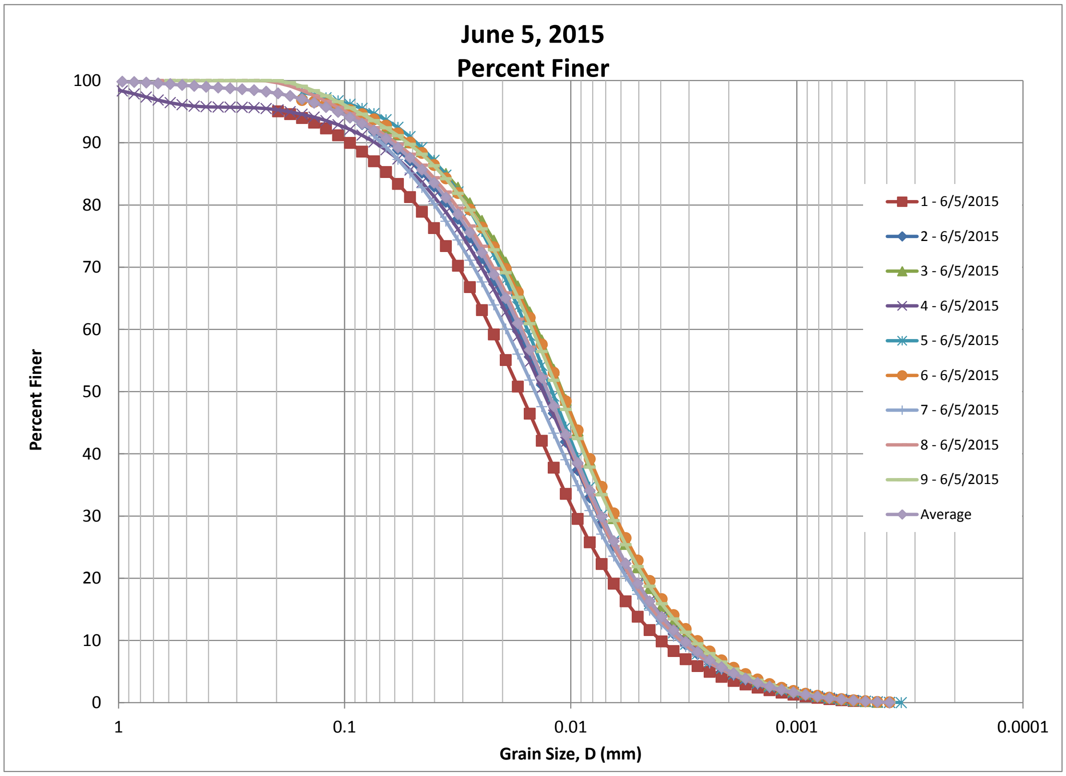

Figure 3-17: Suspended sediment samples, Friday June 5, 2015.

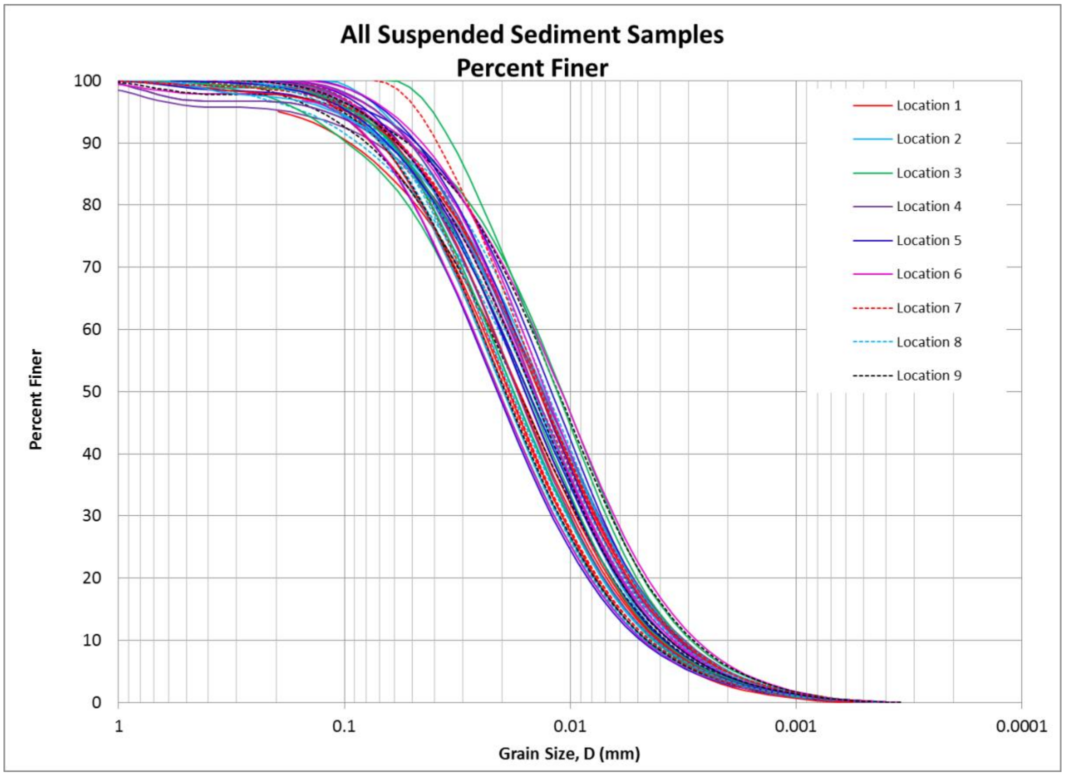

Figure 3-18: All suspended sediment samples, June 1 to June 5, 2015.

3.5.3 Reservoir Sampling

Eleven sediment samples were collected from the reservoir to determine the particle size distribution of the material trapped in the reservoir. The reservoir grain size distribution is important because it helps in determining if the material in the reservoir is bed load or suspended load. Bed load is material that is moving near the river bed while suspended load is material that is moving in suspension in the water column. It is important to note that sediment which may be bedload can become suspended load at a higher river flow. If most of the material in the reservoir has a similar size distribution to the suspended sediment samples, then the opportunities for reducing the amount of sediment pumped to the upper reservoir are more limited. Figure 3-19 shows the location where the sediment samples were collected. A particle size analysis was completed and the D50 for each sample is shown in Figure 3-20. Figure 3-20 shows the complete grain size distributions for each reservoir sample. Results for each individual sample are included in Appendix B.

A single plot showing the particle size distribution for river sediment, suspended sediment and reservoir sediment is shown in Figure 3-21. Some of the river samples are similar to the reservoir samples, however, most are coarser. The river suspended sediments are much finer than the sediments found in the reservoir.

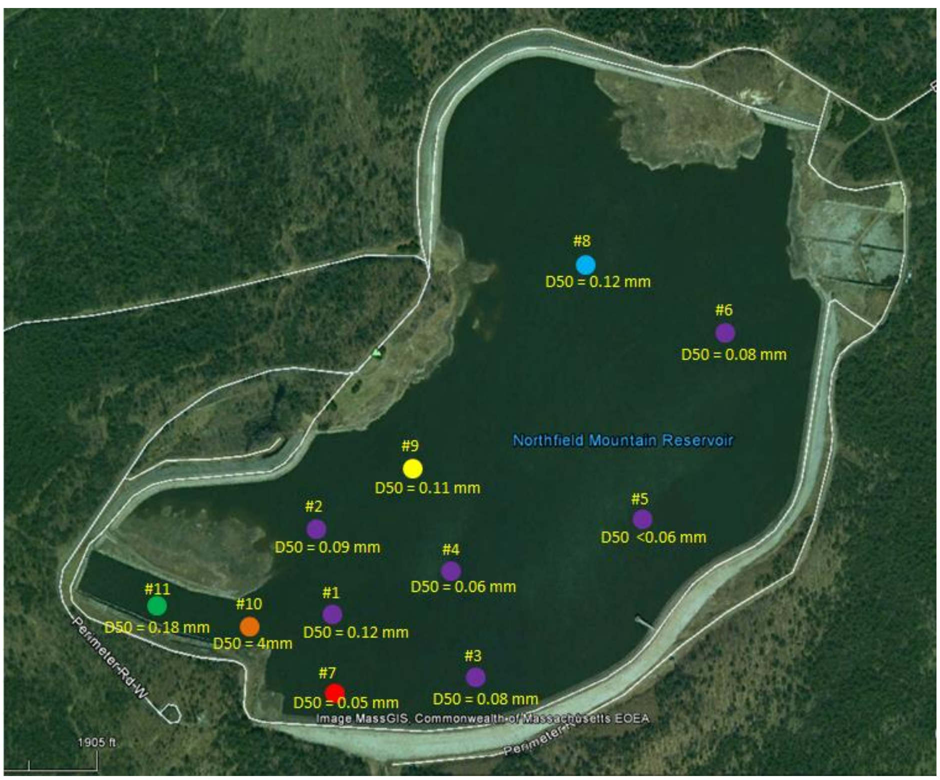

Figure 3-19: Location of reservoir sediment samples.

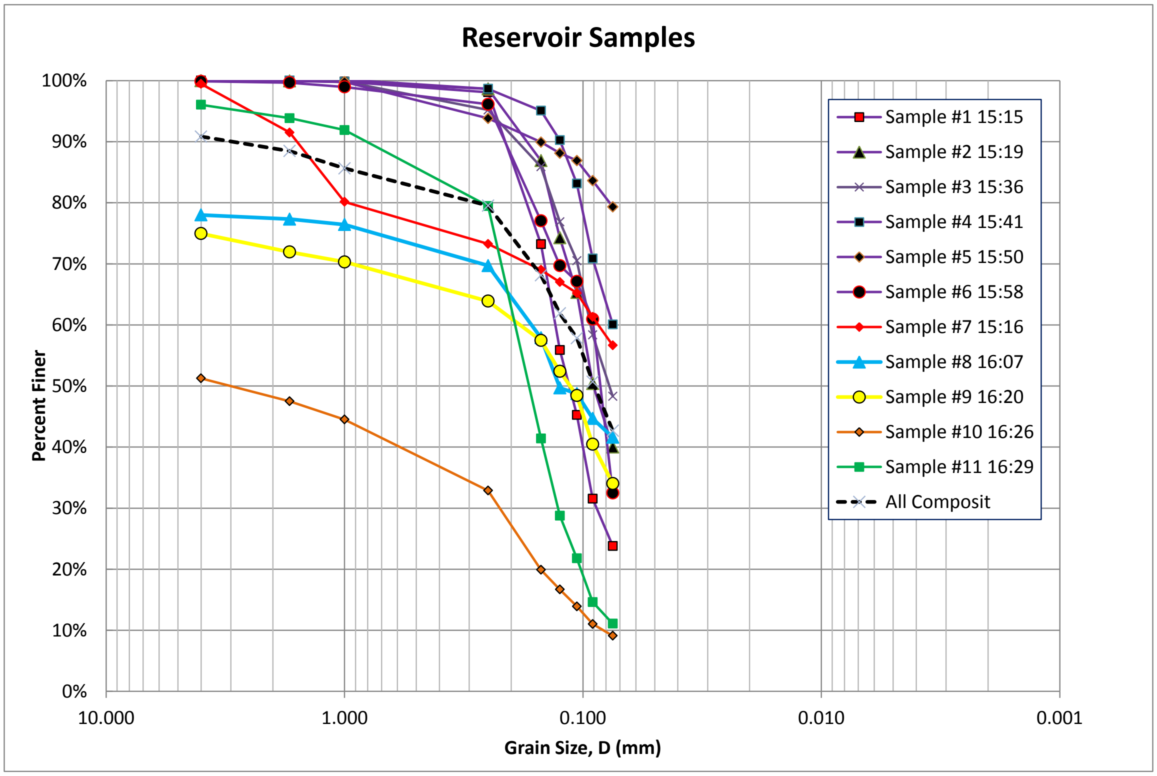

Figure 3-20: Reservoir sediment sample gradations.

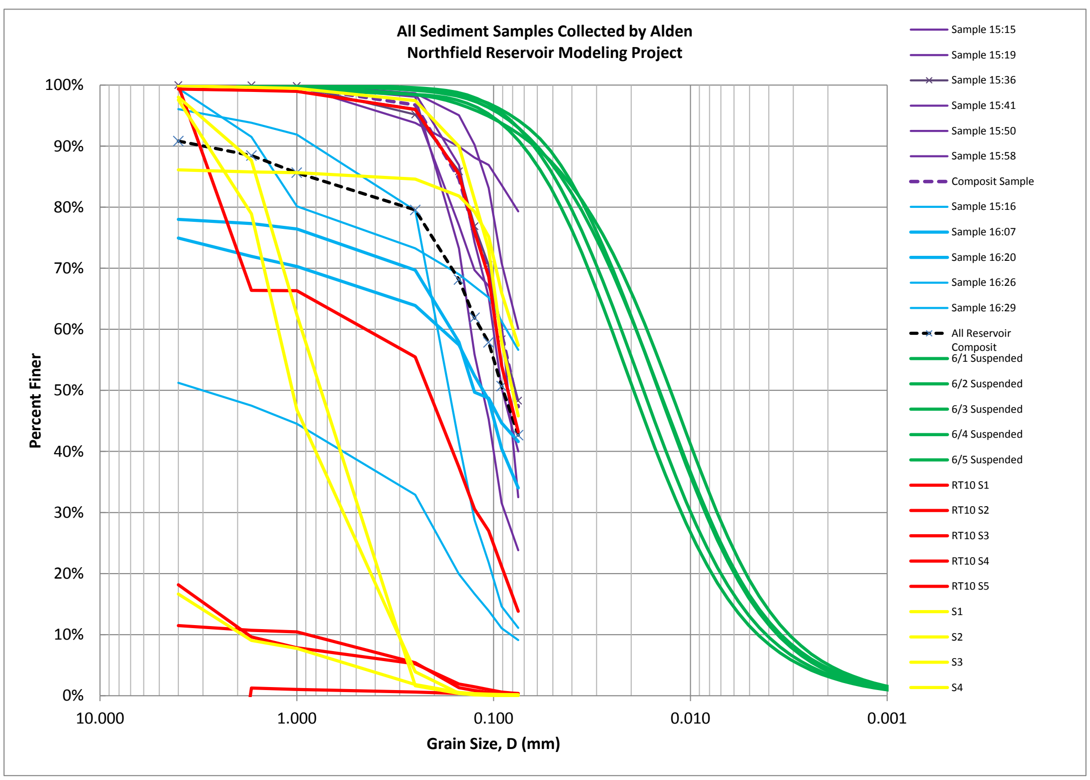

Figure 3-21: All sediment samples collected by Alden for Northfield project.

4.0 Physical Modeling

A 1 to 100 scale live bed model of the Northfield River was constructed. The model domain is about 2.5 miles (4 km as specified in the RFP) in length and extends from about 2 miles upstream of the intake to 0.5 miles downstream of the intake. The river is about 700 feet wide near the intake and river flow between 2000 and 2010 ranged from near zero to about 70,000 cfs. The following sections describe the model scaling, sediment selection, construction, instrumentation, testing program and testing procedure.

4.1 Physical Model Similitude

The Northfield physical model involves free surface flow (an open river) and sediment transport. Scaling criteria must be satisfied for both processes and are discussed in sections 4.1.1 and 4.1.2 respectively.

4.1.1 Model Scaling For Free Surface Flow

Models involving a free surface (rivers) are constructed and operated based on Froude similitude because the flow physics are dominated by gravitational and inertial forces. The dimensionless Froude number, representing the ratio of inertial to gravitational forces, can be defined as,

$$Fr = \frac{V}{\sqrt{gd}} \qquad (4-1)$$

where

V	=	depth average river velocity
g	=	gravitational acceleration
d	=	river depth

The Froude number must be equal in the model and prototype therefore,

$$Fr_r = \frac{Fr_m}{Fr_p} \qquad (4-2)$$

where subscripts m, p, and r denote model, prototype, and the ratio between model and prototype, respectively. In addition to matching the Froude number in the model and prototype, the model Reynolds number must be sufficiently large that flow remains in the fully turbulent range (greater than 10,000). The Reynolds number for open channel flow is given as:

$$Re = \frac{V4d}{\nu} \qquad (4-3)$$

where

ν	=	kinematic viscosity of water.

All other variables are as defined previously.

For a 1:100 scale model, the model scale ratios are given in Table 4-1.

Table 4-1: Model Scale Ratios for 1:100 Scale Model

Scaled Item		Model with Froude Similitude
Length Scale $L_r = L_m/L_p$		1/100
Velocity Scale $V_r = V_m/\ V_p$	$V_r =\ L_r^{1/2}$	1/10
Flow Scale $Q_r = Q_m/Q_p$	$Q_r = u_r A_r =\ L_r^{5/2}$	1/100,000
Time Scale $T_r = T_m\ /\ T_p$	$T_r = \frac{L_r}{u_r} = L_r^{1/2}$	1/10

Based on the available historic flow data, for a river flow of about 70,000 cfs, the water velocity varies from about 2 ft/s near the shore to about 6 ft/s in the main channel, and the water depth ranges from about 5 to 45 feet. The kinematic viscosity of water is 1.210 x 10^{-5} ft^2/s. Based on the scaling ratios given in Table 4-1, at 70,000 cfs river flow the model velocity is about 0.2 ft/s to 0.6 ft/s, and the depth is about 0.05 ft to 0.45 ft, giving a model Reynolds number between about 4,500 and 85,000. For lower river flows the Reynolds number is lower. For the main channel and most of the forebay area the model Reynolds number was in the fully turbulent range. Areas along the shore can have a Reynolds number less than 10,000. Also, low flow conditions with lower water depths and prototype velocities less than 2 feet per second may have a Reynolds number near 10,000. At high flows the model is expected to have minimal viscous scale effects, however, at low flows viscous effects on model results and sediment transport should be considered.

4.1.2 Model Scaling For Sediment Transport

In a mobile bed model, the grain size (sediment size) scales with the length scale of the model. In a 1:100 scale model, a 2 mm sediment particle is modeled with a 0.02mm sediment particle. In some cases, it is not practical to scale the sediment with the length scale. This occurs when the prototype sediment is fine and scaling the sediment with the length scale yields a particle size that is not available. It can also happen when the required model domain is large and the resulting physical model size exceeds the available building space, or the resulting model size becomes cost prohibitive. A model where the sediment is scaled with the length scale is commonly defined as an ‘undistorted’ physical model in the scientific literature.

Engineers have developed compromise methods to model sediment transport when the sediment cannot be scaled with the model length scale. When the sediment is not scaled with the length scale, typically the particle sizes in the model are too large. The larger particles do not transport as readily as the particles in the prototype and the model will require a greater flow at which sediment transport begins (incipient motion). Incipient motion occurs when the shear stress exceeds the critical shear stress for the particle. To increase the sediment transport in the model, the model scale can be distorted by using light weight sediment with a larger grain diameter. The light weight material will more readily transport than sediment with the same density as the prototype. The Shields diagram shown in Figure 4-1 relates the dimensionless critical shear stress where incipient motion begins with the grain

Reynolds number. Based on the Shields diagram a suitable particle diameter and density can be found that can be used as a surrogate in the model. Using a surrogate particle in the model is typically referred to as the use of lightweight sediment.

Using lightweight sediment will result in incipient motion that more closely occurs at the same river flow in the model and prototype. However, the lightweight sediment introduces additional potential scaling problems. The lightweight sediment is too coarse relative to the model length scale, and may result in a channel roughness that is too high and water surface slope that is too steep. In this application, the sediment size used in the physical model has a diameter between 0.09 to 0.22 mm with a D_{50} of 0.17 mm; the prototype reservoir sediment has a D_{50} of about 0.09 mm and the prototype river bed sediment has a D_{50} between 0.06 to 38mm. While the model sediment scaled up to prototype dimensions has a diameter of about 17 mm. In this application, based on detailed analysis of the river sediments and available model sediments, the use of light weight sediment was projected to have minimal adverse effect on the model results.

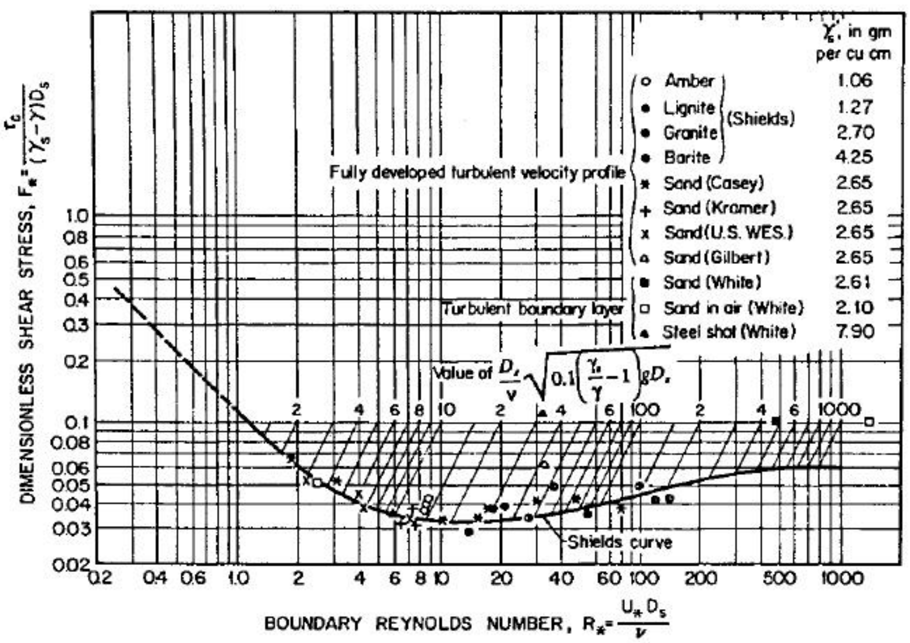

Figure 4-1: Shields diagram relating critical shear stress to grain Reynolds number.

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Sediment transport occurs when the shear stress on a river bed exceeds the critical shear stress required for particle motion. The shear stress can be computed from the following equation (Julien, 1995)

$$\tau_o = S_f \gamma_m R_m \qquad (4-4)$$

where

τ_o	=	shear stress,
S_f	=	friction slope (same in both model scales and the prototype),
γ_m	=	density of water (same in both model scales and the prototype), and
R_m	=	hydraulic radius.

The hydraulic radius is defined as the cross sectional area of a channel divided by the wetted perimeter. For a shallow and relatively wide river such as the Connecticut River, it can be shown that the hydraulic radius is very nearly equal to the depth, d. The depth varies directly with the length scale; therefore the shear stress in the model is directly proportional to the length scale of the model.

The Shields parameter can be computed from the shear stress and the particle diameter:

$$\tau_* = \frac{\tau_o}{(\gamma_s - \gamma_w)d_s} \qquad (4-5)$$

where:

τ_*	=	Shields parameter
γ_s	=	Specific gravity of sediment
γ_w	=	Specific gravity of water
d_s	=	Particle diameter

When the Shields parameter exceeds the critical Shields parameter, particle motion occurs. The Shields parameter in the model must match the Shields parameter in the prototype. The model Shields parameter will match the prototype Shields parameter when the particle diameter scales with the model length scale. Alternatively, a combination of particle diameter and length scale can be used to satisfy the Shields parameter similitude requirement. Once incipient motion is reached, the amount of sediment being transport is a function of shear stress as well and also requires that the model and prototype Shields parameter are equal. Transport volumes are proportional to the length scale and the sediment transport time scale is the same as the hydrodynamic time scale shown in Table 4-1. In this application, the model length scale (1:100) was set by the model RFP.

For a specific model length scale and prototype particle size, particle diameter and density combinations were computed that resulted in Shields parameter parity in the model and prototype.

$$\frac{\tau_{o\,model}}{(\gamma_{s\,model} - \gamma_w)d_{s\,model}} = \frac{\tau_{o\,proto}}{(\gamma_{s\,proto} - \gamma_w)d_{s\,proto}} \qquad (4-6)$$

From equation 4-6 it was shown that the model shear stress is related to the prototype shear stress through the length scale. Therefore equation 4-6 can be rewritten as follows:

$$\frac{(\gamma_{s\,proto} - \gamma_w) d_{s\,proto}}{(\gamma_{s\,model} - \gamma_w) d_{s\,model}} = \frac{\tau_{o\,proto}}{\tau_{o\,proto}/L_r} \qquad (4-7)$$

For a length scale of 1:100, L_r = 100, equation 4-7 simplifies to:

$$(\gamma_{s\,proto} - \gamma_w) d_{s\,proto} = 100\ (\gamma_{s\,model} - \gamma_w) d_{s\,model} \qquad (4-8)$$

The specific gravity of water is 1 and the specific gravity of the prototype sand is 2.65 (specific gravity of quartz). Substituting the values into equation 4-8 yields the following relationship between model particle diameter and specific gravity:

$$0.0165\ d_{s\,proto} = (\gamma_{s\,model} - 1) d_{s\,model} \qquad (4-9)$$

For a specific prototype particle diameter, such as 0.25 mm, combinations of model particle diameter and density can be computed that satisfy equation 4-9 and therefore will also result in Shields parameter parity in the model and prototype. Figure 4-2 shows combinations of particle diameter and density that satisfy equation 4-9 for a 1:100 model scale and prototype particle sizes of 0.05 mm, 0.1 mm, and 2.0 mm.

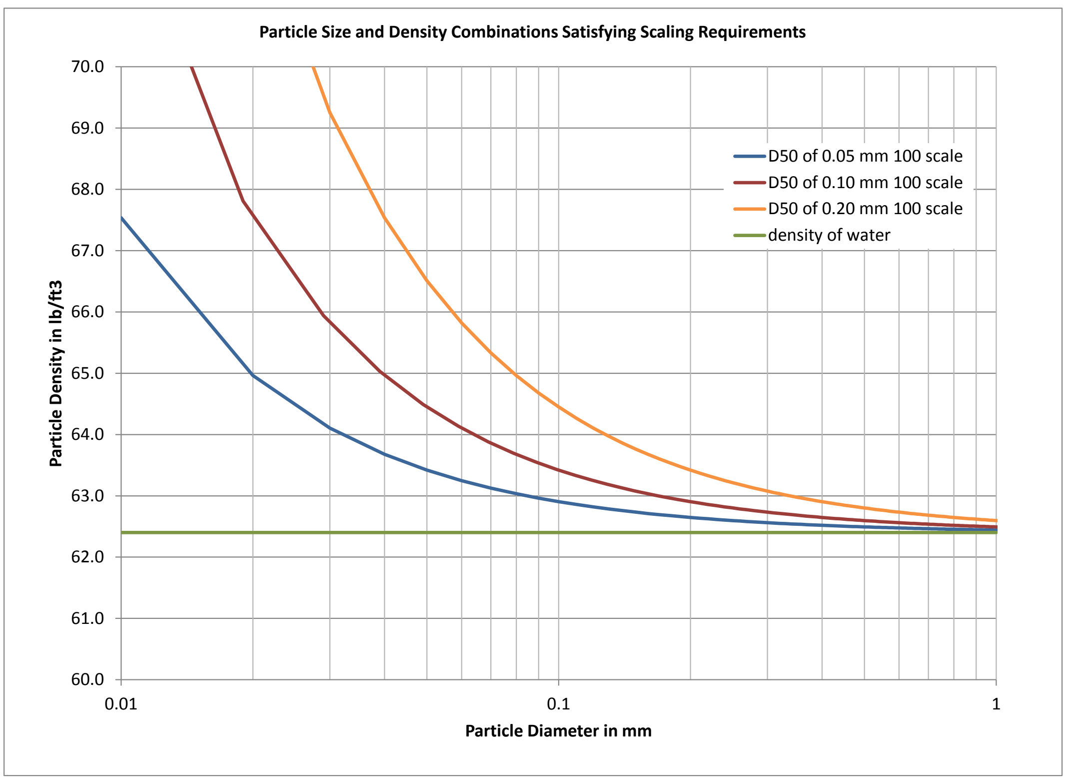

Figure 4-2: Combinations of particle diameter and density that satisfy scaling.

The suspended sediment concentration in a river varies with location in the water column. Concentrations are higher near the river bed and lower near the water surface. This occurs because gravity pulls particles towards the bottom of the water column. Under the assumptions that suspended sediment is sourced from the channel bed and that entrainment and deposition at the bed are in a state of equilibrium, the vertical distribution of sediment concentration, C, can be estimated based on the work of Rouse (1937):

$$\frac{C}{C_a} = \left(\frac{h-z}{z}\frac{a}{h-a}\right)^{Ro=\omega/(\beta_s \kappa u_*)} \quad (4-10)$$

where

z	=	Height above the bottom,
h	=	Total depth,
Ro	=	Rouse number which sets the overall shape of the profile,
C_a	=	Near-bed concentration measured at a height of a.

The assumed constants are $\beta_s \approx 1$ and $\kappa \approx 0.41$. The Rouse number is a function of particle settling velocity, ω, and the boundary shear velocity, u_*.

The settling velocity for each representative grain size is determined from either lab measurements or equations published in various journals. The shear velocity must be determined from the hydrodynamics:

$$u_* = \sqrt{\frac{\tau_0}{\rho_w}} \quad (4-11)$$

Where:

τ_0	=	Bed shear stress and
ρ_w	=	Density of water.

Assuming uniform flow, the average shear stress can be estimated from:

$$\tau_0 \approx \rho_w g h S_0 \quad (4-12)$$

Where:

S_0	=	Water surface slope.

All other variables are as defined previously.

Figure 4-3 shows the Rouse profile for a range of Rouse numbers. For Rouse numbers greater than 2.5, the primary means of sediment transport is bedload. For a Rouse number between 1.2 and 2.5 approximately 50 percent of the sediment transport is in suspension. For Rouse numbers between 0.8 and 1.2 the dominant form of sediment transport is suspended load. For the Connecticut River, the Rouse number varies from about 0.1 to 0.4 for a river flow of 70,000 cfs.

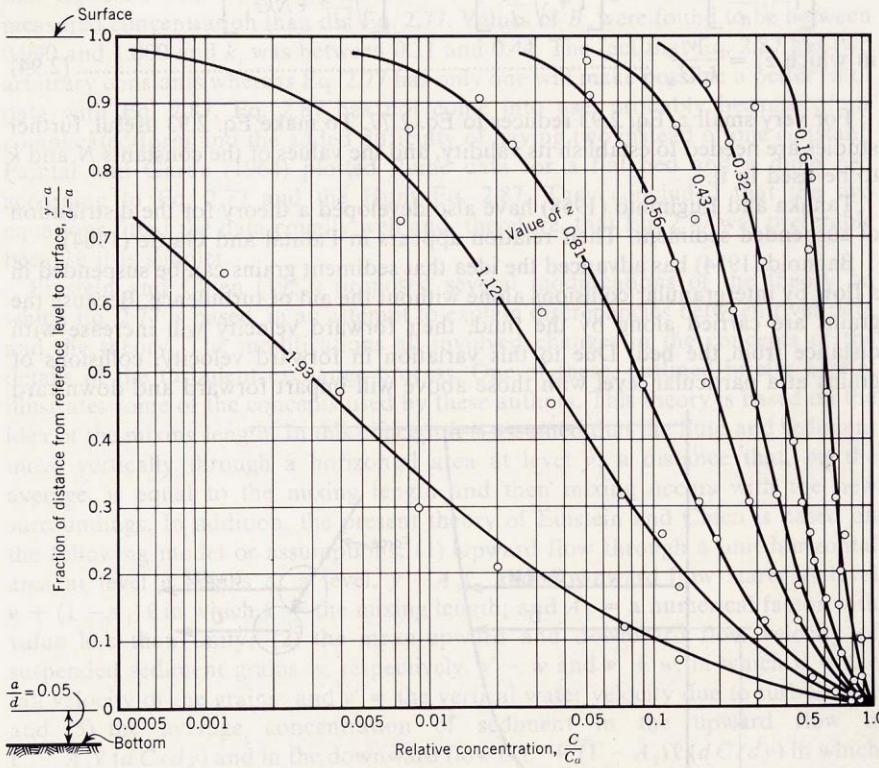

FIG. 2.34.—Vertical Distribution of Relative Concentration C/C_a Compared with Eq. 2.77 for Wide Range of Stream Size and z Values

Figure 4-3: Rouse diagram.

The purpose of the model is to determine the efficacy of a weir concept at reducing the amount of sediment entrained by the Northfield intake. To test the efficacy of a weir, the sediment concentration profile as described by the dimensionless Rouse number should be equal in the model and the prototype. The Rouse number is a ratio of the fall velocity to the shear velocity. Particle fall velocity is a function of particle diameter, density and shape. Fall velocity can be determined experimentally or analytically. Many papers have been written on computing particle fall velocity. Shear velocity is a function of the hydrodynamics, including the shear stress and the fluid density. Shear stress is a function of water depth and slope.

The sediment used in a model must balance technical objectives for the model with material costs. While it is possible to manufacture sediment with a specific gravity as low as 1.08, the sediment can be impractical to use. Particles that are custom manufactured with a prescribed grain size distribution and particle shape can also be manufactured, but the manufacturing costs can exceed the cost for constructing the model. At present, one of the most cost effective sediment materials available in the US is an acrylic type material that is used for blasting media. The material has a specific gravity of 1.18 and D_{50} of 0.17 mm with a very narrow particle size distribution ranging from 0.09 mm to about 0.22 mm. One limitation of the particles is that they are spherical rather than angular. A more detailed description of the model sediment selection is given in Section 4.1.3.

Spherical particles have a higher fall velocity than angular particles that have the same diameter and density. As a result, in the model, the particle fall velocity is 'too high' relative to the shear velocity. Consequently the suspended sediment concentration in the model is too low near the water surface and too high near the river bed. This can be quantified using the Rouse model for computing suspended sediment concentration profiles. Figure 4-4 shows the Rouse curves for three prototype particle diameters from the reservoir: The minimum D50, the average D50 and the maximum D50. For the maximum D50, one of the samples near the intake was not considered because it had a D50 of about 3mm, which is inconsistent with the of other samples. The location of each sample was previously shown in Figure 3-19. The curves are computed for a river flow of 70,000 cfs. All of the curves have a Rouse number less than about 0.4, indicating that suspended load is the dominant form of sediment transport. The average D50 profile shows a mid-depth sediment concentration which is 70 percent of the near bed concentration. For context, Figure 4-4 shows the suspended sediment concentration profile for a Rouse number of 1 and 2.

The suspended sediment concentration for the model sediment is shown with a red dashed line in Figure 4-4. The blue dashed line shows the suspended sediment concentration profile for an angular particle.

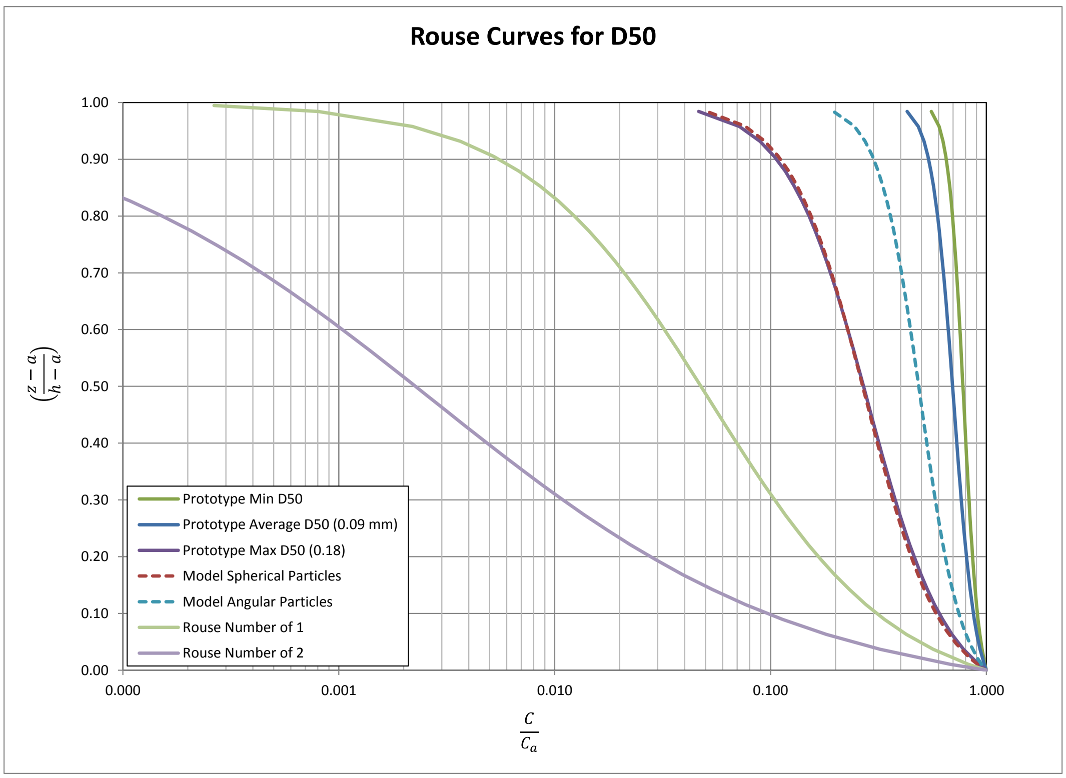

Figure 4-4: Rouse curves for nominal river flow of 70,000 cfs.

4.1.3 Selection of Model Sediment Material

Alden uses a variety of commercially available materials for lightweight sediment in models. Table 4-2 lists seven materials that were considered for the Northfield model. The particle size and density were plotted in combination with the particle size data shown on Figure 4-2 to determine the most suitable particle. The combined plots are shown in Figure 4-5.

Table 4-2: Sediment Material Considered for Model

Material Description	Average Diameter (mm)	Diameter Range (mm)	Density (lbs/ft^3)	Specific Gravity
100 micron sand	0.1		165.36	2.65
Walnut Shells	0.20	0.015 – 0.25	77.38	1.30
Red Beads 1/8th inch	3.175		74.88	1.20
Black Beads 1/8th inch	3.175		64.90	1.04
Acrylic Blasting Media	0.17	0.09 – 0.22	73.63	1.18
Acrylic Blasting Media	0.34	0.25 – 0.42	73.63	1.18
Acrylic Blasting Media	0.49	0.42 – 0.56	73.63	1.18
Clear Cut	0.20		74.88	1.20
Urea/Melamine	0.21	0.16 - 0.25	93.6	1.50
Urea/Melamine	0.34	0.25 - 0.42	93.6	1.50

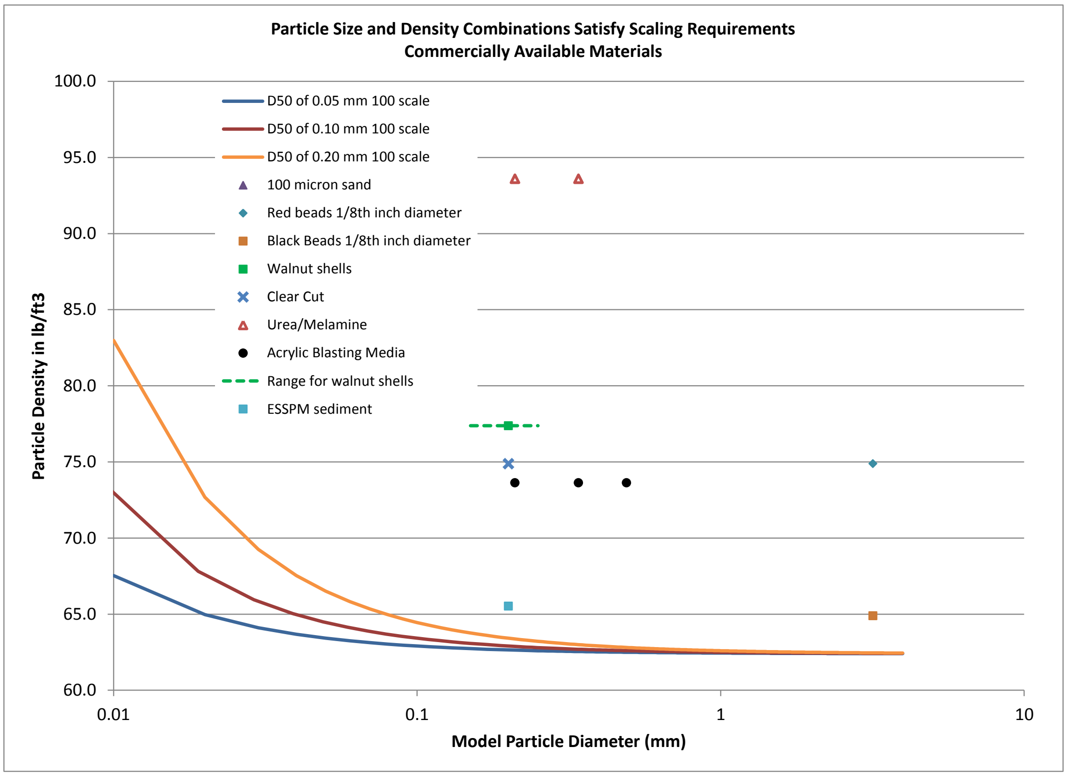

Figure 4-5: Required and available model particle diameters.

The best suited material from a modeling perspective is the ESSPM sediment. However, in the quantities that are required for this project that sediment is not financially viable. Further, the particle density is so near the density of water that use of the sediment requires very precise control of the water temperature with fluctuations no more than +/- 1 degree F. While technically feasible, maintaining water temperature within a 1 degree ranges is cost prohibitive. Of the commercially available material for use as model sediment, the acrylic blast media has the most desirable characteristics, recognizing that it is denser than optimal and spherical, resulting in a fall velocity that is higher than desired and a critical Shields parameter that is higher than desired. An alternative custom manufactured sediment was tested in the model but was found to be unsuitable. A more detailed description of the material is given in Section 4.1.4

4.1.4 Custom Sediment

During the initial phases of the project custom sediment was manufactured and used for the model. The sediment was manufactured by ParTRAC and had a lower specific gravity (~1.08) than the sediment that was ultimately used in the model. The D_{10} for the sediment was 0.11 mm, the D_{50} was 0.15 mm and the D_{90} was 0.25 mm and the particles had an angular shape. ParTRAC was the only vendor that responded to an inquiry for custom lightweight sediment that could be manufactured within project budgets. The sediment provided by ParTRAC had several limitations and after extensive testing in the model was ultimately found unsuitable for use in a hydraulic model. The raw material used by ParTRAC to manufacture the sediment was hydrophobic. Consequently the material would not sink when it came into contact with the water surface. The very low specific gravity was not sufficient to overcome the contact angle between the water and the material. Surfactants were added to the water and sediment to mitigate the hydrophobic properties of the sediment. Further testing with the material showed that suspended sediment concentrations in the river could vary by a factor 5 or more for identical testing conditions. Reproducibility of the riverine sediment concentration was critical to successfully comparing baseline conditions and the various design alternatives. After several months of testing it was concluded that the material provided by ParTRAC was not suitable for use in hydraulic models. The material was replaced with the acrylic blast media which provided highly reproducible results with variations of about 10 percent in river sediment concentration between repeat tests.

4.2 Physical Model Description

The physical model included the area shown in Figure 4-1. The model was constructed in Alden's Building 18 in Holden Massachusetts. Because the model has a live bed and recirculates sediment, it was constructed without a sump. Most hydraulic models withdraw water from a laboratory sump that is located under the building and return the water to the sump at the downstream end of the model. Because the sump will trap sediment, the Northfield model uses an offline water storage tank. At the beginning of a test, water is transferred from the tank to the model until the water level in the model reaches the approximate water level for the test. Water is then pumped from a small pump pit at the downstream end of the model through a pipe to the upstream end of the model, causing the river to flow. The pump pit is very small and is designed not to retain sediment. Suspended sediment and bedload sediment that exit the downstream end of the model are pumped to the upstream end. The resulting model has an inflowing sediment concentration that is approximately equal to the outflowing sediment concentration. As the sediment transport in the river increases or decreases, so does the amount of sediment entering the model. When possible, this system is the preferred approach for supplying sediment to the upstream end of the model. The alternative approach is to use sediment feeders. Sediment feeders are useful in non-equilibrium systems where the amount of sediment entering the model is known and can be set with the feeder. In small scale models that use lightweight sediment, the sediment is unable to break the surface tension of the water and must be injected underwater as a slurry. Figure 4-2 shows the model overview.

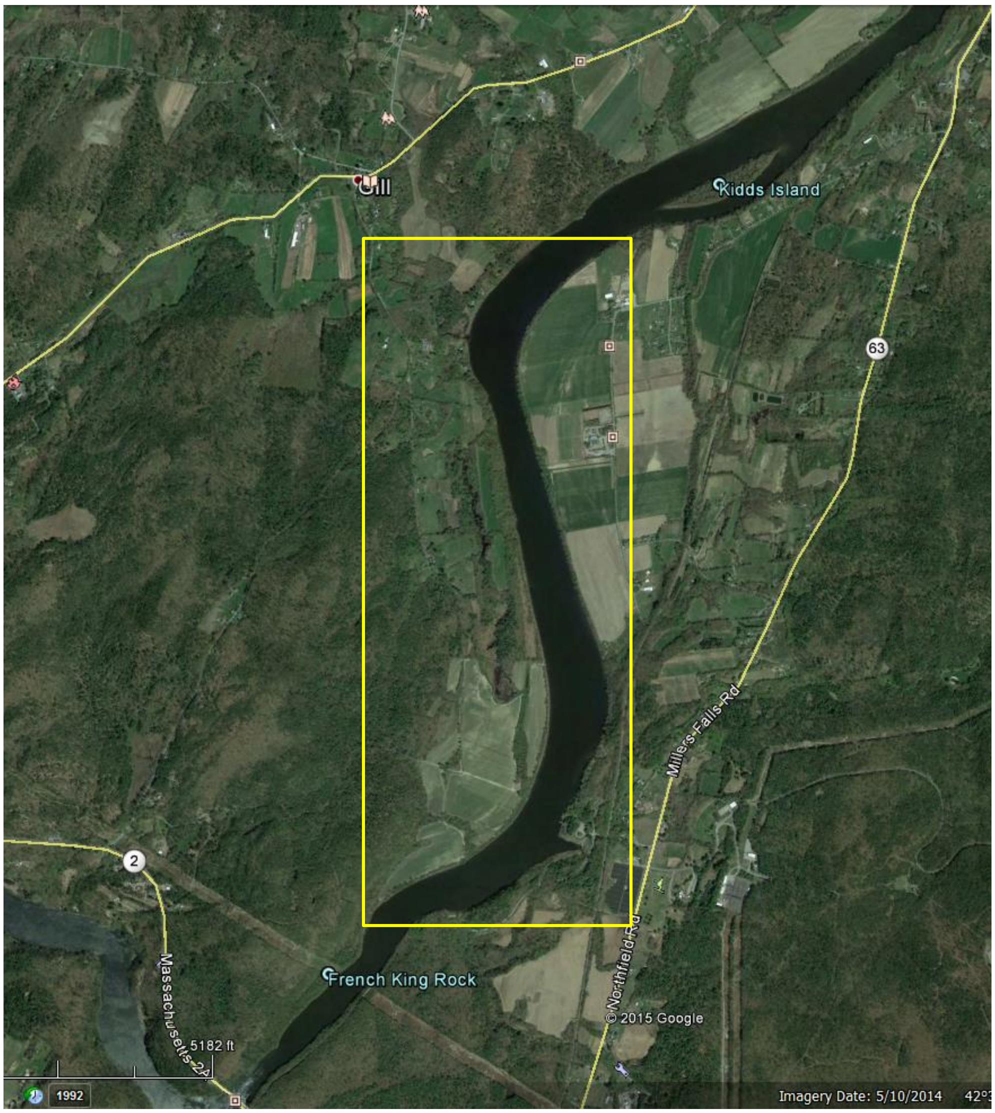

Figure 4-6: Model domain overview in Google Earth.

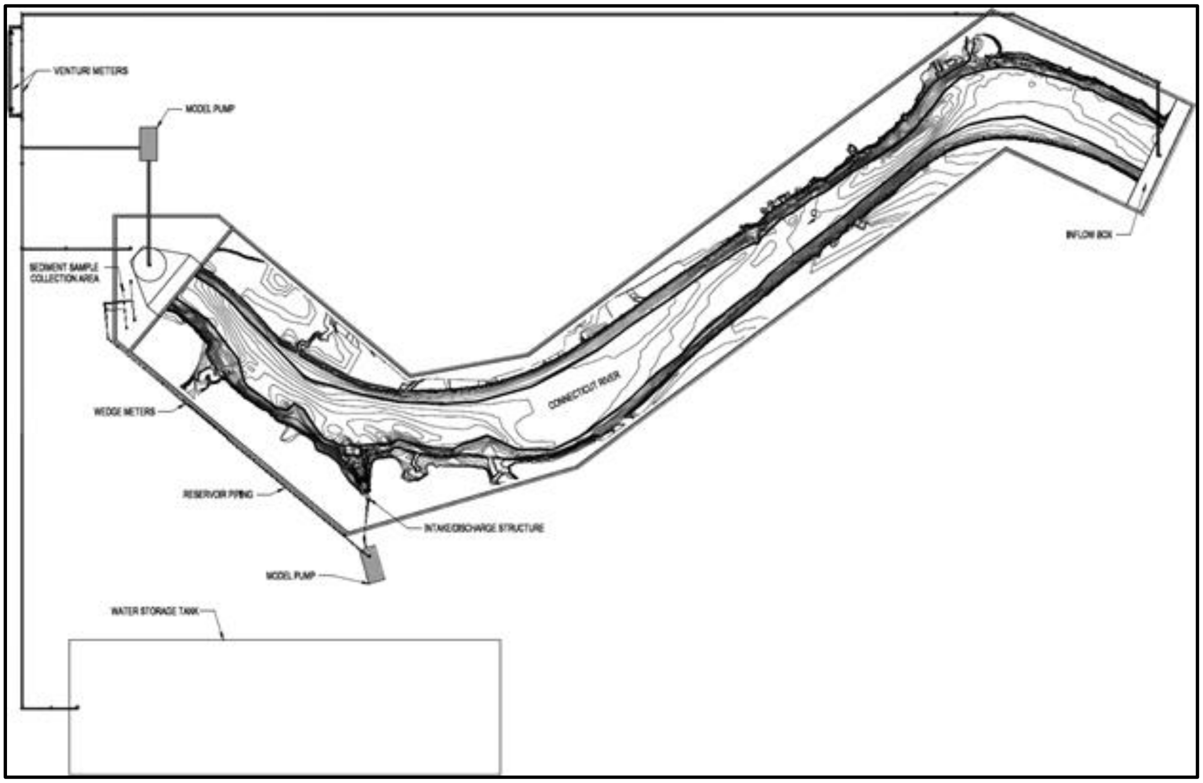

Figure 4-7: Physical model layout and major system components.

4.2.1 Model Construction

A 1:100 scale model of the plant intake/discharge structure was built including the 11,000 feet upstream and 2,600 ft downstream of the plant structure. The model topography was reproduced using 2 ft contour maps based on recent surveys (see Section 3.0). Aluminum templates were placed at 200 ft prototype (2 feet model) intervals perpendicular to the direction of flow from the discharge. The templates were then back filled with crushed stone which was topped with a thin layer of concrete screed to the template contours. Extra time was spent in the area where the river curves, to ensure that the bathymetry was representative in these areas. Figure 4-8 shows the model under construction near the downstream end. Figure 4-9 shows the model under construction near the intake. The mortar cap has been placed over most of the model and the intake is next to be installed.

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Figure 4-8: Model templates and spreading of fill material between templates.

Figure 4-9: Model with mortar cap near the intake which remains to be installed.

The intake/discharge structure was constructed from drawings provided by GDF Suez, and included the water passage ways from the entrance of the intake to where the penstock would connect to the structure. The intake structure was modeled using polylactic acid constructed in a 3D printer to maintain its dimensional accuracy and stability throughout the testing program. A photo of the intake structure is shown in Figure 4-10. Figure 4-11 shows the plan and profile view of the intake structure that was modeled. Figure 4-12 shows a section through the center of the intake\discharge structure. Figure 4-13 and Figure 4-14 show the completed model without sediment.

Figure 4-10: Modeled intake\discharge structure.

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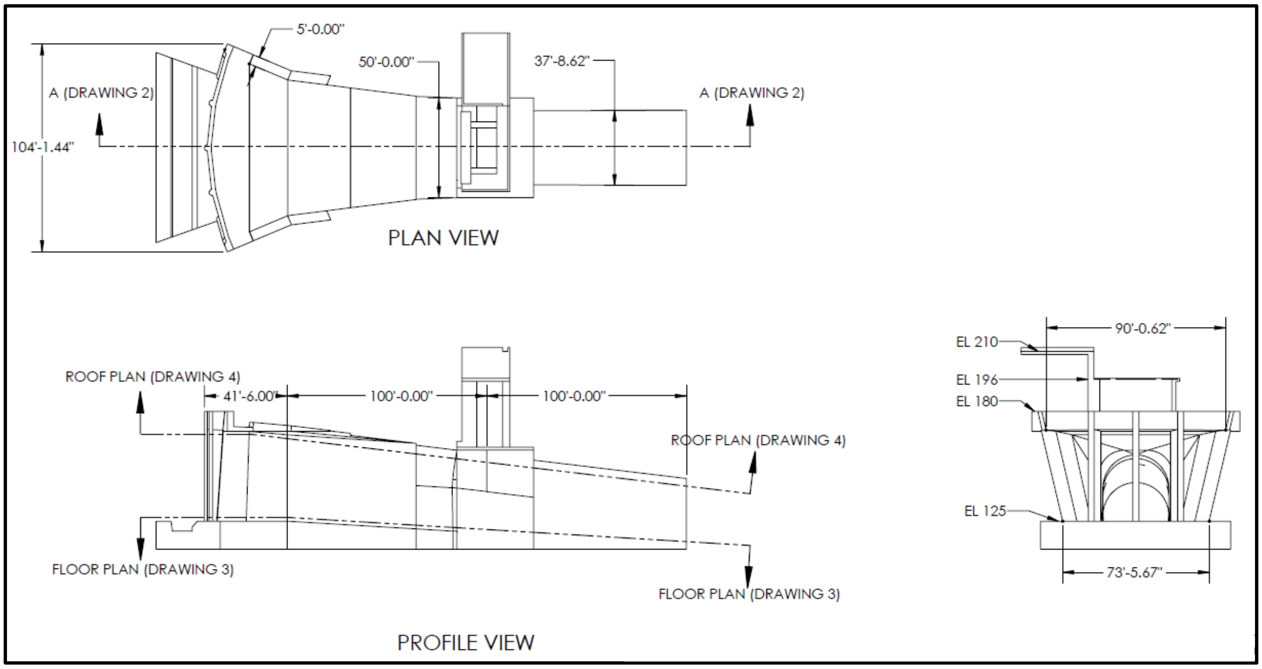

Figure 4-11: Plan and profile of intake\discharge structure.

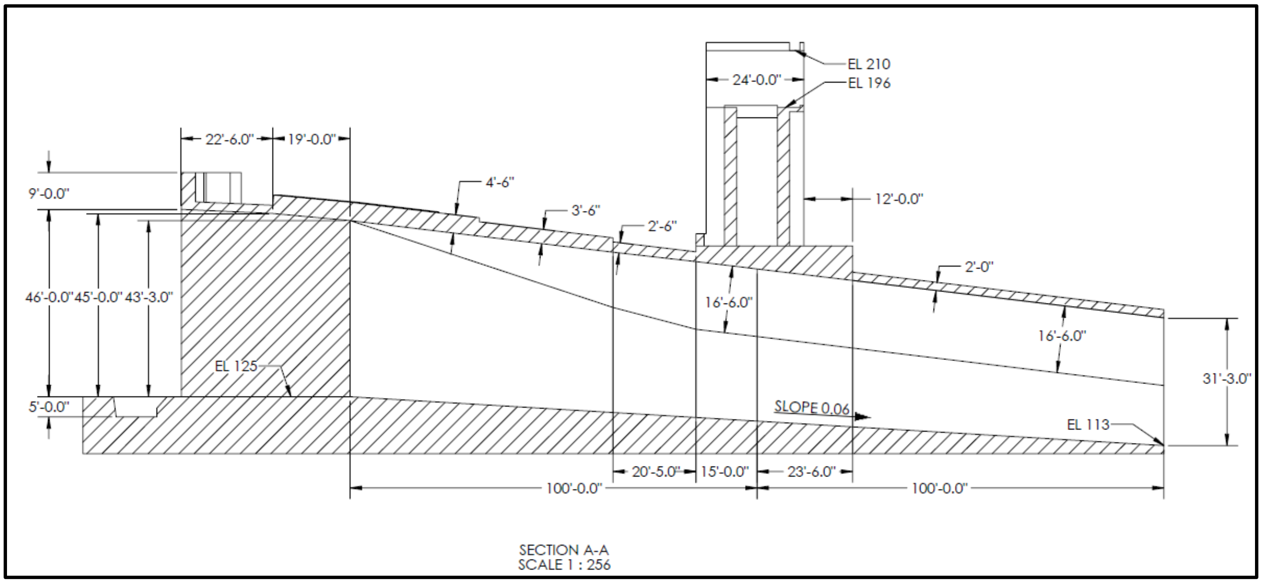

Figure 4-12: Section through intake\discharge structure.

Figure 4-13: Photo looking upstream of the Intake\Discharge structure.

Figure 4-14: Looking downstream from upstream end.

4.3 Instrumentation

The physical model included instrumentation to measure flow, suspended sediment concentrations, turbidity, water surface elevation, and water velocity. The following sections describe the instrumentation that was used for each measurement.

4.3.1 Flow Meters

Flow measurement in the model was accomplished using four differential pressure flow meters. Venturi meters were used in the two main supply lines from the pumps to the head box. Each Venturi meter has a calibration history with repeat calibrations at Alden. Figure 4-15 shows the two Venturi flow meters utilized to measure the main model river flow. The wedge meters were used to measure the plant flow. The wedge meter was used because unlike an orifice plate meter, sediment does not accumulate within the meter, which is important when measuring sediment laden flow. Figure 4-16 shows the reservoir flow meters. The flow meters were fabricated at Alden. Each flow meter was either calibrated or installed per ASME guidelines for flow meters. The estimated accuracy of each flow meter was +/- 2%. Air over water manometers were used to measure the flow meter deflections for the main river flow, while a differential pressure cell connected to a data acquisition system recorded flows to the reservoir.

Figure 4-15: Venturi type flow meters for measuring river flow.

Figure 4-16: Reservoir flow meters.

4.3.2 Water Surface Elevation

Water surface elevations were measured using nine inverted piezometers connected to a set of stilling wells. The piezometers were located along the center line of the river, with Tap 9 located near the intake structure, as shown in Figure 4-17. Figure 4-18 shows a photo of the piezometric tap installed in the model. Using a Vernier gauge, the water levels were measured at the nine stilling as shown in Figure 4-19. A hydraulic grade line was computed from the water surface measurements. The accuracy of the system was approximately ±0.1 ft prototype.

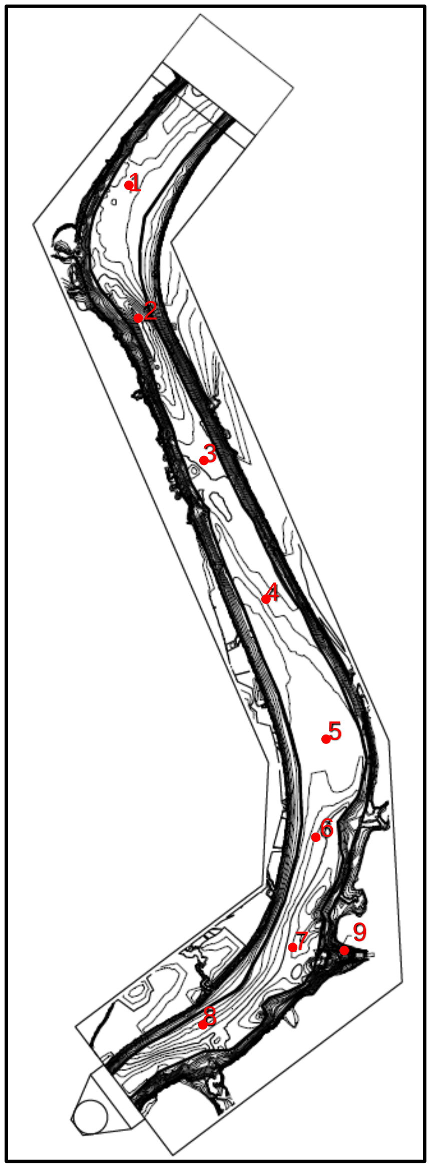

Figure 4-17: Piezometric tap locations.

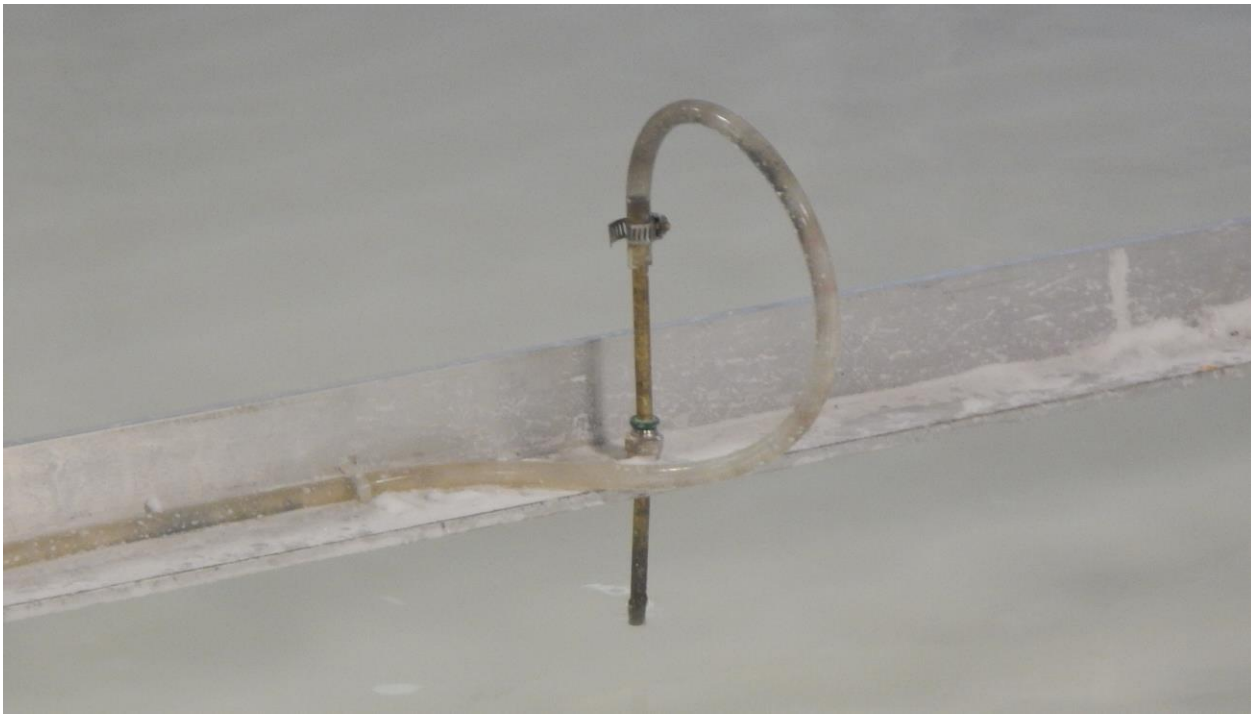

Figure 4-18: Piezometer for measuring water surface elevation in model.

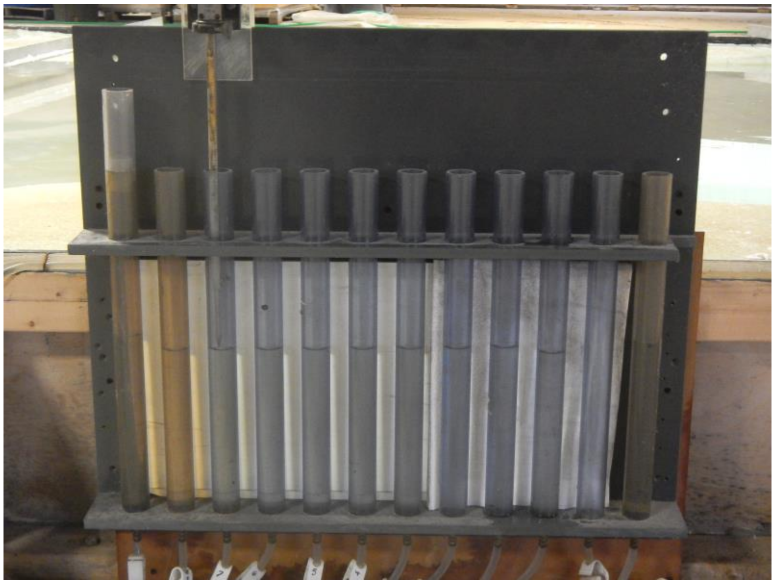

Figure 4-19: Stilling Wells with point gauge.

4.3.3 Velocity Measurements

Velocities were measured by recording dye injection at the same transects as were measured in the field. The dye was injected and recorded at 6 inch intervals along the selected transects. The video was then used to time the how long it took for the dye to move one foot. The velocities were then calculated, using elapsed time and distance traveled.

4.3.4 Suspended Sediment Sampling Ports

Three suspended sediment sampling ports were placed in the model as shown in the picture in Figure 4-20. The three ports were placed upstream of the intake, near the intake and downstream of the intake. The samplers were connected to small pumps to collect suspended sediment samples from the river. The pumps were operated for two minutes prior to taking a sample to ensure that the sampling line was clear of any residual sediment. The suspended sediment sampling port is shown in Figure 4-21. The sediment collection system is shown in Figure 4-22. The sediment samples were then processed to determine a suspended sediment concentration in the river.

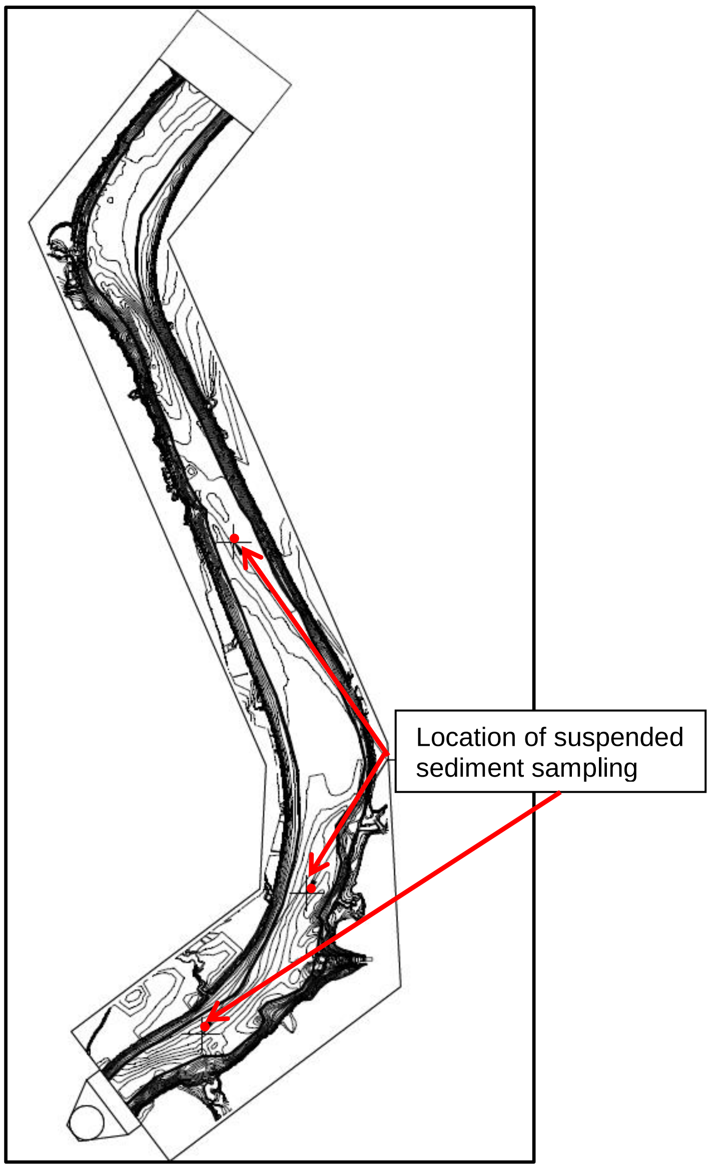

Figure 4-20: Location of suspended sediment samplers.

Figure 4-21: Suspended sediment sampling port.

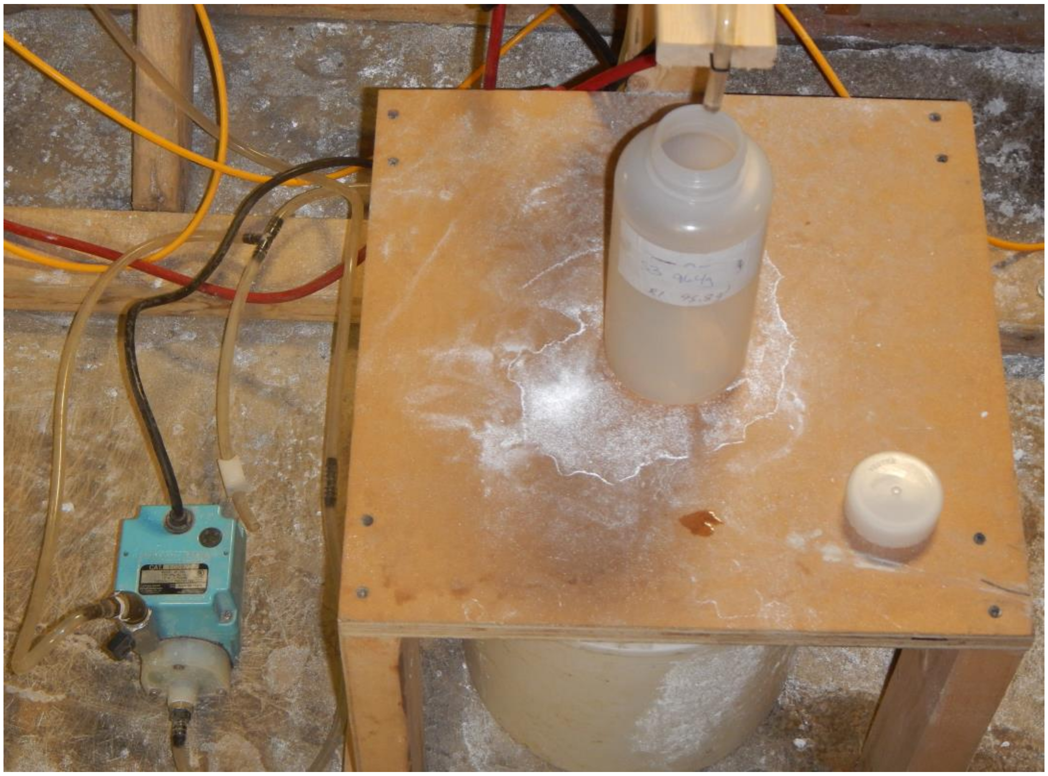

Figure 4-22: Suspended sediment sampling station.

4.3.5 Reservoir Sediment Sampling

The amount of sediment that was pumped to the reservoir was measured by filtering all of the water pumped to the reservoir with a filter bag. The filter bags have an opening size of 20 microns, smaller than the sediment material. Sediment samples were collected for two minutes every ten minutes for two hours. Figure 4-23 shows the sampling station, where bag filters were placed to collect the sediment. The dry bag weight was obtained before each test. After sampling each bag was removed, oven dried and then weighed to determine the mass of sediment in the bag. The sediment data was combined with the flow measurements to determine the suspended sediment concentration. Each sampling station has a pneumatic valve to divert water to the sampling bag or to the pump pit.

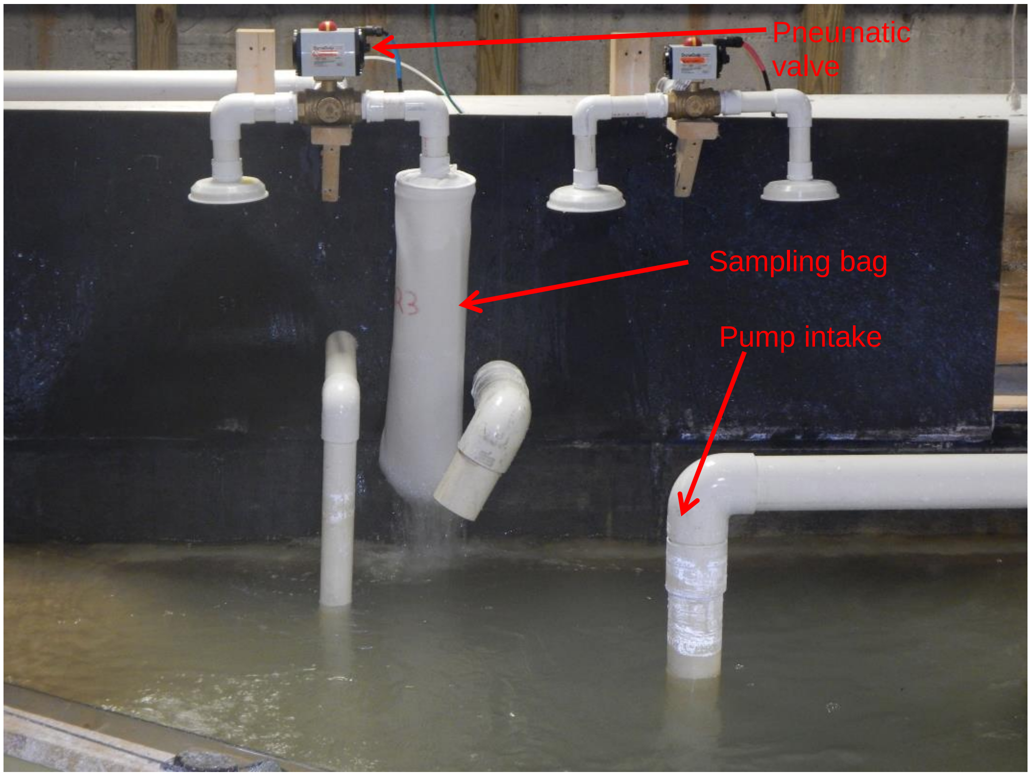

Figure 4-23: Reservoir suspended sediment sampling station.

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4.3.6 Turbidity Meters

Turbidity meters were used during the study to collect instantaneous measurements of suspended sediment concentration. The turbidity meters provide continuous data about the suspended sediment concentration and time dependent variations in the concentration. The turbidity meter used for the study was a YSI 6136 Turbidity Probe. The probe is a fouling-resistant, containing a wiped sensor. It provides accurate, in situ measurement of turbidity in fresh, brackish, and sea water, and features a mechanical self-wiping capability for long-term monitoring, which helps ensure proper turbidity measurements. The meters range is 0 to 1000 NTU, while the resolution is 0.1 NTU. A photo of the turbidity meters is shown in Figure 4-24. Turbidity measurements were used in combination with the suspended sediment samples.

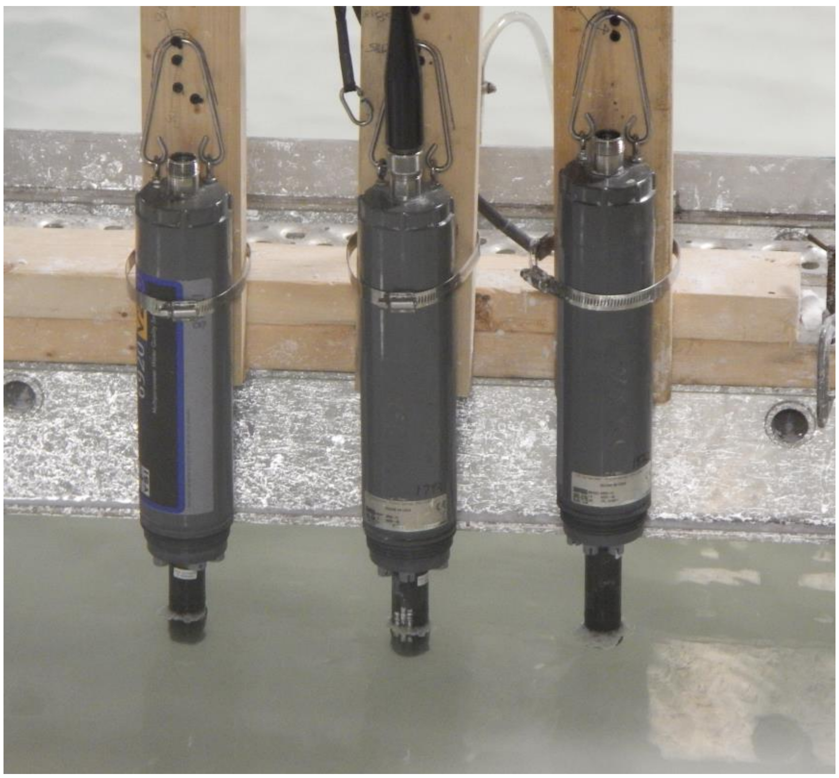

Figure 4-24: Turbidity meters.

4.4 Test Program

The test program evolved significantly during testing. The proposed testing program was built around an assumed number of testing days and an assumed number of tests that could be complete during a day. The most significant changes were the result of the large amount of time required for the model to reach equilibrium conditions. Section 4.4.1 provides information about the proposed testing program while Section 4.4.2 presents the actual testing program followed.

4.4.1 Proposed Testing Program

The proposed testing program was for 12 days of testing. During each test day it was assumed that the model would be set and allowed to run for 2 hours with one unit in operation. After two hours the suspended sediment concentration in the river and the suspended sediment concentration to the reservoir would be measured. When the measurements were complete the plant flow would be increased by one unit. During a single day of testing, one river flow condition would be evaluated with four plant pumping flows. Model calibration was planned at one of the flows where velocity measurements were completed in the field data collection phase.

Baseline testing was planned at four river flows giving four days of testing. Alternatives development testing was planned to evaluate four modifications at two river flow, giving 8 days of testing.

4.4.2 Actual Testing Program

The actual testing program was significantly modified in response to model behavior and following discussions with GDF Suez. The model required significant time to reach equilibrium after startup. Therefore, each testing day included only one river flow and one plant flow. It was not possible to test a range of plant flows in a single day. Major testing components in order of completion were as follows:

1) Two tests were completed to demonstrate the repeatability of the river SSC at a river flow of 70,000 cfs. Both tests were conducted with a water surface elevation of 190 ft. The powerhouse was off during the tests.
2) One test was completed to determine how the river SSC varied with water surface elevation for a river flow of 70,000 cfs. Water levels tested were 184, 186, 188, and 190 ft. The powerhouse was off during the tests.
3) One test was completed to determine how river SSC varied with river flow for a water level of 186 ft. River flows tested were 70000, 80000, 90000, and 100000 cfs. The powerhouse was off during the tests.
4) Three tests were conducted to test the repeatability of river SSC measurements for a flow of 85,000 cfs and a water level of 188 ft.
5) Two baseline tests were run with a powerhouse flow of 13,850 cfs and a river flow of 85,000 cfs with a water level of 188 ft. The second baseline test was run to demonstrate repeatability.
6) Two days of testing were completed to evaluate flow patterns around various proposed weir concepts.
7) Six modifications were tested in the model
8) GDFSuez carried out three visits to the model with their consultant , during which qualitative testing was conducted.

A testing summary of all tests completed is given in Table 4-3. The table provides the test number, test date, river water surface elevation (WSE), river flow (Flow), powerhouse pumping flow (Powerhouse), crest elevation of the weir (Weir Elev), the length of the weir (Weir Length), the purpose or objective of the test and some of the major findings from the test that significantly influenced the subsequent tests.

Table 4-3: Testing Completed with New Sediment

Test #	Test Date	WSE ft	Flow cfs	Power House cfs	Weir Elev ft	Weir Length ft	Purpose/Objective	Finding/Results
1	Mon Mar 21	190	70,000	N/A	N/A	N/A	• First test with new sediment. • Determine River SSC • Included 3 turbidity meters for continuous data • Follow strict setup and testing protocol to minimize variability	• Model was very well behaved; concentrations were no longer changing significantly with time.
2	Wed Mar 23	190	70,000	N/A	N/A	N/A	• Repeat of previous test to evaluate repeatability	• Model was highly reproducible
3	Thur Mar 24	190 188 186 184	70,000	N/A	N/A	N/A	• Determine effect of changing water level on SSC • Because the SSC in tests 1 and 2 was less than desired	• SSC sensitive to changes in WSE. • Ranged from about 100 mg/l at 188 to • 700-800 mg/l at 184 • Documented in April 8 memo
4	Fri Mar 25	186	70,000 80,000 90,000 100,000	N/A	N/A	N/A	• Determine effect of changing flow on SSC • Constant WSE	• SSC sensitive to changes in flow. • Ranged from about 500 mg/l at 80,000 cfs • 2,000 - 2,500 mg/l at 100,000 cfs • All data used to enhance plot correlating NTU to SSC • Documented in April 8 memo
5	Thu Mar 31	188	80,000 85,000	N/A	N/A	N/A	• Fine tune testing conditions and determine repeatability with prototypical SSC	• Test started at 80,000 cfs. Turbidity low • After 2 hrs flow increased to 85,000 cfs to hit target turbidity • Turbidity was same at all 3 measurement locations
6	Tues April 5	188	85,000	N/A	N/A	N/A	• Test repeatability of Test 5	• Test shown to be highly repeatable • Sultan: additional documentation of bed forms • Results are in April 8 memo
7	Tues May 3	188	85,000	N/A	N/A	N/A	• Sultan asked to see more repeatability testing of Test 5 and 6 • Alice requested statistical analysis of all results	• Test shown to be highly repeatable from test 5 and 6 • Max difference in mean concentration of 8.3 % • Results are in May 5 memo
8 Base Test 1	Friday May 13	188	85,000	13,850	N/A	N/A	• Baseline test to determine amount of sediment going to reservoir relative to river SSC • Measured vertical turbidity distribution	• SSC of near 400 mg/l • Statistical analysis completed of Tests 8 and 9 • Results showed less than 10 percent variation in average concentrations
9 Base Test 2	Tues May 17	188	85,000	13,850	N/A	N/A	• Baseline test to determine amount of sediment going to reservoir relative to river SSC • Measured vertical turbidity distribution	• SSC of near 400 mg/l • Reservoir turbidity and SSC highly repeatable • Sultan pleased with measured vertical turbidity distribution • Results in May 20 memo
10 Weir test	Tues May 31	190	70,000	N/A	Above WSE	1100	• Weir Alignment tests • Video documentation of flow patterns and secondary currents	• Determined alignment for weir and qualitative assessment of secondary currents
11 Weir test	Wed June 1	188	85,000	N/A	Above WSE	1100	• Video documentation of flow patterns and secondary currents	• Sultan likes documented alignment and the presence of secondary currents
12 Mod 1	Tues June 7	188	85,000	13,850	171	700	• Test weir modification 1	• ~8 % reduction in SSC to plant from main river SSC

13 Mod 2	Thur June 9	188	85,000	13,850	169	500	• Test weir modification 2 • Evaluate effect of shortening weir	• ~14 % reduction in SSC to plant from main river SSC
14 Mod 3	Tues June 14	188 190	85,000	13,850	185.3	700	• Test weir modification 3 • Reductions in SSC with weir at ~171 disappointing, try much higher weir	• Water level had to be raised during test • High weir starved pumps • ~46 % reduction in SSC to plant from main river SSC
15 Sultan Sensiti vity	Wed June 15	185	100,000 for 1 hour then increase d to 110,000	N/A	185.3	700	• Sultan and Alice visited model and spent a day playing with the weir • Tested at non Froude scale • Achieve more uniform concentration profile • No powerhouse flows is why weir above WSE	• Guided Sultans thinking for next test • Concerned about spherical sediment with higher fall velocity • Excessive scour of bed to concrete • Excessive secondary currents
16 Mod 4	Thurs June 16	185	110,000	13,850	181	700	• Complete a documented test of what Sultan played with on previous day • Piggyback baseline test by removing weir after completion of mod 4 test	• Posttest it was learned that the maximum allowable velocity over weir is 2 ft/s • Max weir height is ~10 ft below WSE
17 Mod 5	Wed June 29	188	85,000	13,850	177.1	700	• Test to determine efficacy of max height weir satisfying velocity requirement • Would require construction of moving weir	• ~30 % reduction in SSC to plant from main river SSC
18 SSC test	Wed July 6	184	48,000	N/A	171	700	• Test to determine river SSC at 184 and 48,000	• Measured river SSC of about 10 mg/l. • Too low for use in actual test • Recommend next test be run at 183 to get higher SSC
19 Mod 6	Fri July 8	183	48,000	13,850	170	700	• Test to determine efficacy of max height weir that does not move • Tested at lowest flow where measurable sediment is moving in model • Previously tested at high flow • Allows estimating reduction to reservoir at low flows	• 40,000 cfs has an exceedance of about 5 percent of the time
20 Base Mod 6	Tues July 12	183	48,000	13,850	N/A	N/A	• Baseline test required to determine amount of sediment going to reservoir at low flow.	• Baseline test for test 19. Required to determine amount of sediment going to reservoir at low flow.
21 Mod 6R	Wed July 27	183	48,000	13,850	N/A	N/A	• Repeat of Test 19 • Test was repeated because results showed that the weir increases sediment to reservoir	• Test 19 and 20 combined to show that at low flows the weir increase sediment to the reservoir. Results seem illogical so test was repeated.
22 Base Mod 6R	Fri July 29	183	48,000	13,850	N/A	N/A	• Repeat of test 20, Mod 6 baseline test. The test was repeated because results showed an increase in sediment to reservoir	• Repeat test, see 21.

4.5 Testing Procedure

A detailed testing procedure was developed and followed for all of the tests used in evaluating the efficacy of the weir. In a 1:100 scale model small differences in procedure or testing control can result in large differences in results. Because of the need to get repeatable quantitative information from a small model all of the tests followed the protocols defined below.

4.5.1 Baseline Testing

The baseline testing was conducted for two tests with a water surface elevation of 188.00 ft (proto) and 85,000 cfs river flow with 13,850 cfs powerhouse flow. The test is designed to produce a suspended sediment transport condition representative of a river flow of 70,000 cfs. The model river flow (85,000 cfs) is approximately 21 percent higher than the nominal river flow (70,000 cfs). The powerhouse flow was also increased by approximately 21 percent such that the ratio of river flow to powerhouse flow in the model is the same as in the prototype for a 70,000 cfs river and 3 unit powerhouse flow. Turbidity sampling was recorded in real-time for the reservoir flow at the 3 main river sampling locations (Upstream, middle, and downstream). The SSC was also measured during this testing to compare the turbidity and SSC values. The location of the SSC samples was shown previously in Section 4.3.

The sediment bed in the model was reset following the method developed during the exploratory and repeatability tests. The day prior to the test the model sediment was 'turned over' and leveled. Testing was started within 24 hours of leveling the bed to minimize the opportunity for packing of the sediment.

Baselines tests were run while sampling turbidity in real-time for the reservoir flow and the middle river sampling location. A total of three turbidity meters at three different water depths (approximately 0.2d, 0.4d and 0.7d) were installed at the middle river sampling station to measure the vertical sediment concentration profile. Hourly SSC samples were collected at the middle river sampling station. Reservoir SSC concentration samples were also collected with bag filters for approximately two minutes, every ten minutes while the powerhouse flow was in pumping mode.

The model river flow of 85,000 cfs, a powerhouse pump flow of 0 cfs and a WSE of 188.00 ft was set and time T=0 (start of testing) called. The model was run with no powerhouse pumping flow for 5 hours (300 minutes) after the start of testing was called to allow the sediment bed to reach a steady condition. At time T=285 minutes the forebay was cleaned of all accumulated sediment. At time T=300 minutes the reservoir flow was turned on to a nominal 3 unit prototype flow. The powerhouse was run from time T=300 minutes until T=420 minutes. During this time, reservoir SSC bag samples were collected for approximately two minutes, at ten minute intervals while the powerhouse was operating.

Each reservoir sediment sample was processed by weighing the filter before sample collection and drying and then weighing the filter again after sample collection to determine the mass of sediment pumped to the reservoir during the period. The total mass can be divided by the total volumetric flow for the sample period to determine the sediment concentration.

Turbidity measurements in the river were recorded every 20 seconds throughout the duration of the test with YSI Sonde meters. The output of the YSI meters is in nominal turbidity units (NTU). Turbidity measurements of the flow to the reservoir were also measured using an Alden designed optical turbidity meter. The output of the Alden meter measurement is not a turbidity value of NTU but rather a voltage ranging from 0-5 volts. As data was collected a correlation between voltage and SSC was developed.

4.5.2 Model Processing

Processing the model for each test consisted of draining the model very slowly (No visibly apparent sediment being transported over the weir crest) using the adjustable weir. Water was transferred to the storage tank. Also a sump pump was utilized at the upstream end of the model to finish draining the water.

The sediment material was then turned over with a shovel, placing the material in the same location it was taken from. The sediment was thoroughly raked to the bottom of the model with a steel tined rake, ensuring that all material is separated through to the concrete bottom.

The entire model sediment bed was set with a screed rake, pulling the screed rake. While screeding occurred, a flat shovel was used to remove all additional material screeded onto the bank and place it into an area where sediment was low. Any areas where additional material was added after the first screed pass, were screeded a second time.

The model was set to start filling with the low flow float valve. At the same time, the banks were washed into the model riverbed utilizing a garden hose and a light spray.

4.5.3 Model Testing Startup

When the model is operated the following series of steps are taken to record the data from the test. First the river turbidity meters are turned on to take 20 second average sample periods for a 12 hour duration. The meters were set at the proper height to be at the correct level in the river water column. The overhead camera was turned on to time lapse recording. The adjustable weir was then raised to the approximate water surface elevation marked on the gate operating winch.

The upstream recirculation valves on each flow meter section were checked to ensure they were closed. The main river pump was started and the butterfly valve was opened slowly a small amount to allow for the river to rise to its target elevation. While the model is slowly filling, all stilling well taps and the middle river SSC tap were bled of all air.

The adjustable weir was used to control the water surface elevation at tap 7 and bring the WSE to the test condition elevation. Once the test water surface elevation was reached, the main butterfly valve opening was slowly increased. While opening the butterfly valve, the tail gate was lowered to maintain the water surface elevation in the river as the flow increased. The data collection software was turned on and the project configuration file loaded once the target flow was reached.

4.5.4 Test Procedure

At the start of the test, the time is recorded and the data acquisition system is started. A water sample at the middle river sampling port is taken and the WSE at all stilling wells was recorded. A river water sample was taken each hour of the testing.

The model was run for five hours without the reservoir pumping flow to allow for stabilization of the sediment movement. After 285 minutes of testing the intake\discharge forebay area was cleaned of all visible sediment from the forebay area with a wet vacuum. A bag filter was placed on the reservoir sampling station and five hours into testing the pumping flow was set to 13,850 cfs, while adjusting the tailwater weir to maintain the WSE in the river. Once the pumping flow reached the target flow, the powerhouse flow was diverted to the bag filter for two minutes. At the end of the two minutes the reservoir flow was switched to an open discharge. The used bag filter was replaced and recorded. A new bag filter was then placed on the inactive line for the next sample in ten minutes.

At ten minute intervals after the start of reservoir sampling flow was switched to the clean filter bag and another two minute sample was collected. The bag filters were changed every ten minutes for two hours of data collection with the reservoir pumps in operation. After each test all filter bags were dried and weighed, and the flow data was used to determine the volume of water pumped to the reservoir. A concentration was then computed using the change in bag weight and the volume of water pumped.

The river water samples that were collected were processed through small filters to remove, dry and weigh the sediment in the sample. The volume of water was determined by measuring the water mass in the bottle. A concentration for the river was calculated.

4.6 Model Validation

Based on experience from previous fixed bed models, the 1:100 Northfield Pumped Storage model topography was modeled in concrete with a brushed finish. The topography was lowered by 12.5 ft (1.5in. model) in the center of the river to allow for the placement of model sediment.

As part of the model study the model validation is necessary to ensure that the model is representing the river hydraulics properly prior to conducting any tests. The validation was conducted at one flow rate by comparing measurements of water velocity in the model and compared to available field data. Figure 4-25 shows the location at which the velocity transects were measured using an ADCP. The locations were then matched in the model and velocity measurements were compared.

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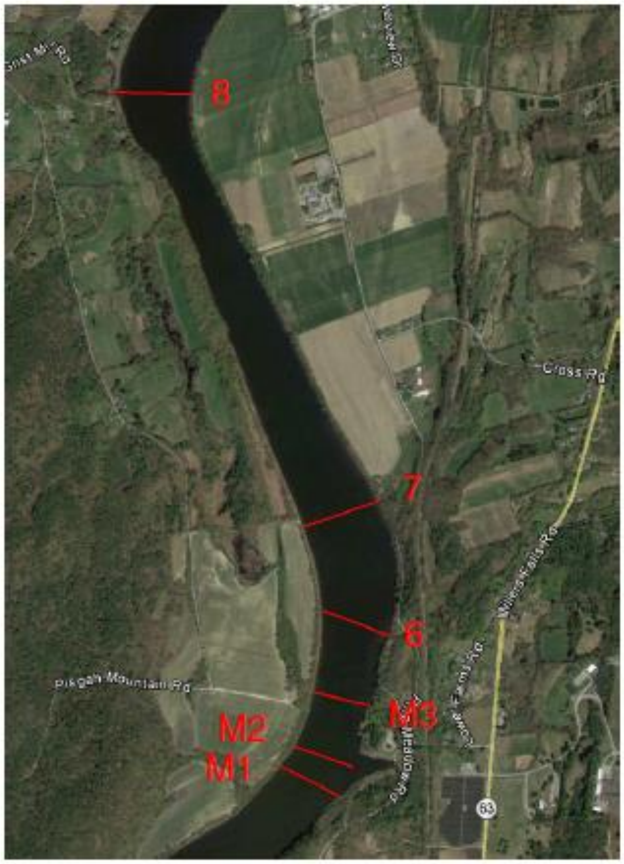

Figure 4-25: Location of velocity transects.

Figure 4-26 through Figure 4-31show a comparison between model and prototype velocity. For most of the transects, the model velocities fall within the variability of the field data. However, Transect M1 (Figure 4-26) shows a significant difference at 200 feet from the shore. This is likely a local effect associated with generating.

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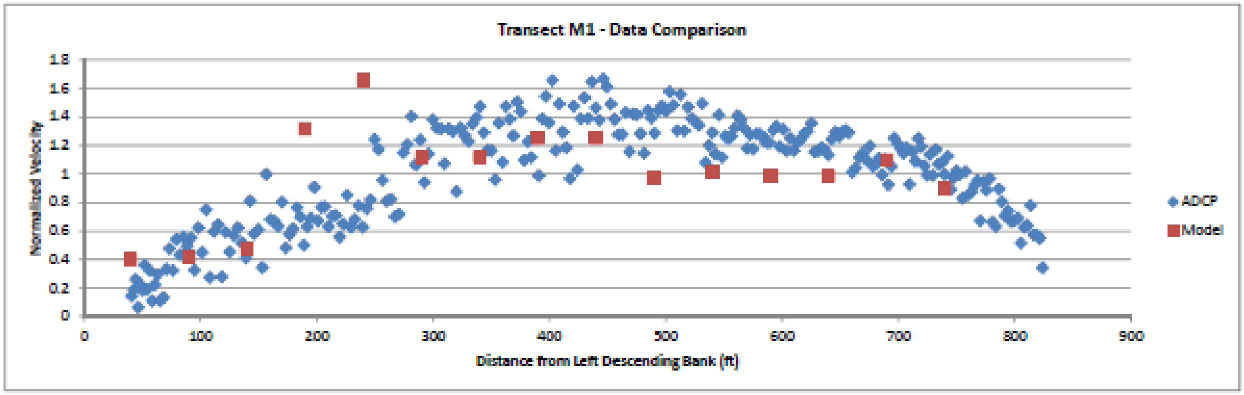

Figure 4-26: Transect M1 velocity comparison.

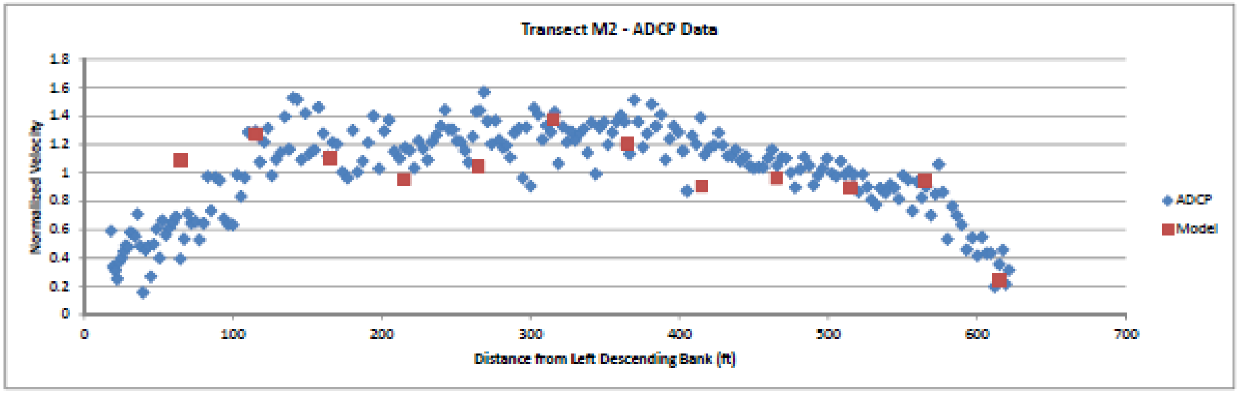

Figure 4-27: Transect M2 velocity comparison.

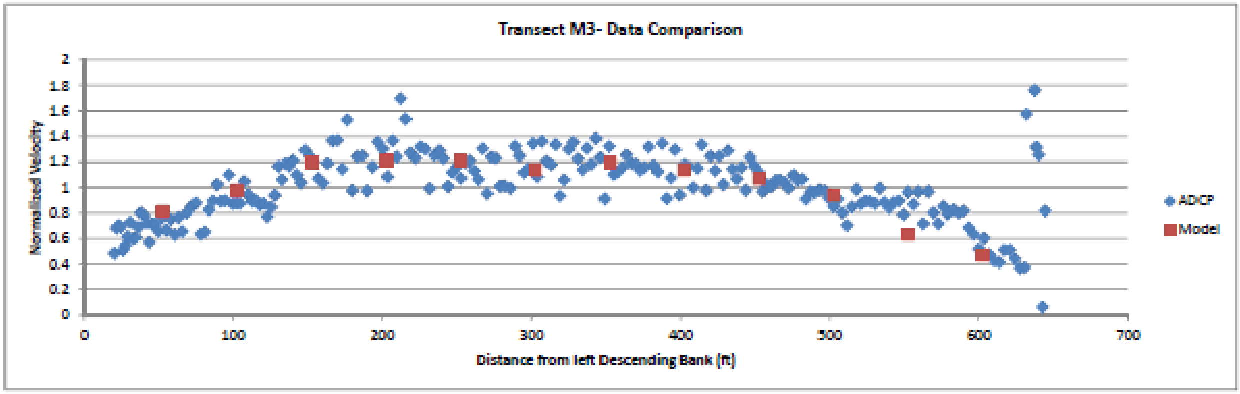

Figure 4-28: Transect M3 velocity comparison.

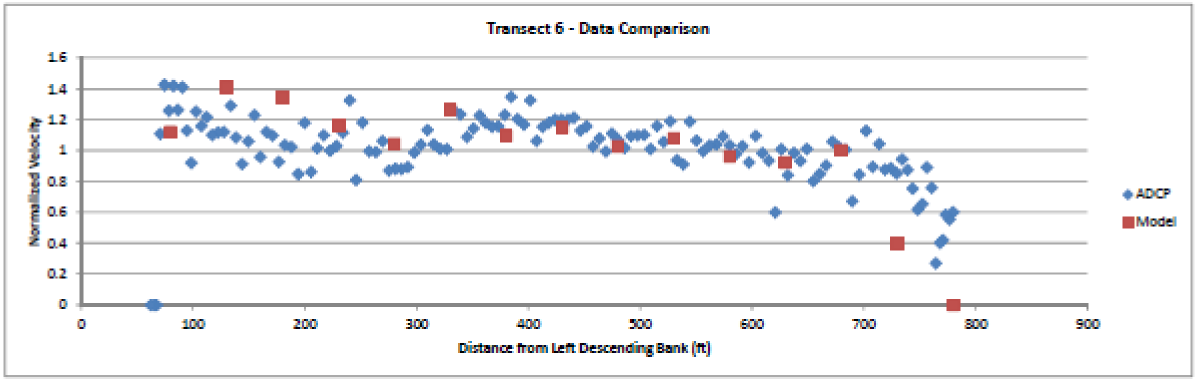

Figure 4-29: Transect 6 velocity Comparison.

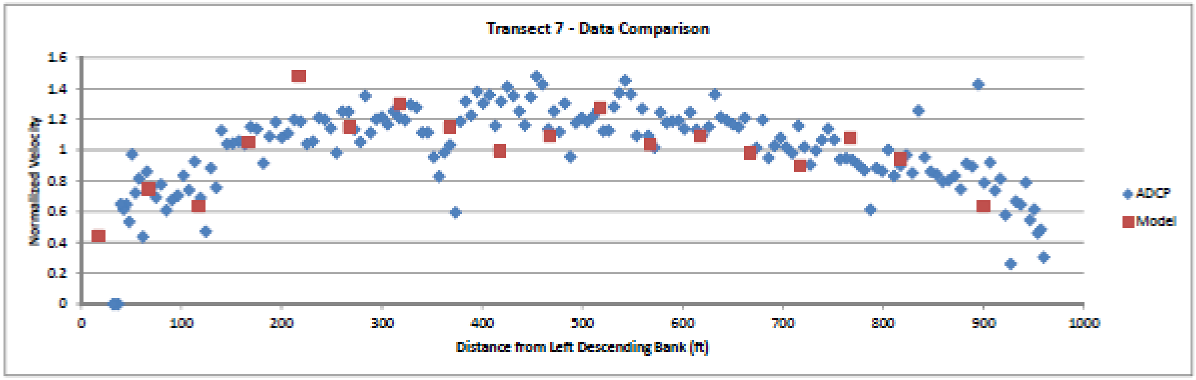

Figure 4-30: Transect 7 velocity comparison.

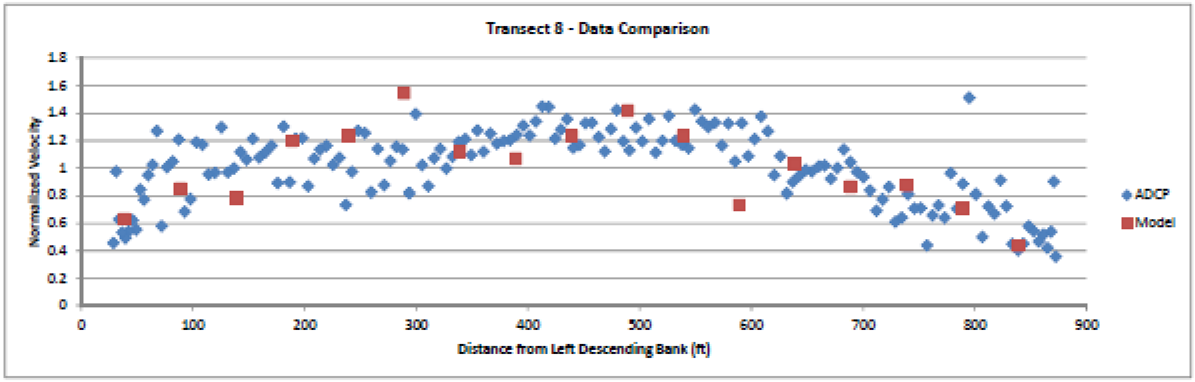

Figure 4-31: Transect 8 velocity comparison.

5.0 Physical Model Results

Physical model results for the 22 tests are summarized in the following sections. The testing program evolved in response to test results and subsequent comments from GDF Suez. GDF Suez contracted Tractebel France and Mr. Alam to help in preparing the model technical specifications documented in the Request for Proposal (RFP) and to assist GDF Suez in guiding and supervising the testing. The model scale and model domain that were utilized for the described testing were specified in the RFP.

A preliminary testing program was undertaken to understand the behavior of the model and develop a testing protocol. The preliminary testing results are presented in Section 5.1. Repeatability testing results are presented in Section 5.1.1, the effect of model flow on suspended sediment concentration is presented in Section 5.1.2 and the effect of depth on suspended sediment concentration is presented in Section 5.1.3. Preliminary tests with the final testing configuration are reported in Section 5.1.4. Section 5.2 presents the results of baseline testing and Section 5.3 presents the results for the modification testing.

5.1 Preliminary Sediment Transport Testing

An extensive testing program was used to establish how the model performed and responded to changes in river flow and water surface elevation. Additionally, repeatability of the model suspended sediment concentrations was validated during this testing.

5.1.1 Repeatability Testing

Two tests were completed to determine the repeatability of the model. To determine the effect of adding a weir to the model, it is important that the model produce similar results when tests are repeated. Excessive changes between repeat tests, limits the model utility for understanding changes in response to installed modifications. The model was tested at a Froude scale river flow of 70,000 cfs and a Froude scale water surface elevation of 190 ft. The powerhouse flow was off during the tests and river suspended sediment samples were collected. Tests were conducted on March 21 and March 23, 2016. Prior to each test the model bed was reset following the same procedure. The river sediment was raked and then scree-leveled.

Three turbidity meters were installed as shown in Figure 5-1 and in the locations shown in Figure 5-2. The turbidity measurements allowed for real time data to inform subsequent testing. Additionally, suspended sediment concentration (SSC) samples were collected at corresponding locations to correlate SSC to turbidity. River suspended sediment samples were collected at the start of each test and at each subsequent hour for eight hours, producing a total of nine samples per test. The turbidity measurements were logged every 20 seconds for the duration of the tests.

Test results showed good consistent behavior between the two model tests and good correlation between the turbidity and SSC measurements. Figure 5-3 shows a plot of the turbidity and the SSC as a function of time for the two tests. Results showed good repeatability, however the SSC values were lower than the prototypical SSC values for corresponding river flow and water surface conditions. Figure 5-4 shows the correlation between the turbidity and SSC measurements for the two tests.

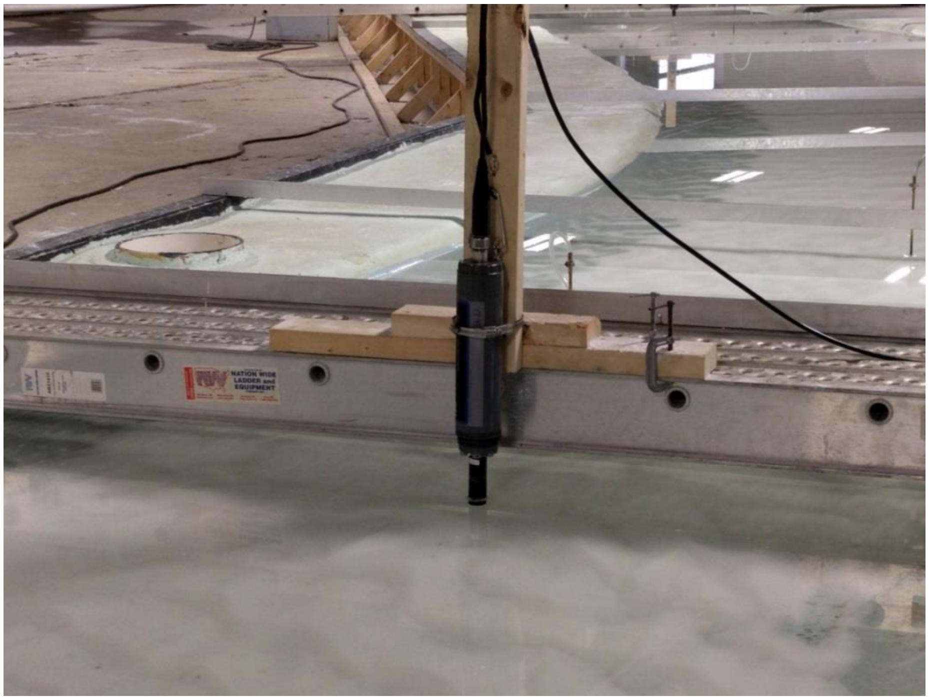

Figure 5-1: Photo of turbidity meter installed.

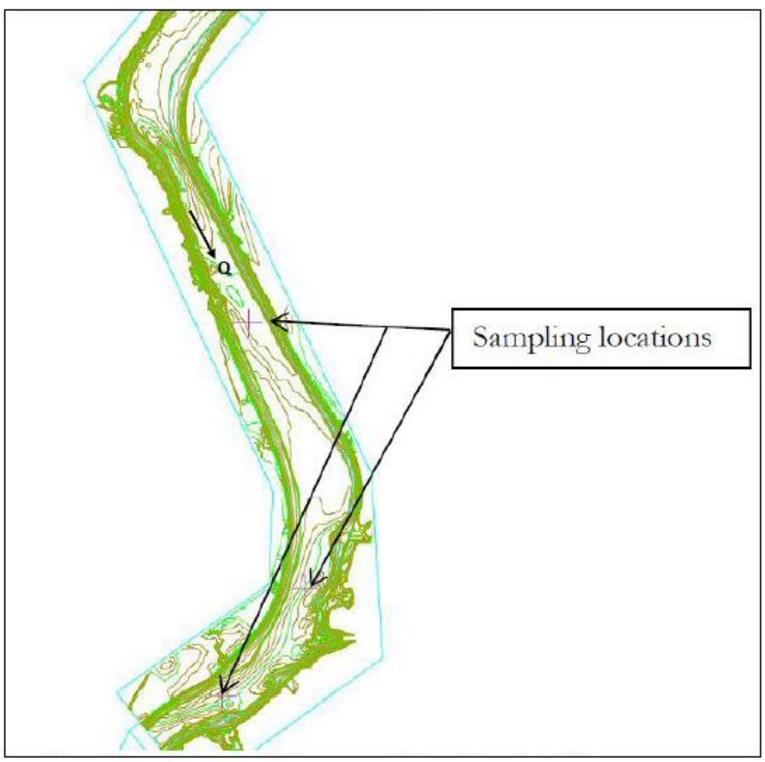

Figure 5-2: Location of turbidity and suspended sediment sampling.

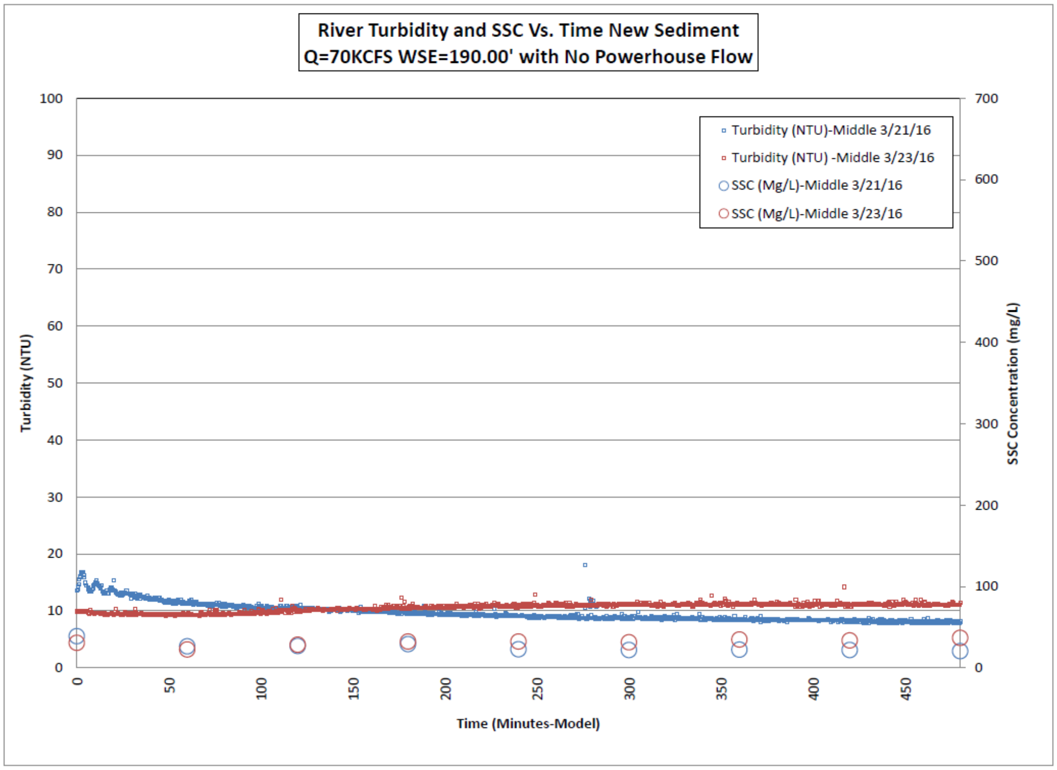

Figure 5-3: Turbidity and SSCs for initial exploratory tests.

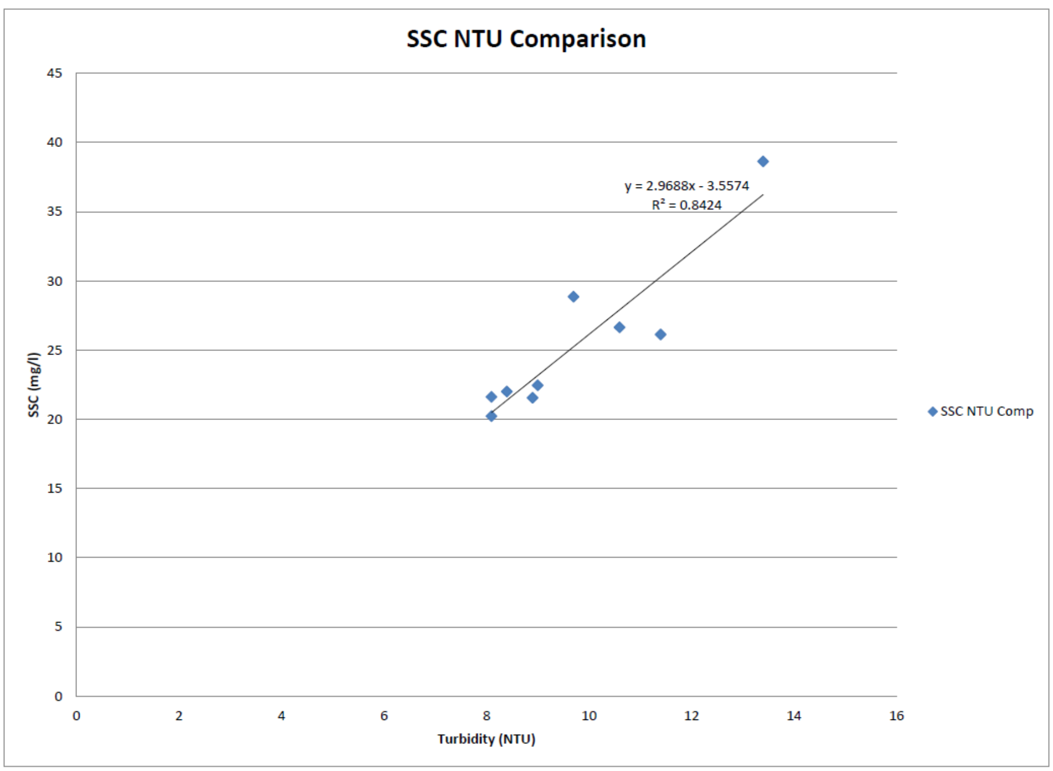

Figure 5-4: SSC as a function of turbidity.

5.1.2 Effect of Depth on SSC

After the two initial repeat tests were completed, additional testing was conducted to determine the water level or flow rate required to achieve more prototypical SSC concentrations (200-400 mg/L) at the mid-stream sampling station. The first test was conducted on March 24 and focused on the impact of changing the water surface elevation (WSE) while holding river flowrate constant. Prototype WSEs of 188.00 ft, 186.00 ft, and 184.00 ft were tested at a flow rate of 70,000 cfs. Turbidity and SSC were measured and recorded. The detailed time sequence for this is as follows (The paragraph numbers for each test condition below correspond to the label numbers shown in Figure 5-5):

1. Model started and set to elevation 190.00 ft and 70,000 cfs prototype.
2. Stable Test Point Called: WSE at 190.00 ft and flow at 70,000 cfs prototype.
3. Middle turbidity meter set to vertical centerline of water column.
4. Model adjusted to have a water surface elevation of 188.00 ft and 70,000 cfs prototype. All turbidity meters adjusted to vertical centerline of water column.
5. Stable Test Point Called: WSE at 188.00 ft and 70,000 cfs prototype.
6. Model adjusted to have a water surface elevation of 186.00 ft and 70,000 cfs prototype. All turbidity meters adjusted to vertical centerline of water column.
7. Stable Test Point Called: WSE at 186.00 ft and 70,000 cfs prototype.
8. Model adjusted to have a water surface elevation of 184.00 ft and 70,000 cfs prototype. All turbidity meters adjusted to vertical centerline of water column.
9. Stable Test Point Called: WSE at 184.00 ft and 70,000 cfs prototype.

Turbidity is shown on the left vertical axis of Figure 5-5 and SSC is shown on the right vertical axis. The horizontal axis shows time. The test demonstrates that the suspended sediment concentration increases as water depth decreases while maintaining a constant discharge. Test results also showed that the suspended sediment concentration and turbidity varied during the period where water level was constant. The varying concentration shows that a longer time period is required to achieve steady state conditions. The final model testing protocol uses a longer period between calling a stable test point and the start of powerhouse data collection.

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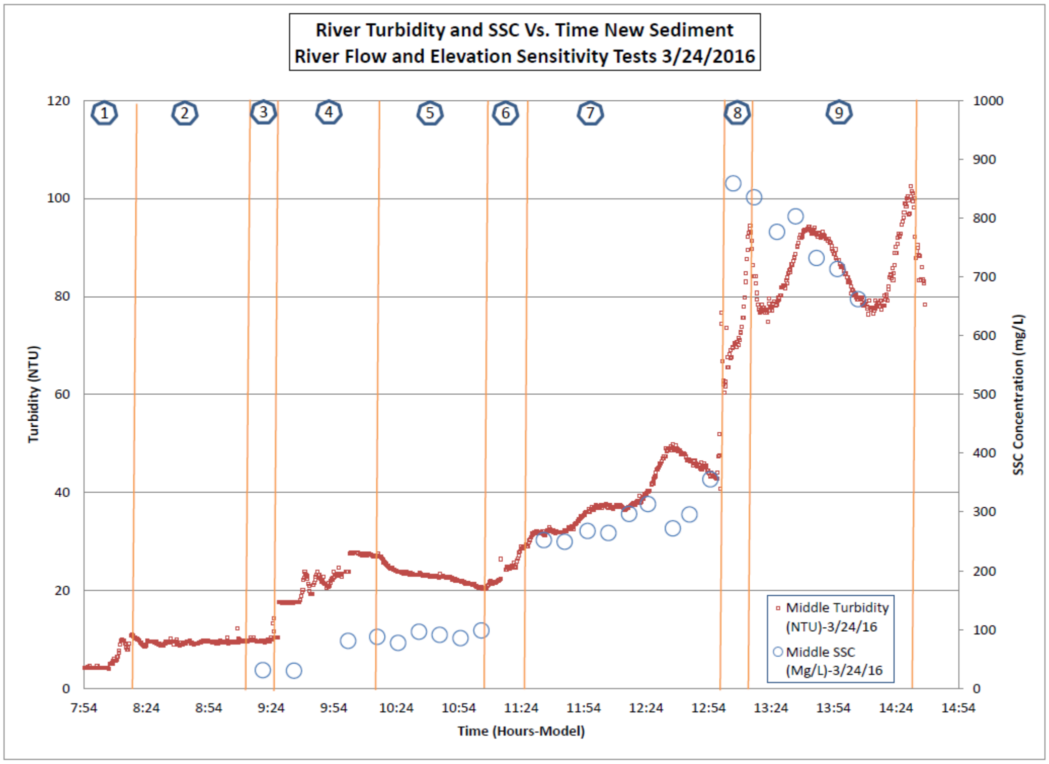

Figure 5-5: Turbidity and SSC at different WSE (March 24 Test).

5.1.3 Effect of Flow on SSC

Testing conducted on March 25th focused on increasing the flow rate in the river while maintaining a steady WSE. The testing was conducted at 70,000 cfs, 80,000 cfs, 90,000 cfs and 100,000 cfs. The SSC increased with the flow rate as shown in Figure 5-6. The test details for this test are as follows (The paragraph numbers for each test condition below correspond to the label numbers shown in Figure 5-6):

1. Model started and set to water surface elevation of 190.00 ft and 70,000 cfs prototype.
2. Stable Test Point Called: WSE at elevation 190.00 ft and 70,000 cfs prototype.
3. Model adjusted to WSE 186.00 ft and 80,000 cfs prototype. All turbidity meters adjusted to vertical centerline of water column.
4. Stable Test Point Called: WSE 186.00 ft and 80,000 cfs prototype.
5. Model adjusted to WSE 186.00 ft and 90,000 cfs prototype. All turbidity meters adjusted to vertical centerline of water column.
6. Stable Test Point Called: WSE 186.00 ft and 90,000 cfs prototype.
7. Model adjusted to WSE 186.00 ft and 100,000 cfs prototype. All turbidity meters adjusted to vertical centerline of water column.
8. Stable Test Point Called: WSE 186.00 ft and 100,000 cfs prototype.

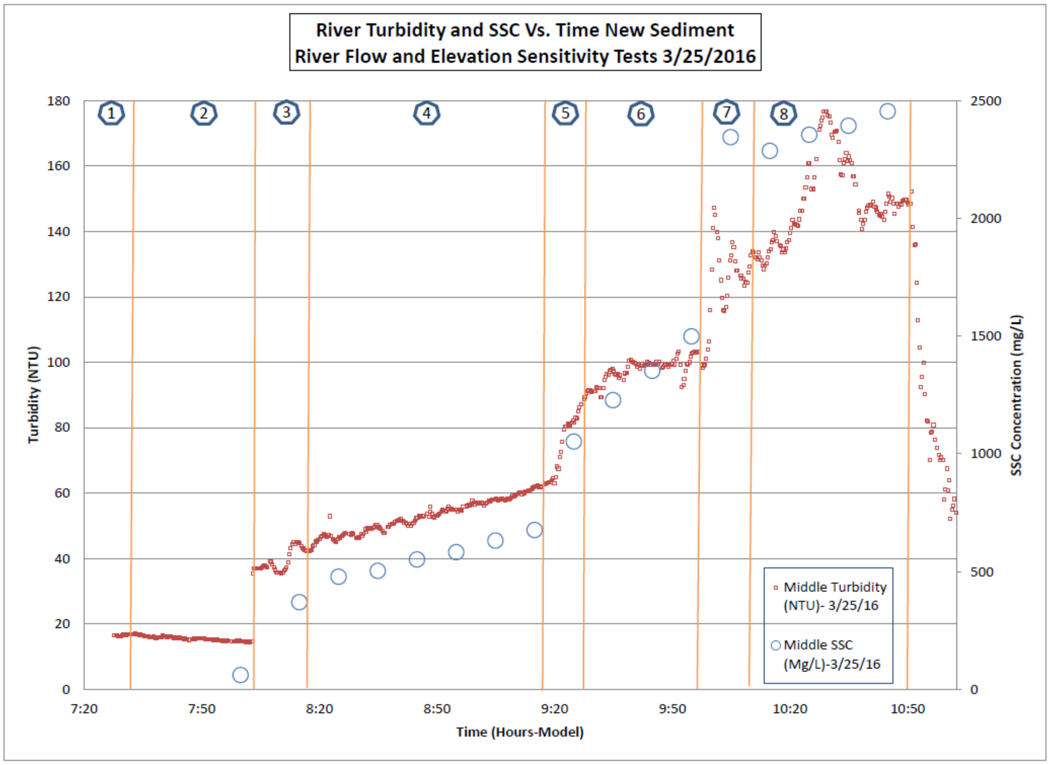

Figure 5-6: Turbidity and SSC at different flow rates (March 25 Test)

Figure 5-7 shows a plot of the SSC as a function of turbidity in the river. The correlation between the two is approximately linear. This plot provides useful information as it allows the real time turbidity measurements to be used to adjust the test conditions required to achieve prototypical SSC values. For example to achieve prototypical SSC of 300-400 mg/l requires an NTU measurement of 40-50. However it should be noted that small discrepancies in the vertical height of the turbidity sensor in the water column and local bed form effects cause a large variation in turbidity readings as shown in Figure 5-5.

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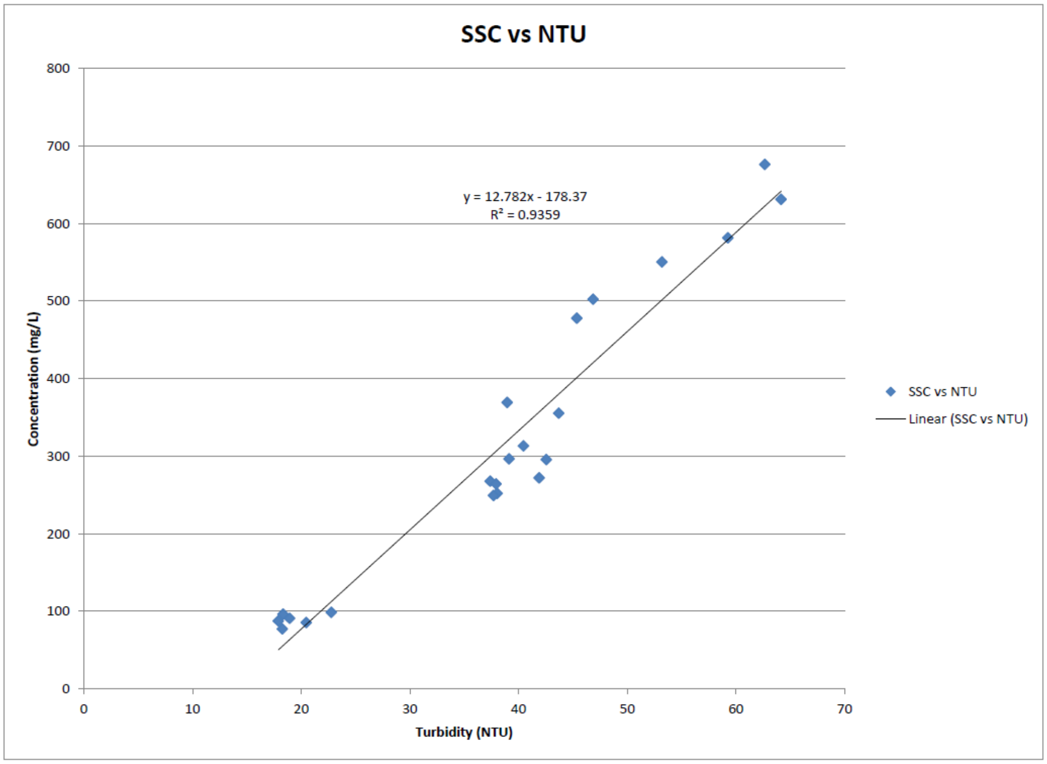

Figure 5-7: Suspended sediment concentration as a function of turbidity (all test data).

5.1.4 Final Test Configuration Repeatability

Three tests were completed to evaluate the repeatability of the model in the final testing configuration and protocol. Two tests were completed in close succession on March 31 and April 5. A third repeatability test was completed at the request of GDF Suez on May 3 for final confirmation of the results of the first two tests. The validation tests were outside of the scope defined by GDF Suez, but were completed at no additional cost. Results of the testing are presented in the order the data was collected.

Based on the testing to determine the effect of water depth and river flow on SSC, additional testing was conducted to fine tune the river SSC and determine the repeatability of the final testing configuration with more prototypical river SSC values. On March 31, the model was run at a water surface elevation 188.00 ft and a river flow rate of 80,000 cfs while the turbidity was monitored in real time. Figure 5-8 shows the turbidity vs time for the duration of the testing. After 2 hours, the flow rate in the model was increased to 85,000 cfs to increase the turbidity to between 40 and 50 NTU. River suspended sediment samples were also collected and compared to the turbidity measurements. With the model operating at 85,000 cfs and a water surface elevation of 188.00 ft, a SSC between 300 mg/L and 400mg/L was measured after approximately 2 hours of additional run time, as shown in Figure 5-9. Figure 5-8 also showed that the turbidity measurements are similar in all three measurement locations along the length of the model.

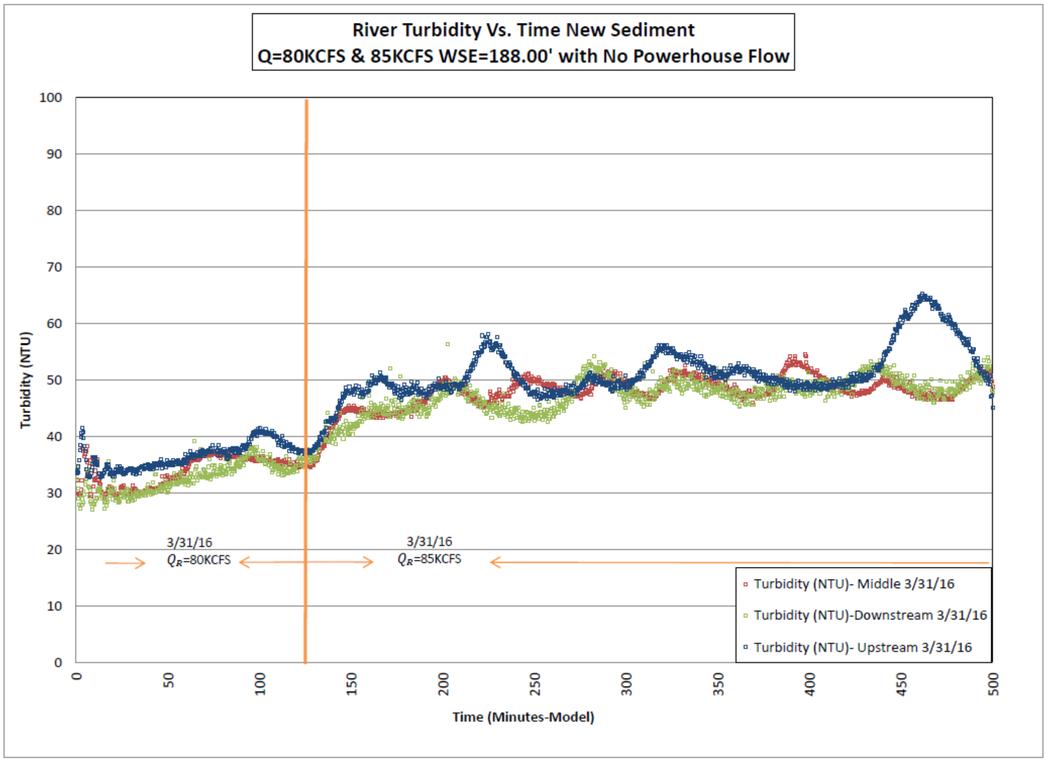

Figure 5-8: River turbidity as a function of time (March 31 Test).

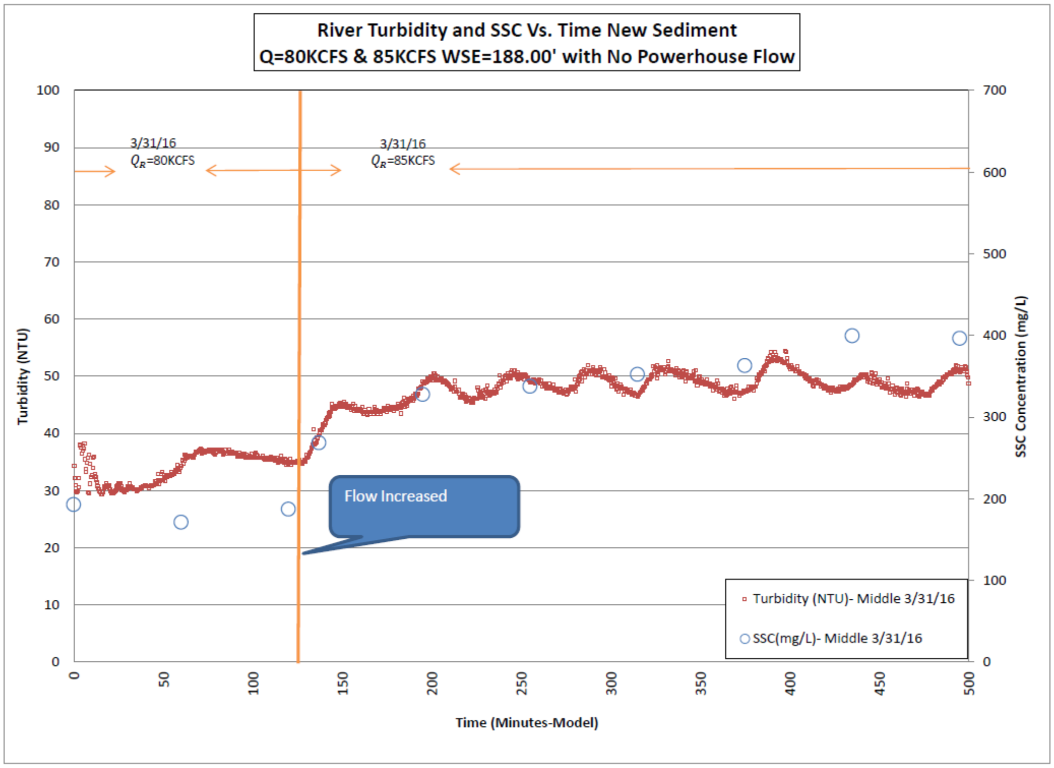

Figure 5-9: River turbidity and SSC as a function of time (March 31 test).

On April 5, the 85,000 cfs and 188.00 ft test condition was repeated to verify that the model sediment behaved similarly with the same river flow and elevation conditions. The bed was reset following the same procedure as the other acrylic sediment tests. Figure 5-10 shows a plot of the turbidity measurements and SSC vs. time for the repeat 85,000 cfs test at the middle measurement location.

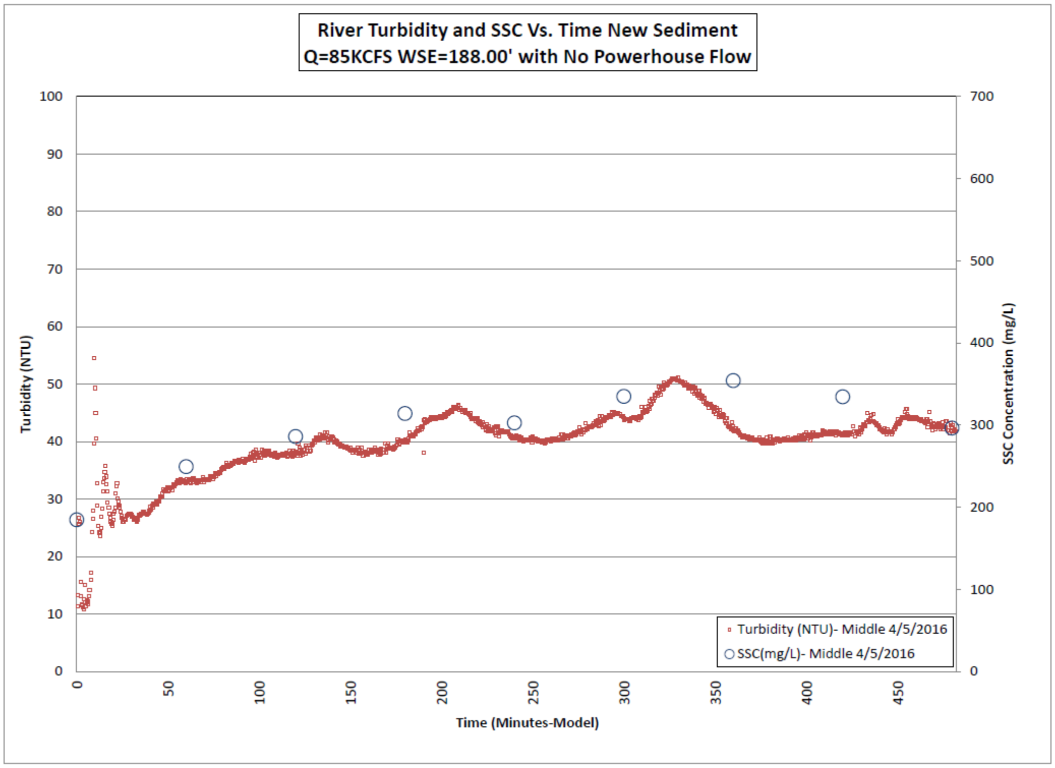

Figure 5-10: River turbidity and SSC as a function of time (April 5 Test).

Results from the March 31 and April 5 test were combined in Figure 5-11. Test results show that the suspended sediment concentration in the model is similar for repeated tests. In each case, the turbidity measurement after 2 hours stabilized between 40 to 50 NTU while the SSC was between 300 mg/L and 400 mg/L.

Based on the telephone conference on April 26, a third repeat test was conducted on May 3, 2016 to further verify the repeatability of the model river SSC and turbidity conditions. Testing followed the same procedure for resetting the model and data collection as the previous tests. The model was run for 8 hours (model) with no powerhouse flow. The river flowrate was 85,000 cfs with a WSE of 188.00 ft. Turbidity data was collected at the same location as the March 31 and April 5 testing. SSC samples were collected hourly at the same location used in previous testing. The first 130 minutes of turbidity meter data during the ramp up period was lost due to a computer recording error, however the critical data during the steady state period of the test was collected as planned.

The turbidity and SSC data for the May 3, 2016 testing is shown in Figure 5-12. The 8-hour testing period ended at 480 minutes while turbidity was declining. The model was operated for an additional 25 minutes to determine if the decreasing turbidity was a trend. Turbidity was seen to increase and the test was ended. The additional 25 minutes of data was not utilized in the statistical analysis.

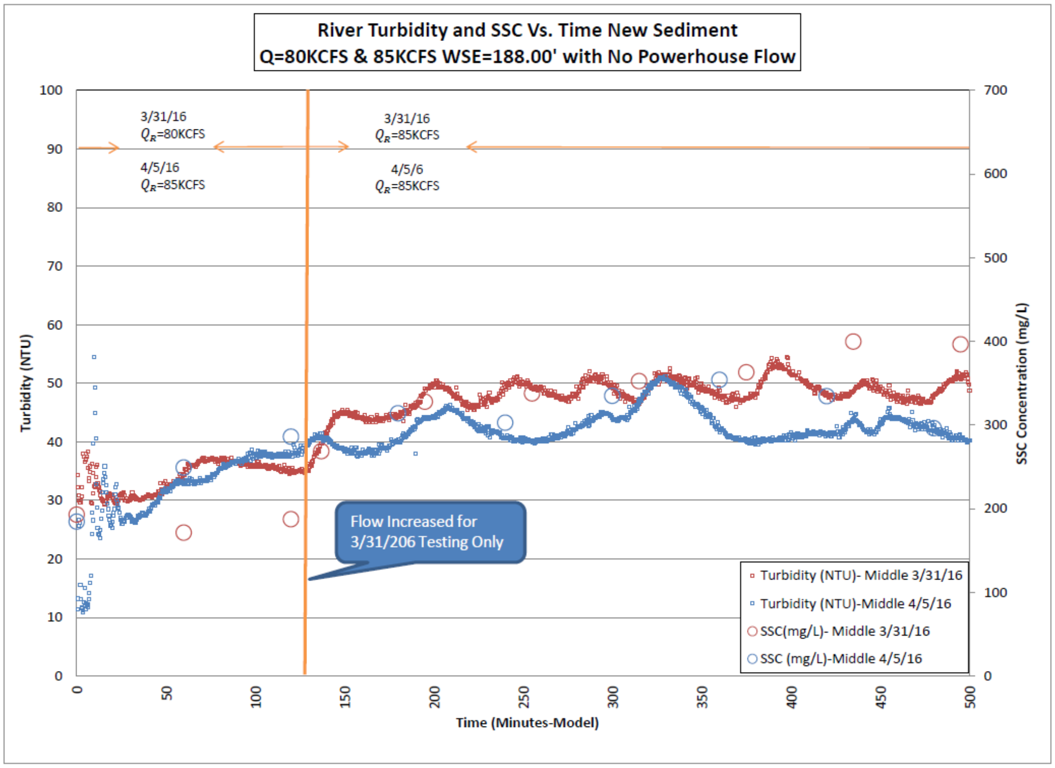

Figure 5-11: River turbidity and SSC as a function of time (March 31 and April 5 Test).

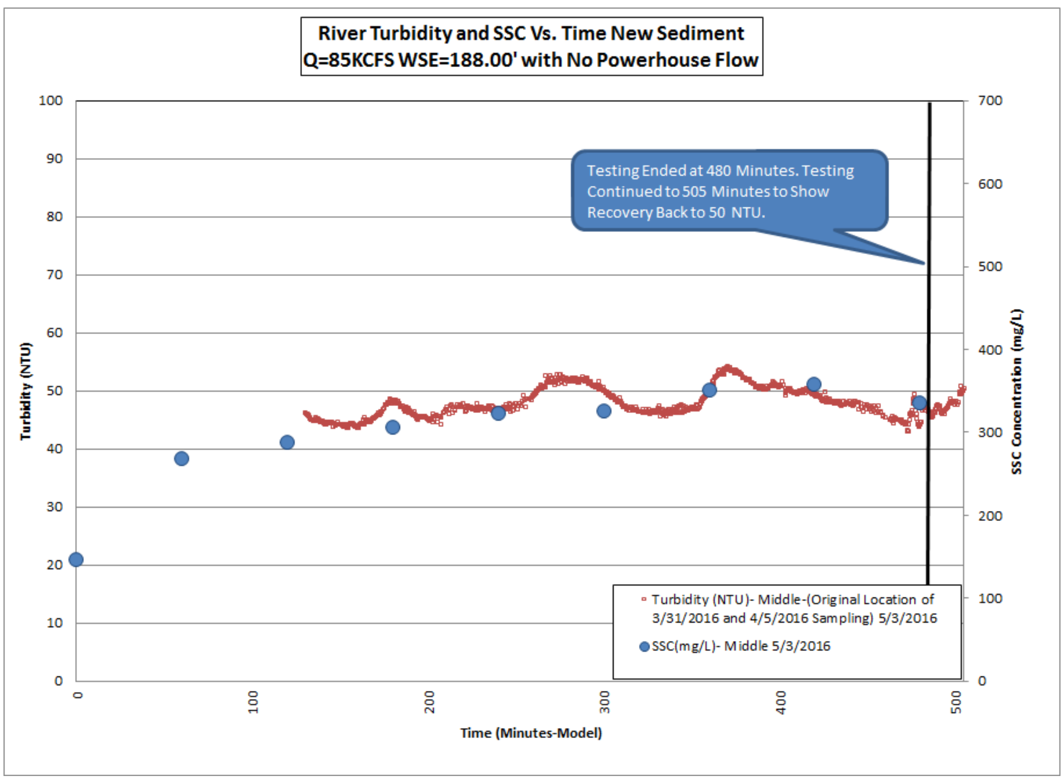

Figure 5-12: River turbidity and SSC as a function of time (May 3 Test).

The data from the May 3 testing was compared with the testing conducted on March 31 and April 5. The turbidity and SSC data from all three tests is shown in Figure 5-13. The May 3 testing results are very similar to the March 31 and April 5 results. The May 3 measured turbidity and SSC appeared to stabilize at approximately 180 minutes. This is almost identical to the other tests.

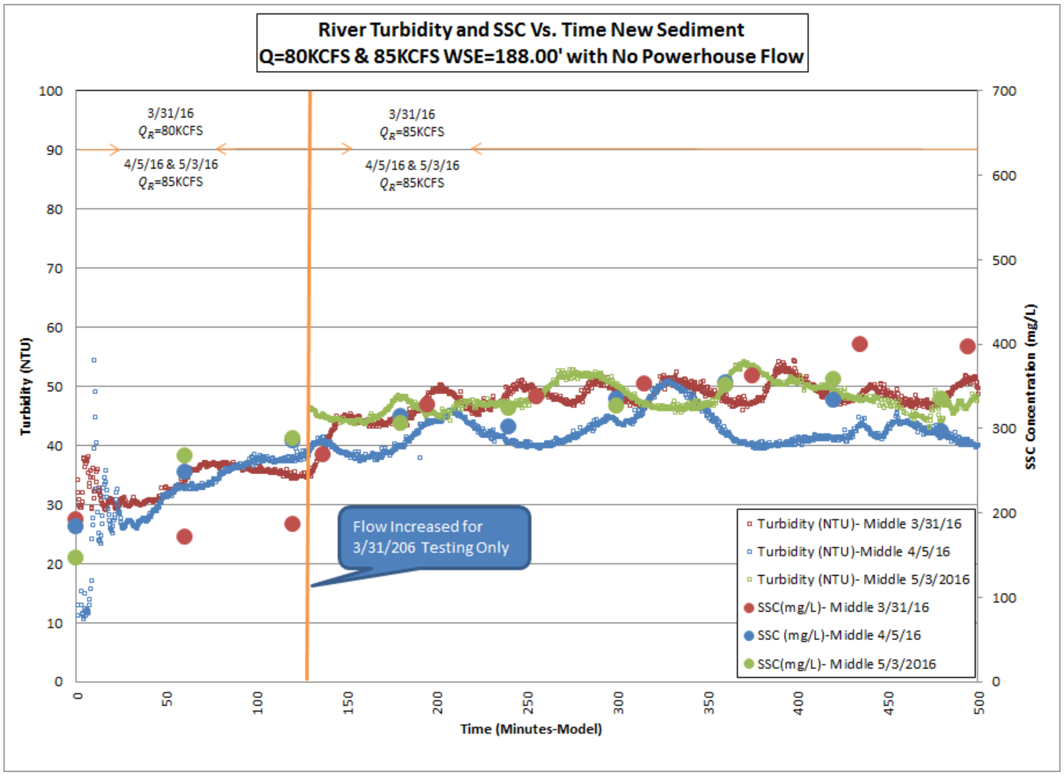

Figure 5-13: River turbidity and SSC data comparison of three tests.

A brief statistical analysis of the three test's data was performed. For purposes of analysis it was assumed that model stability was obtained at T=180 minutes and statistical analysis for all three tests is shown for the testing period of T=180 minutes to T=480 minutes. The mean, standard deviation, coefficient of variance, and difference in test mean from the mean of all three tests were calculated. This is shown in Table 5-1 for the river turbidity data and in Table 5-2 for the river SSC data. The May 3 repeat test showed excellent agreement with the March 31 and April 5 tests. The May 5 mean was between the March 31 and April 5 mean. In addition the maximum variation in the three test mean was shown to be 8.3%.

Table 5-1: Turbidity Three Test Statistical Analysis

Based on Middle River Sampling Station 20 Second Average Turbidity Running Data												
Statistical Measure	Standard Deviation (NTU)			Mean (NTU)			Coefficient of Variance			Test Mean Delta from 3 Test Average (%)		
Test Date	3/31/2016	4/5/2016	5/3/2016	3/31/2016	4/5/2016	5/3/2016	3/31/2016	4/5/2016	5/3/2016	3/31/2016	4/5/2016	5/3/2016
180-480 Minutes	1.8	2.7	2.4	48.8	43.0	48.7	0.04	0.06	0.05	4.3%	8.3%	4.0%

Table 5-2: SSC Three Test Statistical Analysis

Based on Middle River Sampling Station 1 Hour SSC Sampling					
3/31/2016		4/5/2016		5/3/2016	
Time (Minutes from Start of Testing)	SSC (mg/L)	Time (Minutes from Start of Testing)	SSC (mg/L)	Time (Minutes from Start of Testing)	SSC (mg/L)
195	328	180	314	180	306
255	338	240	303	240	324
315	352	300	335	300	327
375	363	360	354	360	351
435	400	420	334	420	358
495	396	480	296	480	335
Average	362.8	Average	322.7	Average	333.5
St. Dev	29.8	St. Dev	22.1	St. Dev	19.2
Cv	0.08	Cv	0.07	Cv	0.06
Test Mean Delta from 3 Test Average	7%	Test Mean Delta from 3 Test Average	5%	Test Mean Delta from 3 Test Average	2%

The three repeat tests with an 8.3% maximum difference, demonstrates the ability of the model to reproduce river SSC and turbidity. Based on the test results, Alden recommended to move forward with baseline testing.

5.2 Physical Model Baseline Tests

Baseline testing was conducted to determine how much sediment is transported to the reservoir under the existing prototypical conditions. Results from the modification tests are compared to the baseline tests to quantify the effectiveness of the modification. The protocol for the baseline test was as follows:

1) Reset the model following the procedure utilized during the three sensitivity tests. The model sediment is turned over and leveled to the final elevation on the day prior to the test. The test must be conducted within 24 hours of leveling the model to ensure there is no consolidation of sediments due to extended periods without testing.

2) Conduct a baseline test and a repeat baseline test at a WSE 188.00 ft and 85,000 cfs main river flow. The 85,000 cfs model river flow represents a prototype flow of 70,000 cfs. The model flow is 21.4 percent higher than the flow based on Froude scale.

3) The powerhouse flow is set at 13,850 cfs, which is equal to the nominal 3 unit prototype flow of 11,400 cfs increased by 21.4 percent to maintain the same ratio of powerhouse flow to river flow in the model and prototype.

4) Turbidity was measured in real-time for the powerhouse flow and at the middle river sampling location. At the river location, the turbidity was measured at three locations in the water column to determine the suspended sediment concentration profile.

5) Hourly SSC samples were taken at the middle river sampling station.

6) Powerhouse SSC concentration samples with bag filters were taken for approximately two minutes, every ten minutes while the powerhouse flow was operating.

7) The test is initialized with a model river flow of 85,000 cfs, a powerhouse flow of 0 cfs and a WSE of 188.00 ft. When the target initialization values are achieved, T=0 was called.

8) The river with no powerhouse flow was run for 5 hours after T=0.

9) At T=285 minutes the forebay was cleaned of all accumulated sediment.

10) At T=300 minutes the powerhouse was turned on to the nominal 3 unit prototype flow (13,850 cfs). The powerhouse was run from T=300 minutes until T=420 minutes while taking a SSC sample every ten minutes of the powerhouse flow.

5.2.1 70,000 cfs Baseline Test

Baseline testing was completed on May 13 and May 17 to determine the amount of suspended sediment transported to the reservoir for the existing conditions for a nominal river flow of 70,000 cfs. The testing protocol followed a similar path as previous testing. The model bed was raked and scree-leveled prior to each test. The model river flow and WSE was then set. The model was then allowed to operate for a period of 5 hours with no powerhouse flow while taking a river SSC sample every hour and 20 second turbidity measurements. At T=300 minutes the powerhouse flow was turned on and set to a nominal three unit operating flow. The powerhouse flow was then allowed to run for two hours while filter sampling the flow stream for sediment concentration and flowrate. These samples were taken on a 10-minute period for the entire length of powerhouse sampling.

To increase the suspended sediment concentration during the baseline tests, the model river flow was increased to a Froude scale flow of 85,000 cfs, while maintaining a water surface elevation of 188.00 ft. The powerhouse flow was set to a nominal three unit flowrate of 11,400 cfs (Yielding an actual powerhouse flow of 13,850 cfs when the Froude scaling from 70,000 cfs to 85,000 cfs is taken into account). Turbidity and SSC in the river are plotted as a function of time in Figure 5-14 for both the 5/13/2016 and 5/17/2016 baseline tests. The 5/17 test showed a short increase in turbidity at about time = 300 minutes. The reason for the increase is thought to be a large dune which passed under the turbidity meter. The duration of the increase was about 60 minutes. The increase does not affect results for two reasons: First, the SSC measurements are used in the analysis not turbidity. Second, the increase occurred before the final hour of testing.

SSC in the powerhouse flow is plotted as a function of time in Figure 5-15 for both the 5/13/2016 and 5/17/2016 baseline tests. Table 5-3 shows the measured SSC values for the baseline conditions. For each test, the percentage of the river SSC transported to the power plant was computed. The river

SSC is the average of the two final SSC measurements made at T=360 and T=420 minutes. The powerhouse flow was operated for the final two hours of the test and SSC samples were collected at 10 minute intervals. The average SSC to the powerhouse was determined by averaging the seven samples collected during the final hour of testing, T-360 to T=420 minutes. During the final hour of testing, the suspended sediment concentration in the powerhouse flow was 45 percent of the suspended sediment concentration in the river flow for both baseline tests. For baseline test 1, the average river SSC during the final hour was 393 mg/l and the powerhouse SSC was 178 mg/l. For baseline test 2, the average river SSC during the final hour was 372 mg/l and the powerhouse SSC was 166 mg/l.

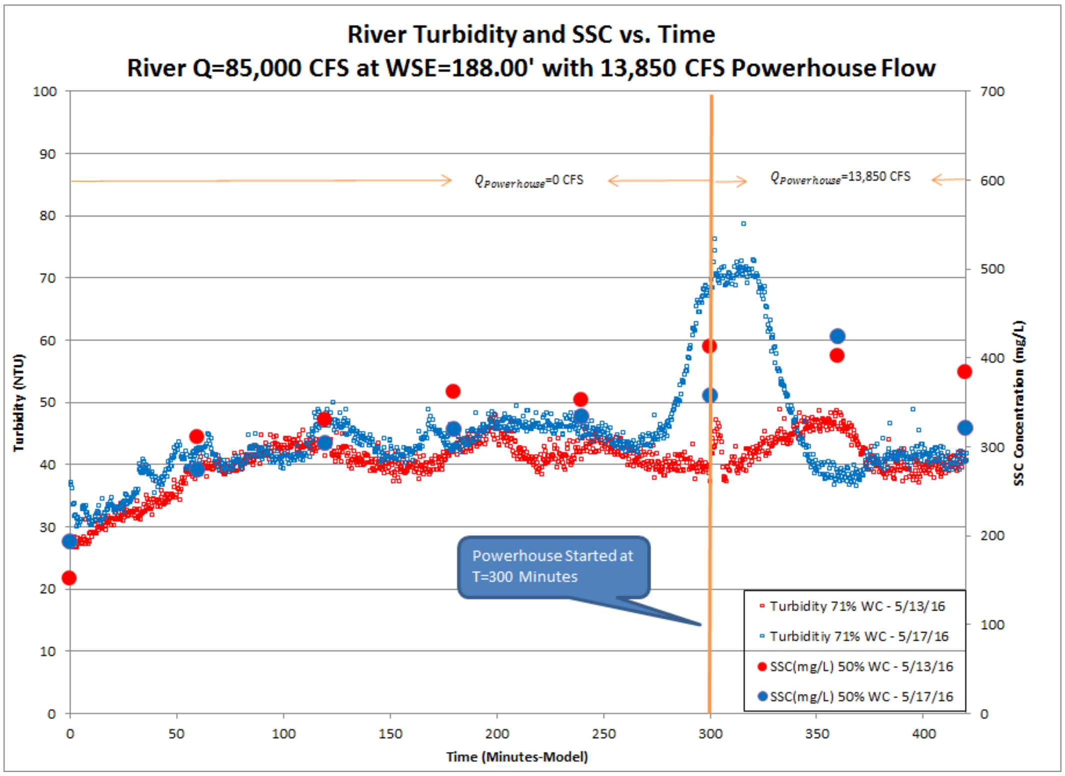

Figure 5-14: Baseline test river turbidity and SSC, 70,000 cfs.

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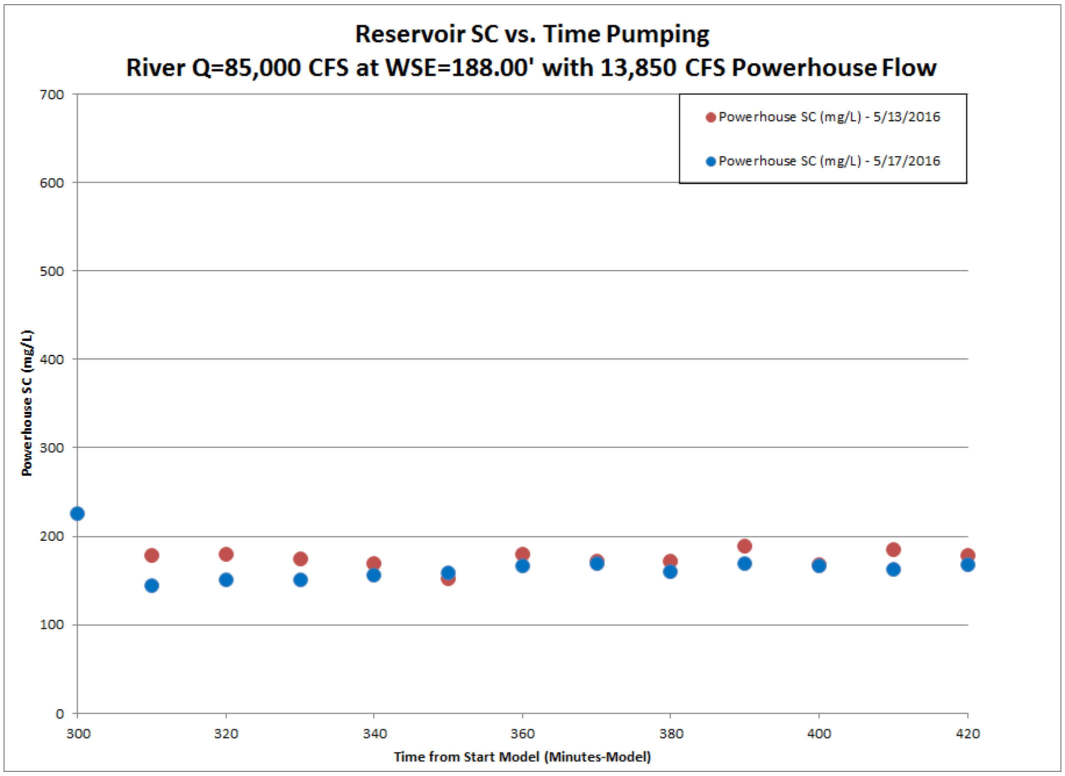

Figure 5-15: Baseline test powerhouse SSC, 70,000 cfs.

Table 5-3: Measured SSC During Baseline Testing, 70,000 cfs

Time from Start of Test	River Flow SSC (mg/l)		Powerhouse Flow SC (mg/l)	
(Minutes)	Test 1	Test 2	Test 1	Test 2
360	402.1	423.8	179.5	166.2
370	-	-	172.4	169.1
380	-	-	172.2	160.4
390	-	-	189.1	169.1
400	-	-	168.6	167.2
410	-	-	185.0	163.1
420	383.4	320.4	178.6	167.6

5.2.2 40,000 cfs Baseline Test

Baseline testing at a nominal river flow of 40,000 cfs was completed on July 12 and July 29 to determine the amount of suspended sediment transported to the reservoir for the existing conditions for a nominal river flow of 40,000 cfs. To increase the suspended sediment concentration during the test, the model flow was increased to a Froude scale flow of 48,000, while maintaining a water surface elevation of 183.00 ft. Turbidity and SSC in the river are plotted as a function of time in Figure 5-16. SSC in the powerhouse flow is plotted as a function of time in Figure 5-17. Table 5-4 shows the measured SSC values for the baseline conditions. For each test, the percentage of the river SSC transported to the power plant was computed. The river SSC is the average of the two final SSC measurements made at T=360 and T=420 minutes. The powerhouse flow was operated for the final two hours of the test and SSC samples were collected at 10 minute intervals. The average SSC to the powerhouse was determined by averaging the seven samples collected during the final hour of testing, T-360 to T=420 minutes. During the final hour of testing, the suspended sediment concentration in the powerhouse flow was 50.1 percent and 91.9 percent of the suspended sediment concentration in the river for the July 12 and July 29 test respectively. For the July 12 test, the average river SSC during the final hour was 20.6 mg/l and the powerhouse SSC was 10.3 mg/l. For the July 29 test, the average river SSC during the final hour was 6.9 mg/l and the powerhouse SSC was 6.3 mg/l.

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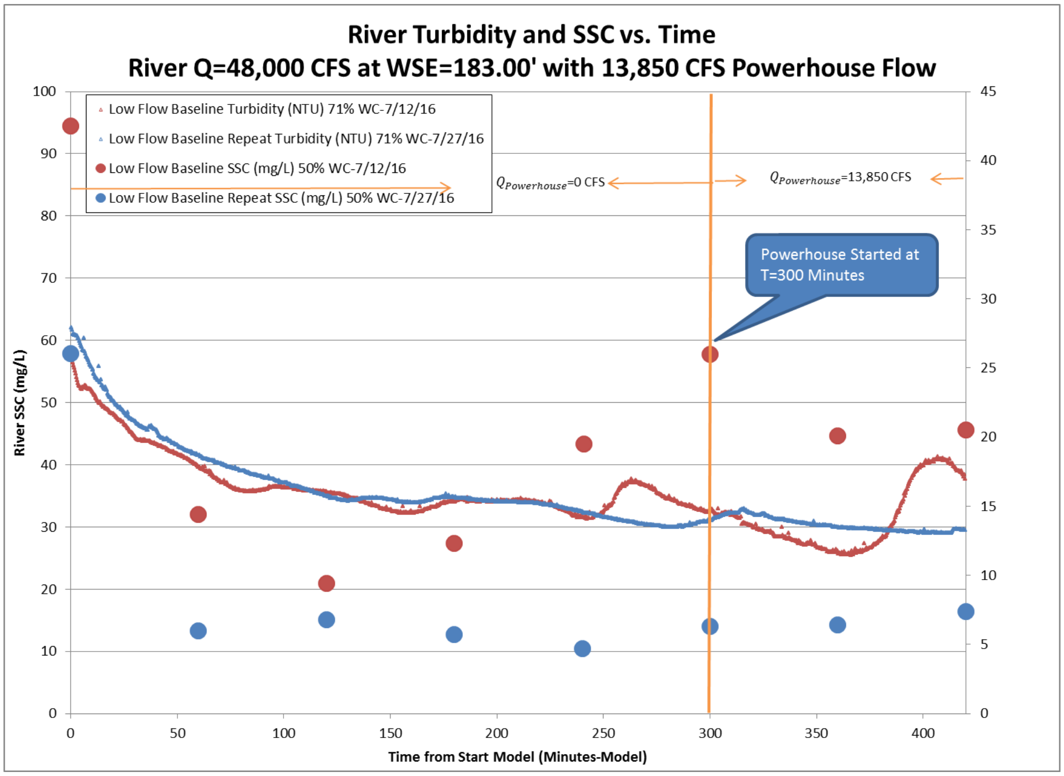

Figure 5-16: Baseline test river turbidity and SSC, 40,000 cfs.

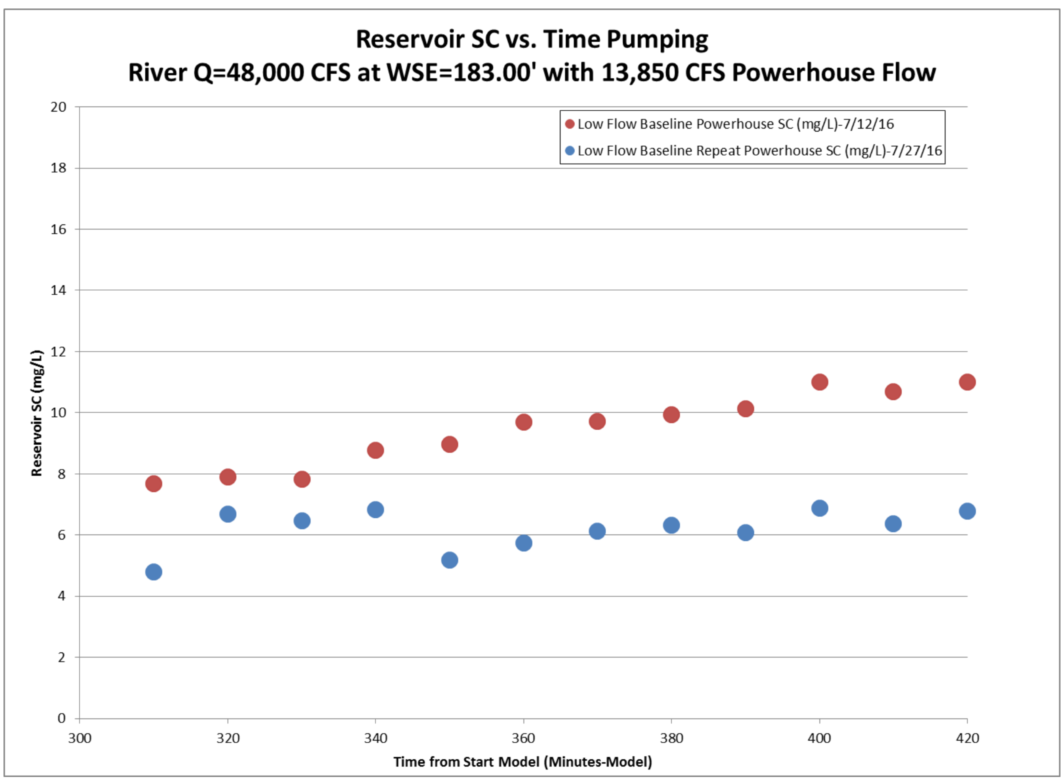

Figure 5-17: Baseline test powerhouse SSC, 40,000 cfs.

Table 5-4: Measured SSC During Baseline Testing, 40,000 cfs

Time from Start of Test	River Flow SSC (mg/l)		Powerhouse Flow SC (mg/l)	
(Minutes)	Low Flow Baseline	Low Flow Baseline Repeat	Low Flow Baseline	Low Flow Baseline Repeat
360	20.1	6.4	9.7	5.8
370	-	-	9.7	6.1
380	-	-	9.9	6.3
390	-	-	10.1	6.1
400	-	-	11.0	6.9
410	-	-	10.7	6.4
420	21.1	7.4	11.0	6.8

5.3 Physical Model Modification Tests

Six modifications were tested in the physical model; some of the modifications were tested multiple times to evaluate reproducibility of the results. Early testing did not consider the velocity over the weir as a limiting parameter. In an effort to maximize the efficiency of the weir, the weir crest elevation was maximized to withdraw water from the top of the water column. In the later stages of testing, a maximum velocity of 2 ft/s over the weir was added as a limiting condition. Testing results show how the efficacy of the weir changes with changes in crest elevation.

Two weir types can be considered: a fixed weir and a weir with a movable crest elevation. The crest elevation of the fixed weir is determined from the weir length, the low water level and the maximum allowable velocity at the low water level. Construction of a movable crest weir is technically possible, however, maintenance and construction costs are expected to be higher. Part of the challenge in constructing a movable weir at this location is that flow must pass over the weir in both directions.

5.3.1 Exploratory Testing

Exploratory testing was completed on May 31 and June 1. The purpose of the tests was to analyze flow patterns approaching the weir with particular interest in secondary currents. The exploratory testing was used to determine the initial weir layout for live bed testing based on flow patterns. The May 31 test was defined by GDF Suez and was run at 70,000 cfs with a water surface elevation of 190 ft. The weir had a length of 1100 feet and the crest elevation was above the water surface elevation. Powerhouse flow was turned off. Video documentation was used to record the secondary currents. No sediment measurements were made during the test. Video results are included in Appendix C, on the storage media. GDF Suez reviewed the video and found the secondary currents to be favorable. A second test was requested by GDF Suez with a flow of 85,000 cfs and a water surface elevation of 188.00 feet. The test was completed on June 1 and had the same weir configuration as the May 31 test. Video was used to document the secondary currents and is included in Appendix C. Based on the test results; the weir alignment for modification 1 was defined. Figure 5-18 shows the weir alignment used in the testing.

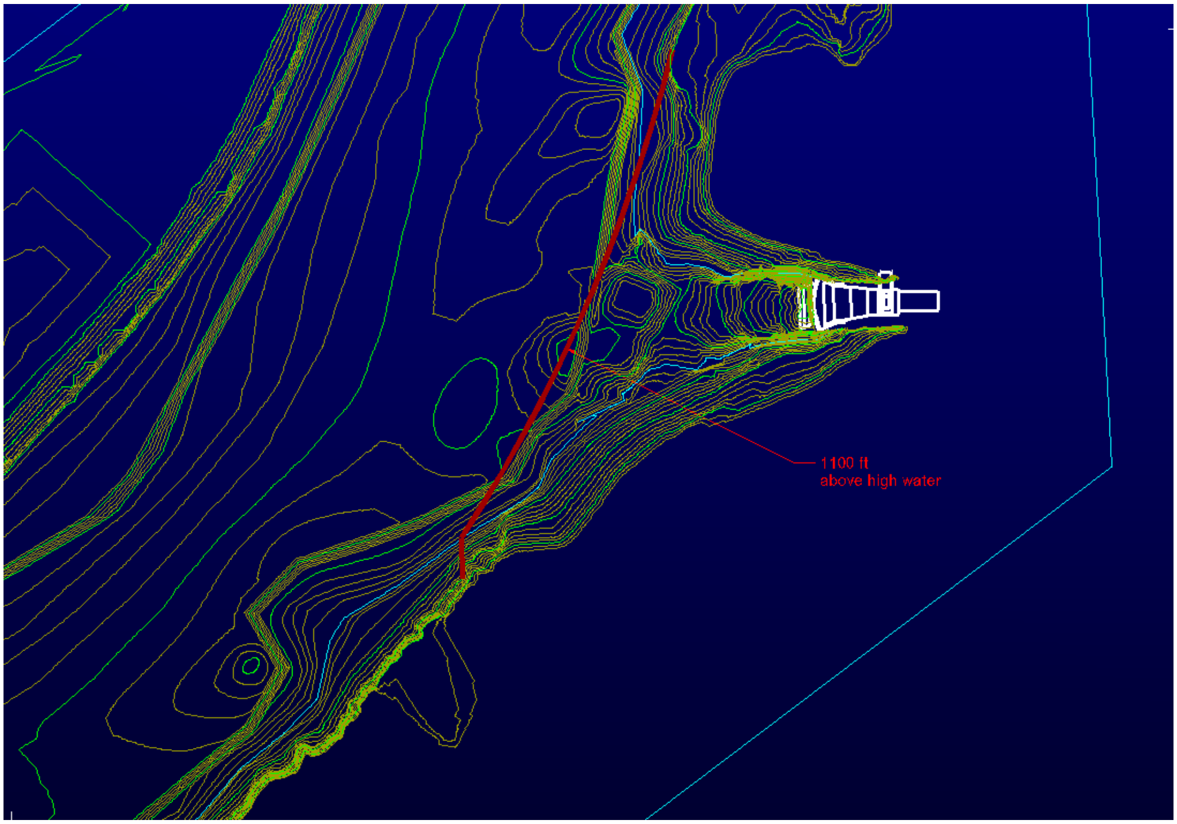

Figure 5-18: Weir alignment for May 31 and June 1 exploratory testing.

5.3.2 Modification 1 at 70,000 cfs

Modification 1 was tested on June 7 with a nominal river flow of 70,000 cfs and a water surface elevation of 188.00 ft. The weir length is approximately 700 feet and the weir crest elevation is 171.00 ft. Figure 5-19 shows a plan view of the weir layout. The same test procedure was followed that was used in the baseline testing and the river flow was increased to a Froude scale flow of 85,000 cfs. Turbidity and SSC in the river are plotted as a function of time in Figure 5-20. SSC in the powerhouse flow is plotted as a function of time in Figure 5-21. Table 5-5 shows the measured SSC values for the Modification 1 conditions. For each test, the percentage of the river SSC transported to the power plant was computed. During the final hour of testing, the suspended sediment concentration in the powerhouse flow was 38 percent of the suspended sediment concentration in the river. The baseline tests had a powerhouse suspended sediment concentration of 45 percent relative river SSC. The seven percent reduction in SSC from 45 to 38 percent is about a 15 percent reduction in sediment relative to baseline conditions.

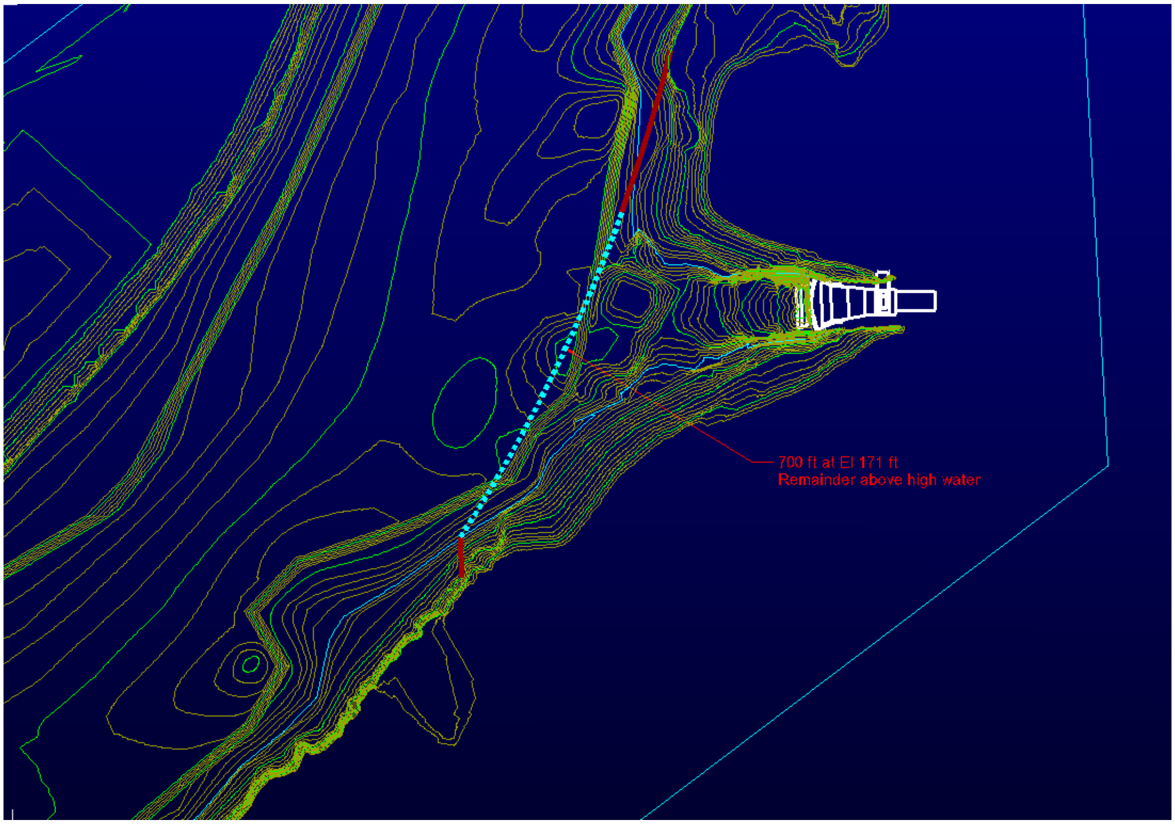

Figure 5-19: Modification 1 plan view drawings.

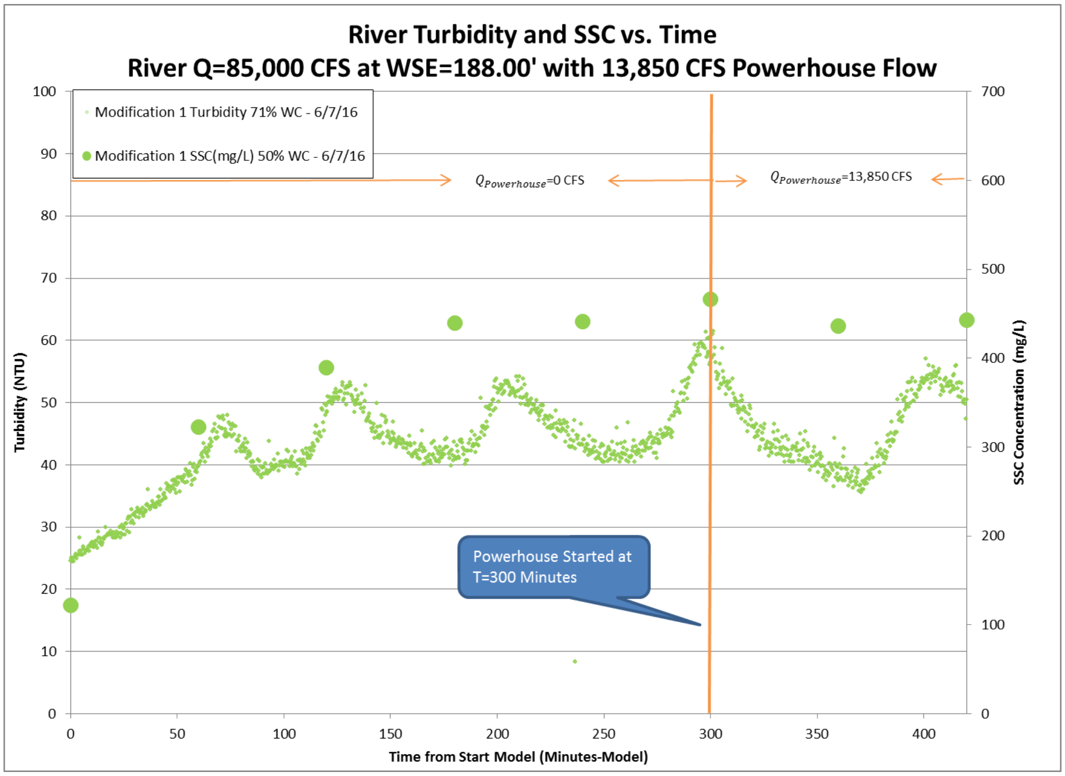

Figure 5-20: Modification 1 river turbidity and SSC, 70,000 cfs.

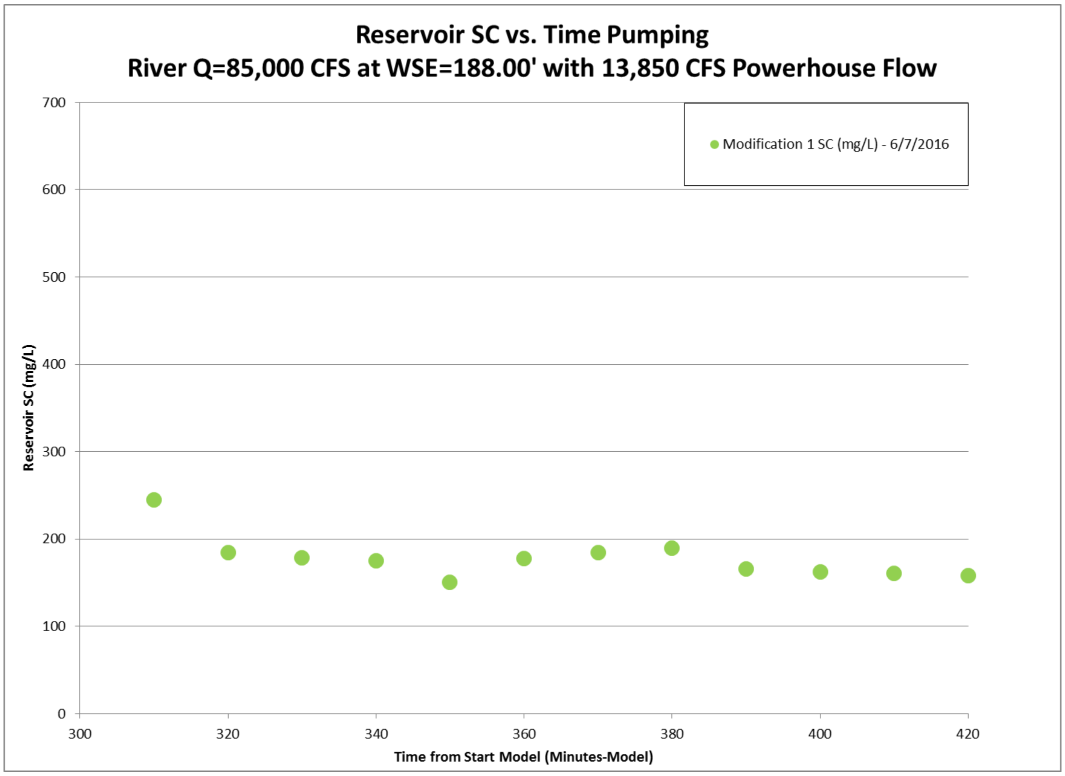

Figure 5-21: Modification 1 powerhouse SSC, 70,000 cfs.

Table 5-5: Measured SSC During Modification 1, 70,000 cfs

Time from Start of Test	River Flow SSC (mg/l)	Powerhouse Flow SC (mg/l)
(Minutes)	Mod 1	Mod 1
360	392.0	177.5
370	-	184.6
380	-	189.6
390	-	165.5
400	-	162.3
410	-	160.8
420	399.2	157.8

5.3.3 Modification 2 at 70,000 cfs

Modification 2 was tested on June 9 with a nominal river flow of 70,000 cfs and a water surface elevation of 188.00 ft. The weir length is approximately 500 feet and the weir crest elevation is 169.00 ft, two feet lower than modification 1. Figure 5-22 shows a plan view of the weir layout. The same test procedure was followed that was used in the baseline testing and the river flow was increased to a Froude scale flow of 85,000 cfs. Turbidity and SSC in the river are plotted as a function of time in Figure 5-23. SSC in the powerhouse flow is plotted as a function of time in Figure 5-24. Table 5-6 shows the measured SSC values for the modification 2 conditions. For each test, the percentage of the river SSC transported to the power plant was computed. During the final hour of testing, the suspended sediment concentration in the powerhouse flow was 34 percent of the suspended sediment concentration in the river. The baseline tests had a powerhouse suspended sediment concentration of 45 percent relative river SSC. The 11 percent reduction in SSC from 45 to 34 percent is about a 25 percent reduction in sediment load relative to baseline conditions.

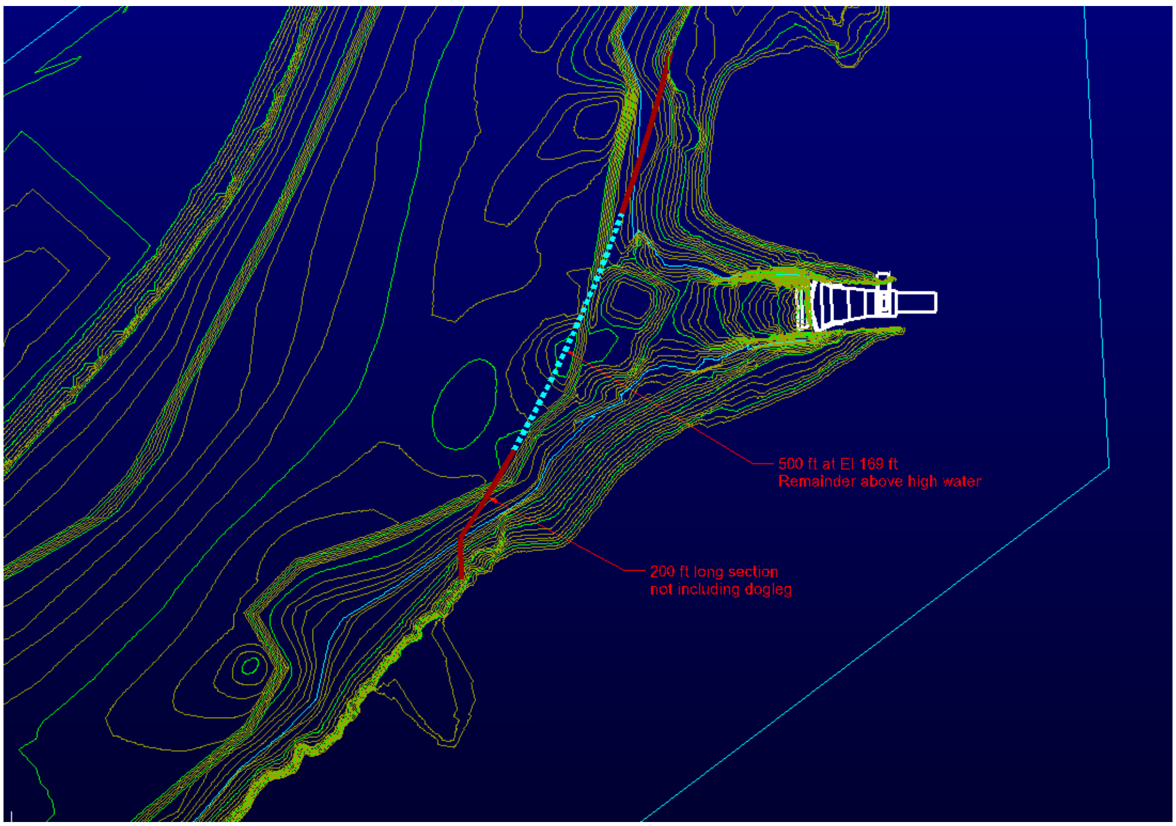

Figure 5-22: Modification 2 plan view drawings.

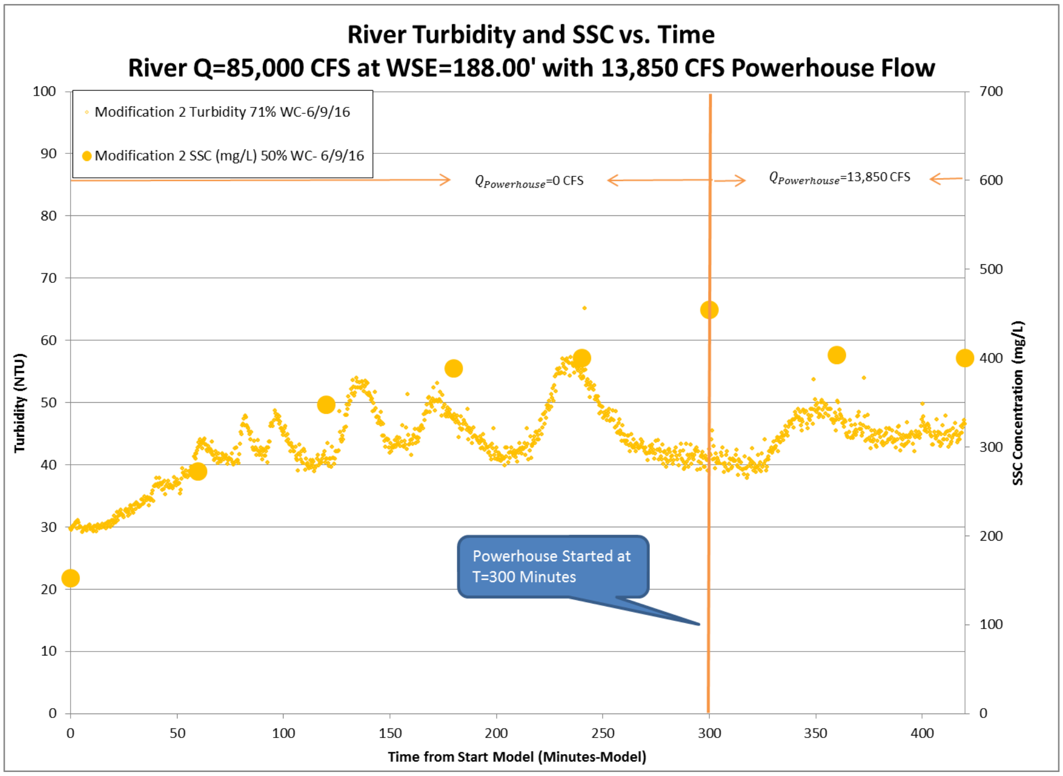

Figure 5-23: Modification 2 river turbidity and SSC, 70,000 cfs.

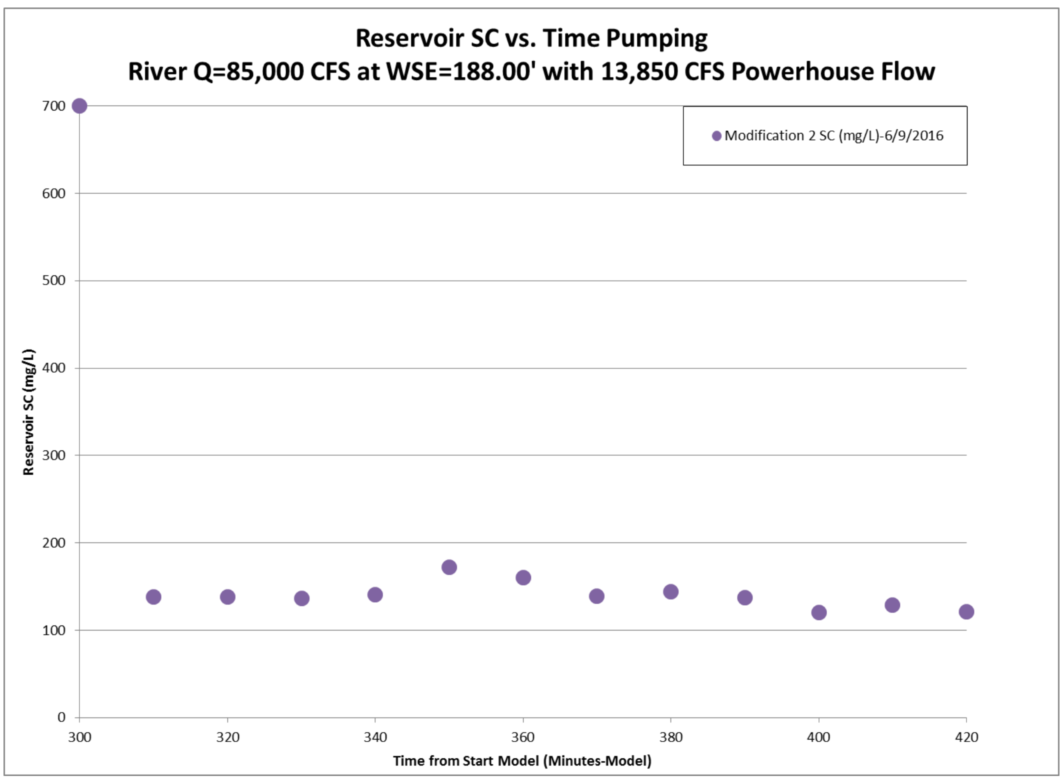

Figure 5-24: Modification 2 powerhouse SSC, 70,000 cfs.

Table 5-6: Measured SSC During Modification 2, 70,000 cfs

Time from Start of Test	River Flow SSC (mg/l)	Powerhouse Flow SC (mg/l)
(Minutes)	Mod 1	Mod 1
360	372.7	159.9
370	-	139.1
380	-	143.9
390	-	137.1
400	-	120.4
410	-	128.7
420	391.2	120.9

5.3.4 Modification 3 at 70,000 cfs

The reduction in suspended sediment concentration to the reservoir was disappointing for modifications 1 and 2. After discussion with GDF Suez, the crest elevation of the Modification 1 weir was increased from 171 to 185.3 ft for the Modification 3 test. Figure 5-22 shows a plan view of the weir layout. The same test procedure was followed that was used in the baseline testing and the river flow was increased to a Froude scale flow of 85,000 cfs. The water surface elevation was initially set at 188.00 ft, consistent with the Modification 1 test. However, when the plant flow was started after five hours of testing, the pumps were starved for water and the forebay was drawn down. The water level in the model was increased to 190.00 ft to increase the submergence over the weir crest, the flow remained unchanged. The change in water level did not appear to influence model results, the SSC in the river and to the power house were stable during the final 60 minutes of testing that are used to evaluate a modification.

Turbidity and SSC in the river are plotted as a function of time in Figure 5-23. SSC in the powerhouse flow is plotted as a function of time in Figure 5-24. Table 5-6 shows the measured SSC values for the Modification 3 conditions. For each test, the percentage of the river SSC transported to the power plant was computed. During the final hour of testing, the suspended sediment concentration in the powerhouse flow was 15 percent of the suspended sediment concentration in the river. The baseline tests had a powerhouse suspended sediment concentration of 45 percent relative river SSC. The 30 percent reduction in SSC from 45 to 15 percent is about a 66 percent reduction in sediment load relative to baseline conditions.

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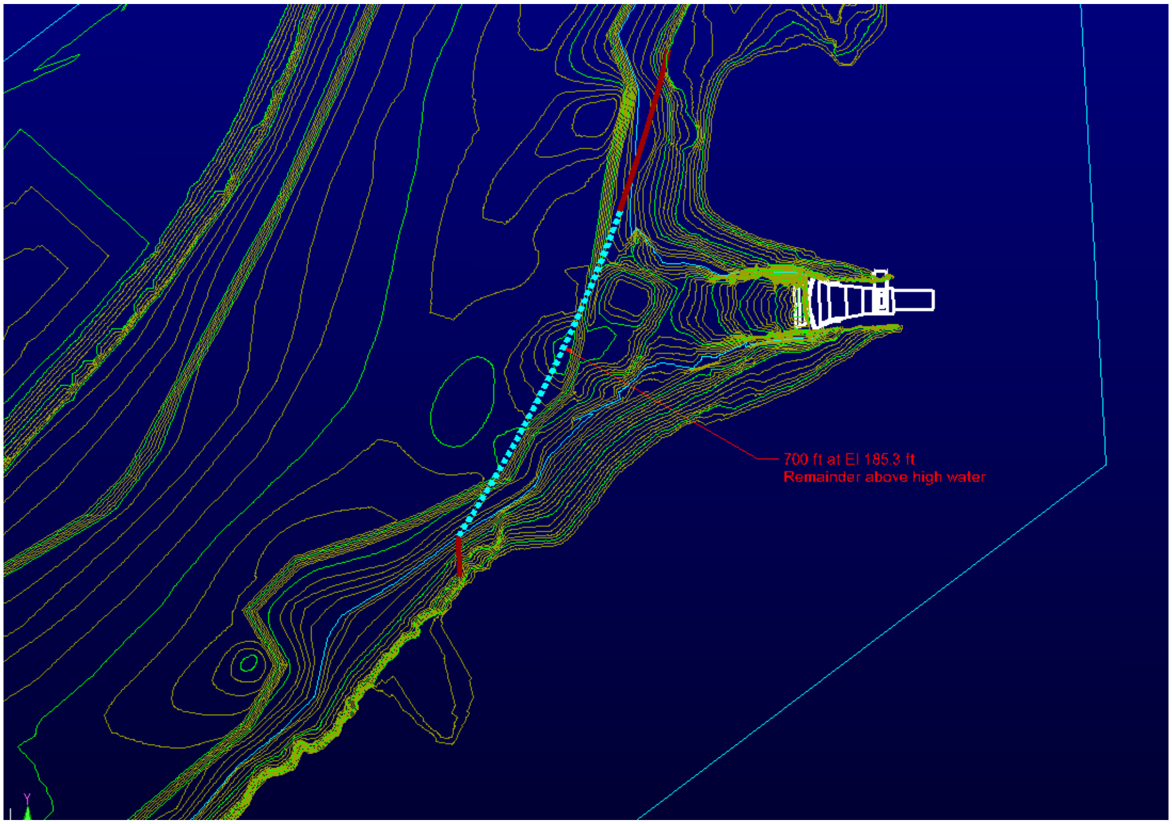

Figure 5-25: Modification 3 plan view drawings.

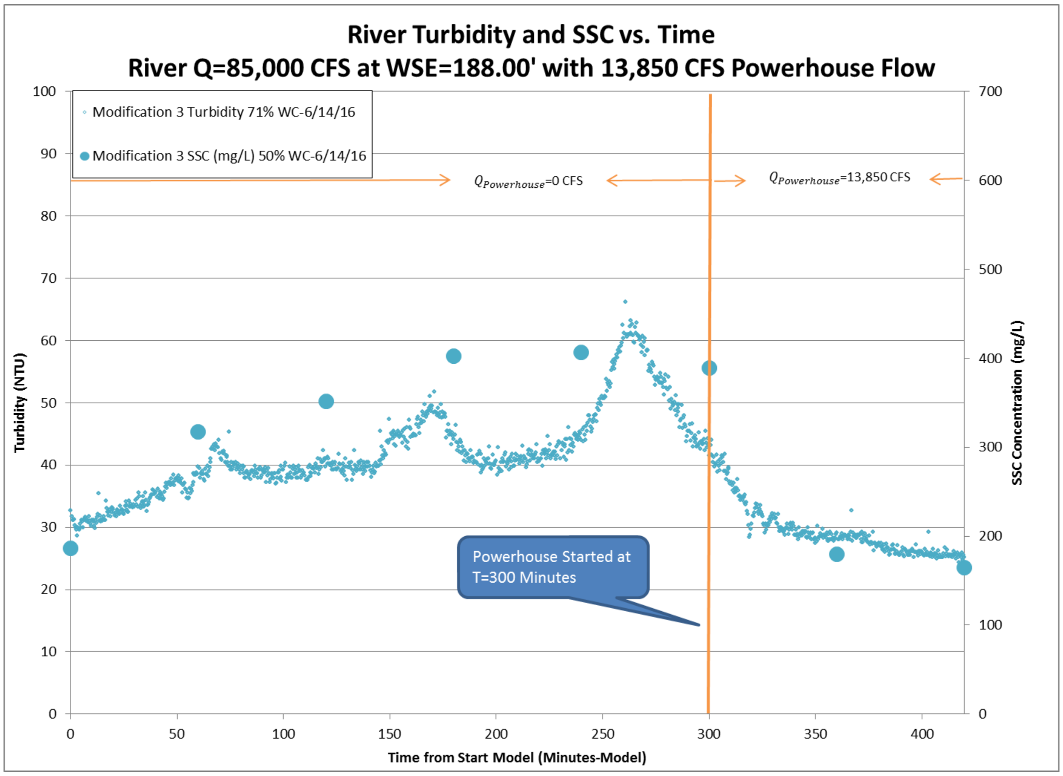

Figure 5-26: Modification 3 river turbidity and SSC, 70,000 cfs.

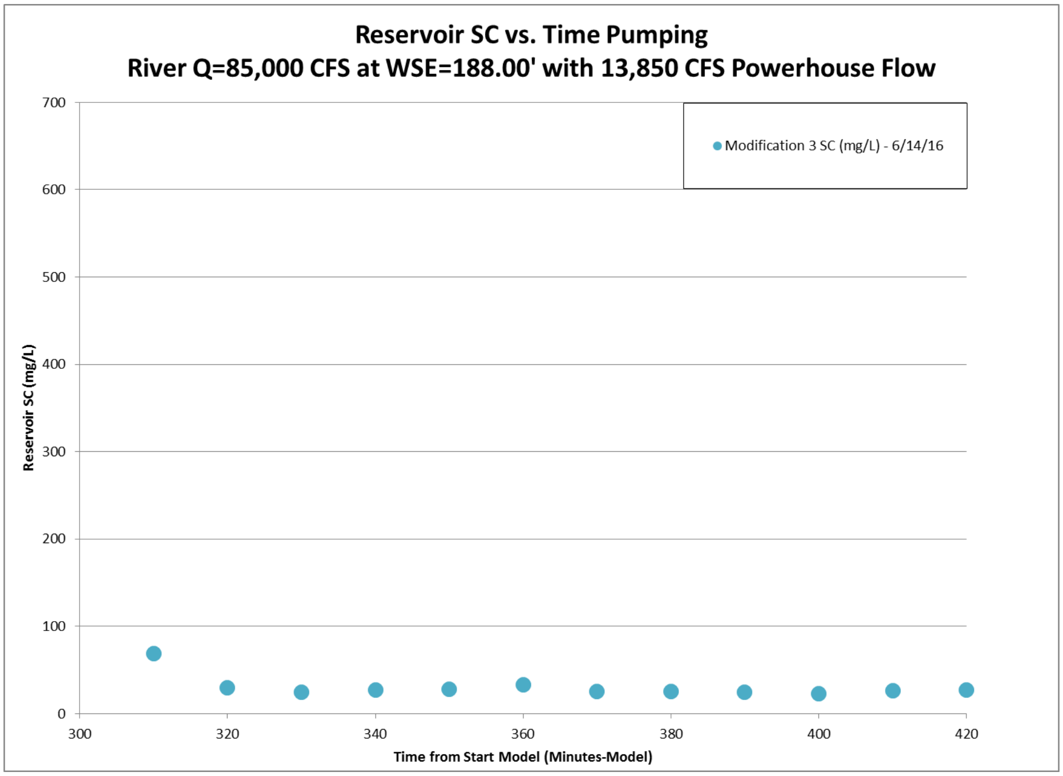

Figure 5-27: Modification 3 powerhouse SSC, 70,000 cfs.

Table 5-7: Measured SSC During Modification 3, 70,000 cfs

Time from Start of Test	River Flow SSC (mg/l)	Powerhouse Flow SC (mg/l)
(Minutes)	Mod 1	Mod 1
360	388.7	33.1
370	-	25.4
380	-	25.1
390	-	24.7
400	-	23.2
410	-	26.0
420	164.8	26.9

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5.3.5 Modification 4 at 110,000 cfs

The week of June 13th, GDF Suez visited the model to witness the testing. On June 15th GDF Suez used the model for exploratory testing. Testing was conducted without resetting the bed from the previous Modification 3 test and no previously created test protocol was followed for this testing or the subsequent Modification 4 and high flow baseline testing. Testing was conducted with a water surface elevation of 185.00 ft and a river flow that varied from about 100,000 to 110,000 cfs. The weir length was 700 feet and the weir crest elevation 185.3 ft, above the water surface. The powerhouse was not used during any of the testing. Based on the observations made on June 15, a documentation test was run on June 16, following a new testing protocol.

Under the guidance of Mr. Alam, the model bed was not reset or modified before the June 16th testing. The previous testing on June 15th had caused severe scour and deposition of the bed material in the model. The June 16 test was run with a river flow of 110,000 cfs (as computed using Froude scaling),a water surface elevation of 185.00 ft, and a powerhouse flow of 13,850 cfs. The test was designed by Mr. Alam to be a “back-to-back” baseline and modification test. The model with Modification 4 installed was turned on and river flow and WSE were set. The model was allowed to run for 30 minutes and the powerhouse flow was then turned on and set. The powerhouse flow was run for 60 minutes while sampling SSC every 10 minutes. River SSC samples were taken approximately every 15 minutes during testing. After 60 minutes of powerhouse flow, the weir was removed without shutting down the model (all test conditions remained identical besides the removal of the weir). After the weir was removed the “baseline” testing started. The “baseline” condition was run for 60 minutes while taking 10 minute powerhouse SSC samples.

The June 16th testing had a weir crest elevation was 181.00 ft and the weir length was 700 feet. Figure 5-28 shows the plan view layout of the weir. At the end of the standard testing period, the weir was removed from the model and the baseline data was collected on the same day without interrupting model flow. The test was run at a non-Froude scale flow while the powerhouse flow was maintained at 13,850 cfs, the same flow that was used for the previous modification tests.

Turbidity and SSC in the river are plotted as a function of time in Figure 5-29. SSC in the powerhouse flow is plotted as a function of time in Figure 5-30. Table 5-8 shows the measured SSC values for the Modification 4 conditions. For each test, the percentage of the river SSC transported to the power plant was computed. The test results cannot be compared with any other model results for multiple reasons:

- The model was operated significantly outside Froude scale
- The ratio of river flow to powerhouse flow was significantly different from the other tests. This intensified the secondary currents causing unrealistic flow patterns at the weir and significant scour along the weir.
- The testing procedure for collecting baseline data was not followed.

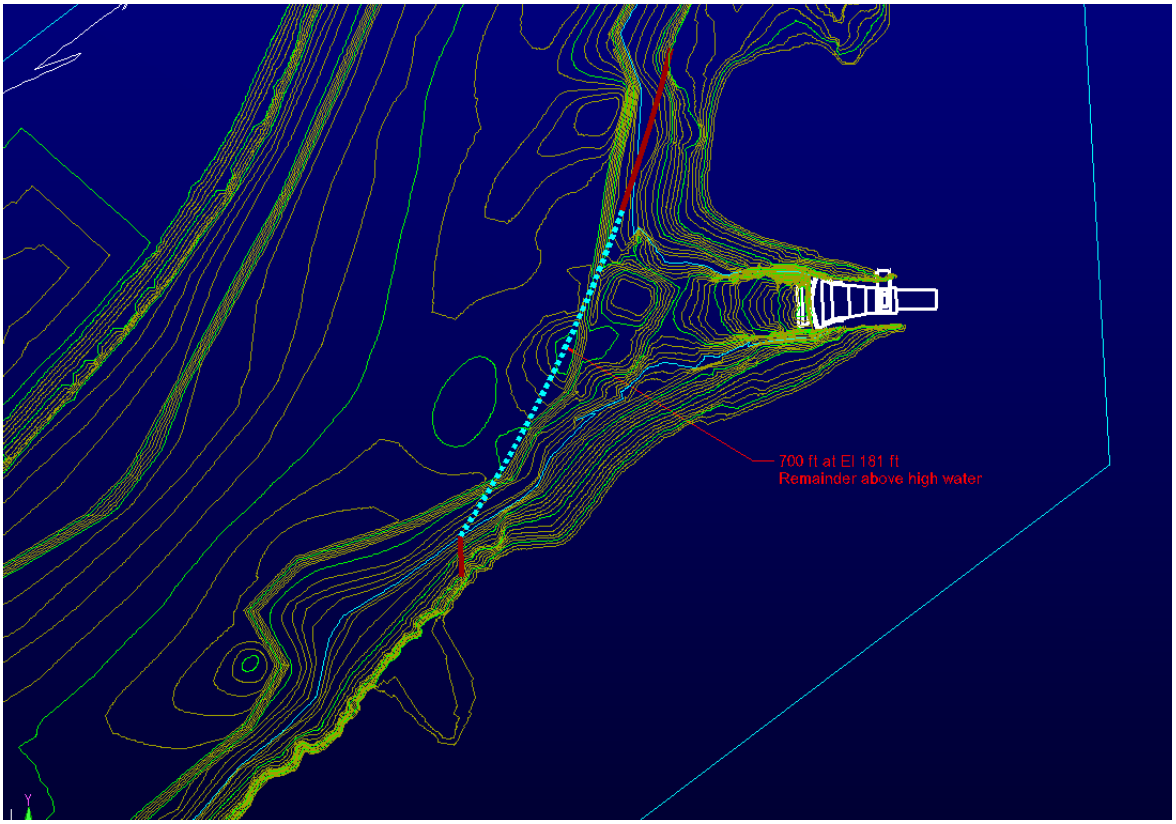

Figure 5-28: Modification 4 plan view drawings.

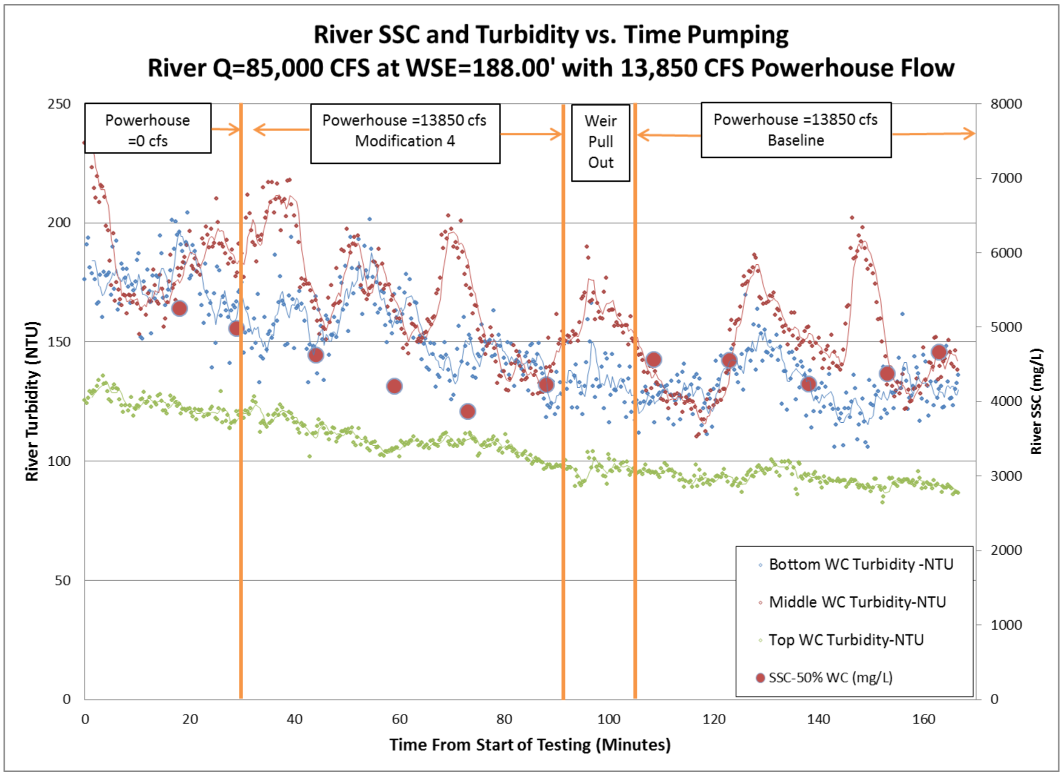

Figure 5-29: Modification 4 river turbidity and SSC, 70,000 cfs.

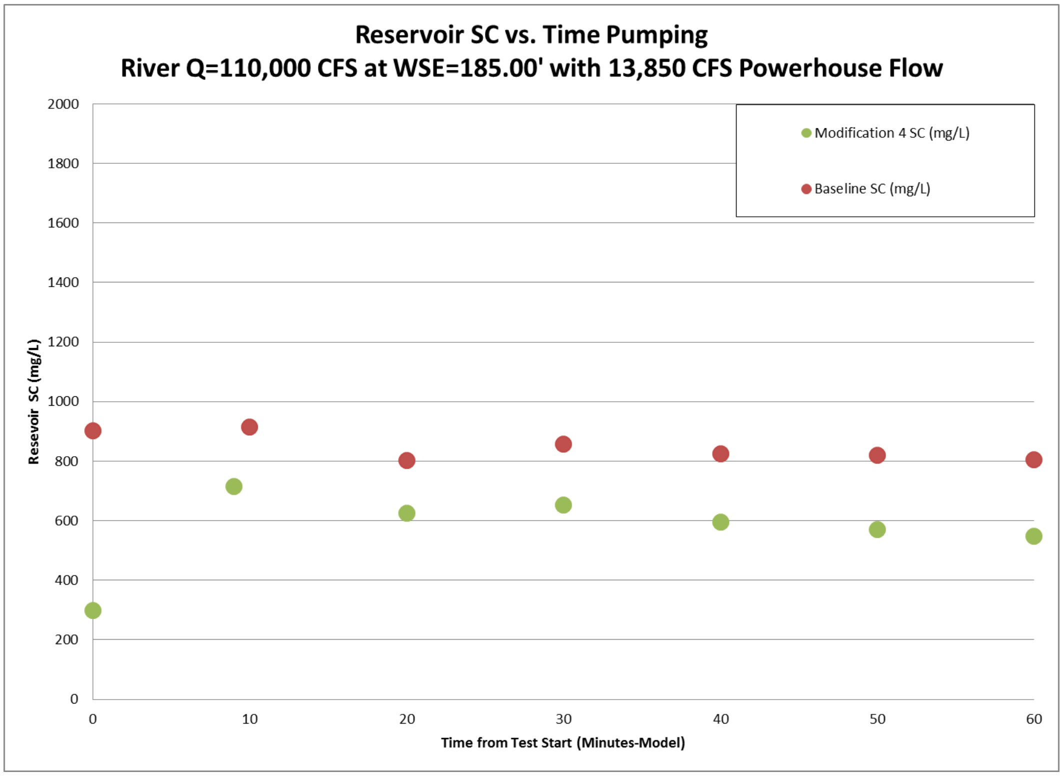

Figure 5-30: Modification 4 powerhouse SSC, 70,000 cfs.

Table 5-8: Measured SSC During Modification 4, 70,000 cfs

Baseline				Modification 4			
River		Powerhouse		River		Powerhouse	
Time from Start of Test (Minutes)	SSC (mg/l)	Time from Start of Test (Minutes)	SC (mg/l)	Time from Start of Test (Minutes)	SSC (mg/l)	Time from Start of Test (Minutes)	SC (mg/l)
5.5	4565.6	0	903.2	18	5255.9	0	299.3
20	4559.8	10	915.1	29	4980.7	9	714.8
35	4232.8	20	803.2	14	4628.4	20	624.2
50	4378.6	30	857.4	29	4207.8	30	652.8
60	4670.1	40	824.1	44	3866.1	40	596.0
-	-	50	820.8	59	4228.5	50	569.2
-	-	60	805.2	-	-	60	548.5

5.3.6 Modification 5 at 70,000 cfs

After Modification 4 testing, GDF Suez checked with the fisheries biologists what the maximum allowable velocity is over the weir crest. It was found that the project will likely be limited to about 2 ft/s, with perhaps some flexibility on very low flow conditions. Based on a weir length of 700 feet, a maximum plant flow of 15,200 cfs, and a minimum river level of 176.0 ft, the maximum weir elevation that will satisfy the 2 ft/s requirement is approximately 170 feet, approximately 11 feet below the low water level of 181 feet. Figure 5-31 is a plot of the minimum weir elevation versus the weir effective length.

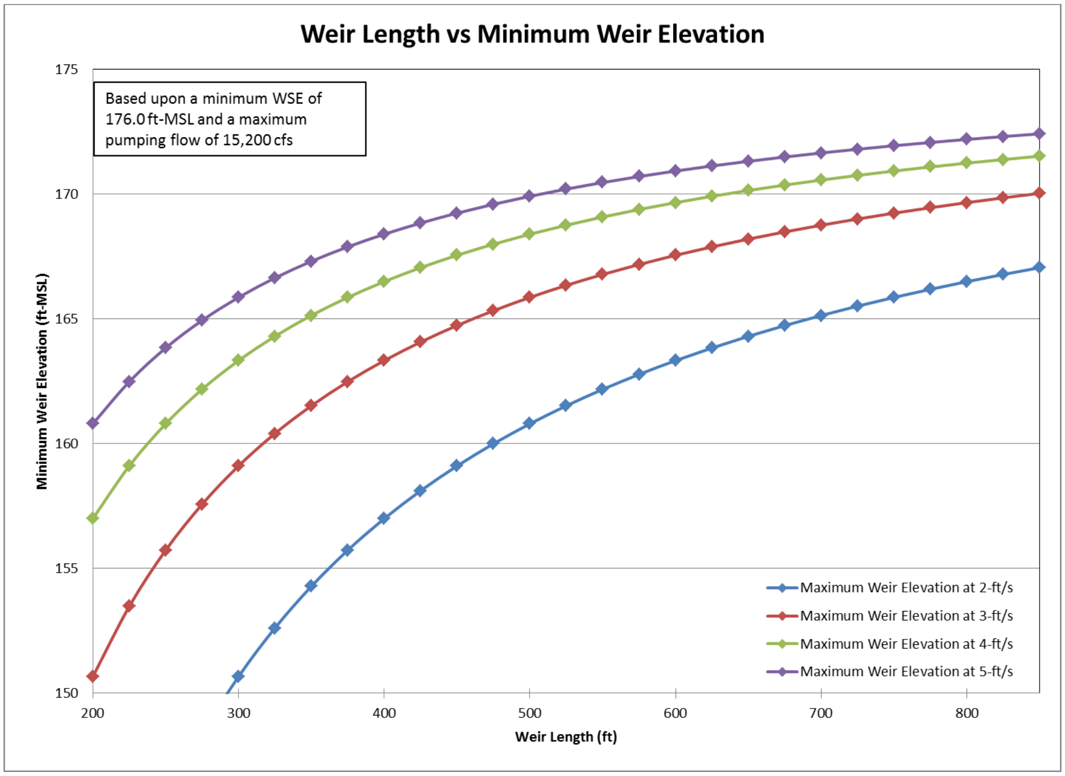

Figure 5-31: Weir minimum elevation as a function of length.

At a river flow of 70,000 cfs, the water level is about 188 feet and would require a maximum weir crest elevation of 177.1 feet. Modification 5 was tested with a weir crest elevation of 177.1 feet, Figure 5-32 shows a plan view of the weir layout. A weir crest elevation of 177.1 is the maximum weir crest elevation that satisfies the 2 ft/s requirement, however, it would require construction of a moving weir, because at lower river flows the allowable velocity will be exceeded. The test was designed to assist in quantifying the benefits of a moving weir.

The Modification 5 test was completed on June 29. The same test procedure was followed that was used in the baseline testing and the river flow was increased to a Froude scale flow of 85,000 cfs. The water surface elevation was set at 188.00 ft, consistent with the Modification 1 test. Turbidity and SSC in the river are plotted as a function of time in Figure 5-33. SSC in the powerhouse flow is plotted as a function of time in Figure 5-34. Table 5-9 shows the measured SSC values for the Modification 5 conditions. For each test, the percentage of the river SSC transported to the power plant was computed. During the final hour of testing, the suspended sediment concentration in the powerhouse flow was 23 percent of the suspended sediment concentration in the river. The baseline tests had a powerhouse suspended sediment concentration of 45 percent relative river SSC. The 22 percent reduction in SSC from 45 to 23 percent is about a 50 percent reduction in sediment load relative to baseline conditions.

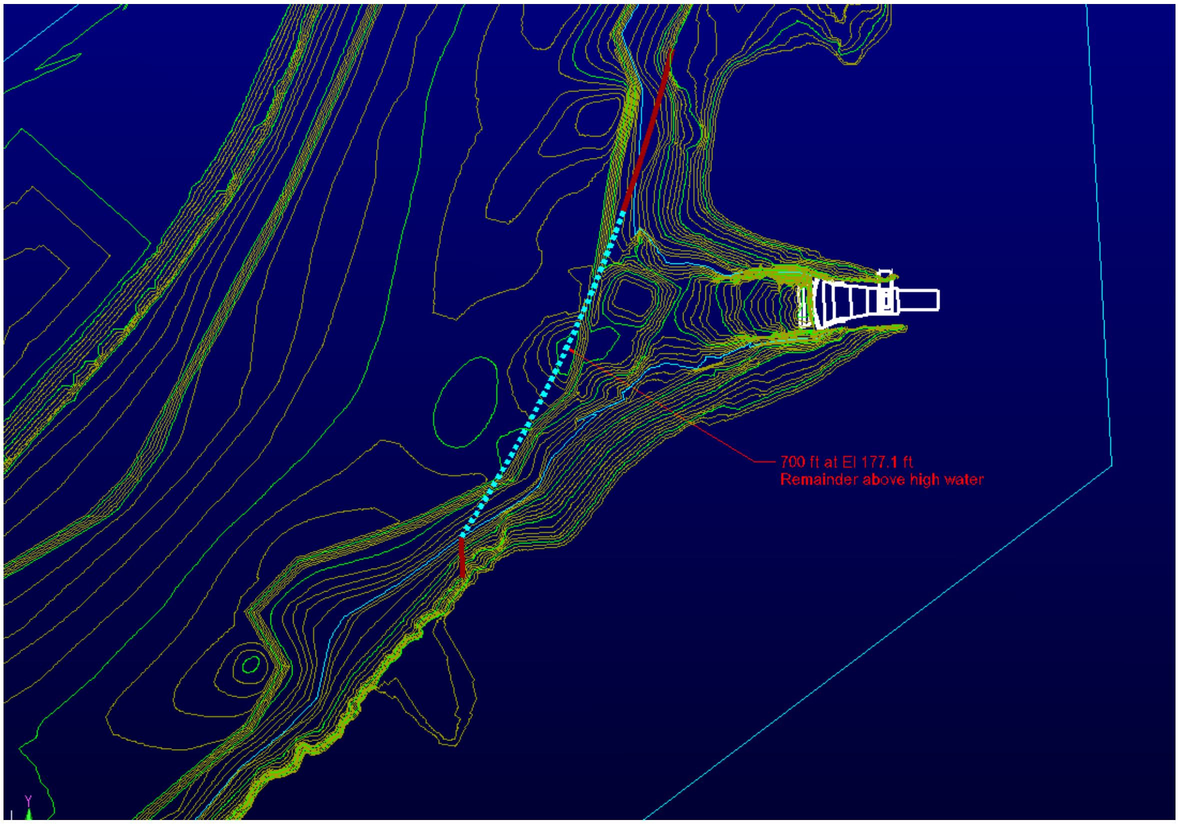

Figure 5-32: Modification 5 plan view drawings.

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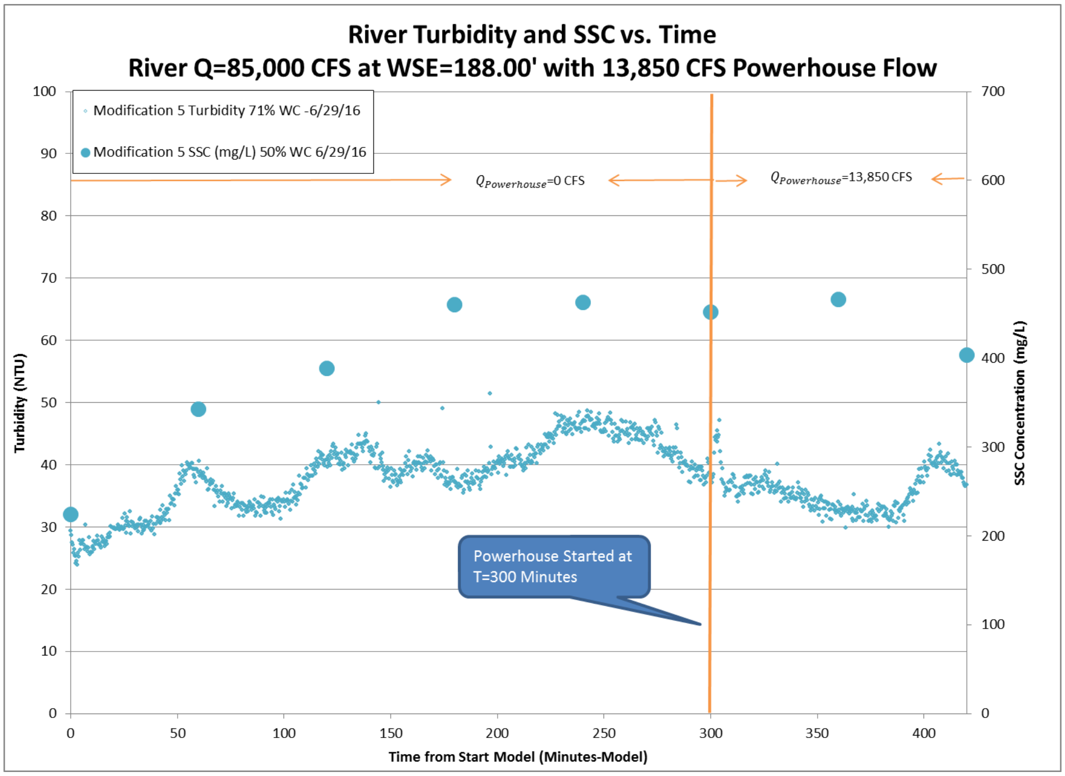

Figure 5-33: Modification 5 river turbidity and SSC, 70,000 cfs.

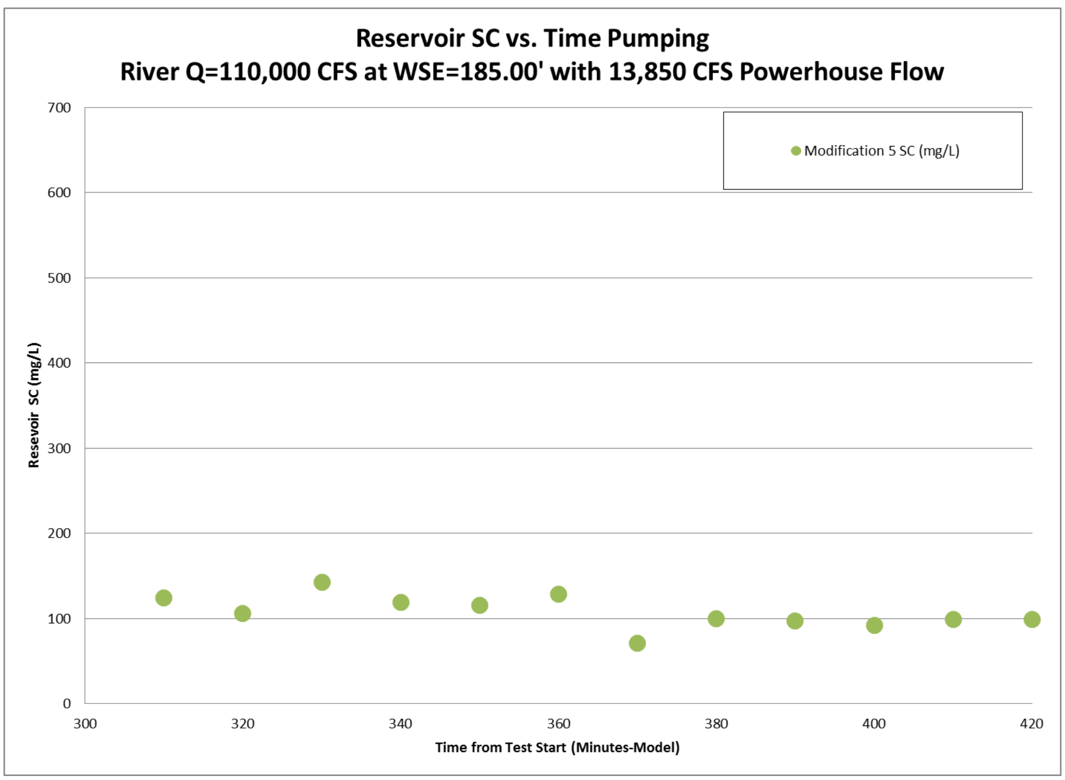

Figure 5-34: Modification 5 powerhouse SSC, 70,000 cfs.

Table 5-9: Measured SSC During Modification 5, 70,000 cfs

Time from Start of Test	River Flow SSC (mg/l)	Powerhouse Flow SC (mg/l)
(Minutes)	Mod 5	Mod 5
360	465.7	128.7
370	-	71.3
380	-	99.8
390	-	97.7
400	-	92.2
410	-	99.1
420	403.9	98.9

5.3.7 SSC Exploratory Test for Modification 6

Based on the results of the first five modification tests, it was decided to complete a test representative of conditions with a river flow of 40,000 cfs. Prior to running the full day model test, it was necessary to determine the appropriate water level for the test that resulted in a suspended sediment concentration representative of prototype conditions. On July 6, a short test was run to determine the suspended sediment concentration in the river for a flow of 40,000 cfs. Similar to the previous tests, the river flow was increased by about 20 percent while maintaining the same water level to increase the suspended sediment concentration. The test was run with a Froude scale flow of 48,000 cfs and a water surface elevation of 184.00 ft. The sensitivity testing did not reset the bed prior to testing. The test was run for 90 minutes after stable conditions were reached (T=0). Suspended sediment samples were collected at T= 25, 60, and 90 minutes. Turbidity and SSC in the river are plotted as a function of time in Figure 5-35.

Test results showed SSC lower than what is desired for a 40,000 cfs test condition. SSC values of eight to 10 mg/l are difficult to measure because and can be influenced by small changes in the model. To increase the SSC during the low flow test, it was decided that Modification 6 testing should be completed with a water level of 183.00 ft. Results and discussion of the baseline testing is in Section 4.5.1

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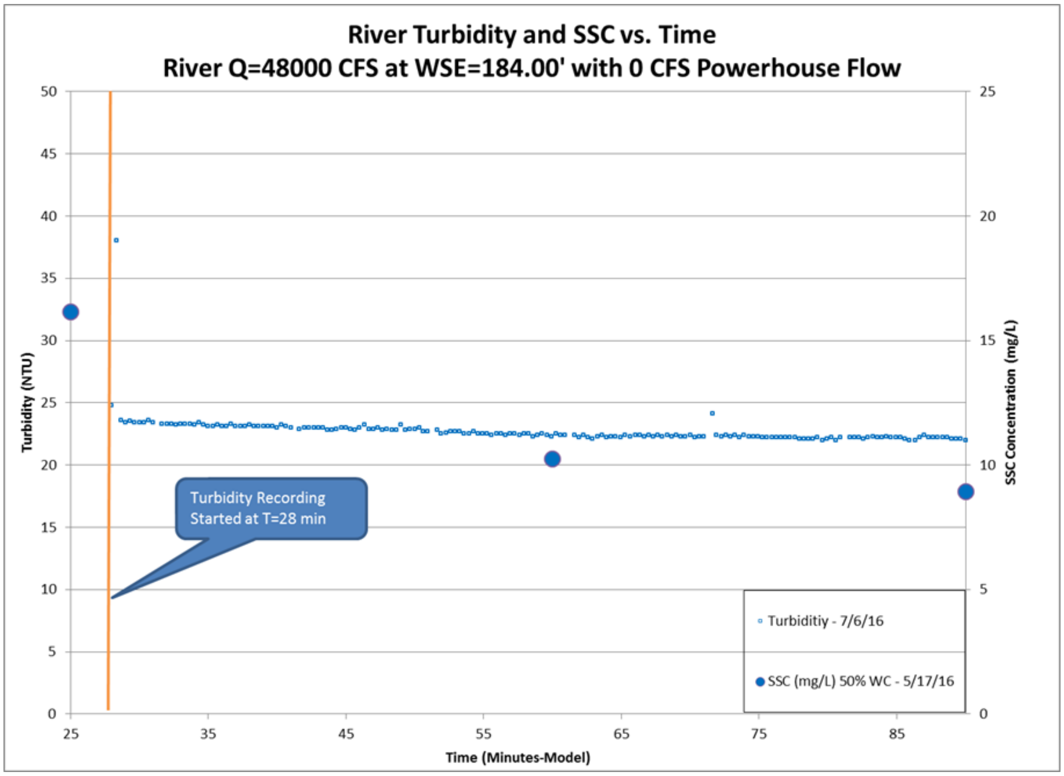

Figure 5-35: Exploratory testing results at 40,000 cfs.

5.3.8 Modification 6 at 40,000 cfs

Testing with Modifications 1 through 5 showed that consistent and reproducible reductions in suspended sediment concentration as a function of weir height. However, all of the testing was completed with a nominal river flow of 70,000 cfs. Based on the 2000 to 2010 flow data, a river flow of 70,000 is equaled or exceeded about 0.1 percent of the time (Section 2.3). A flow of 50,000 cfs is exceeded about 2.5 percent of the time and a flow of 30,000 cfs is exceeded about 10 percent of the time. Because the flow rarely equals or exceeds 70,000 cfs, it is of interest to determine how the system performs at lower river flows.

Four tests were run with a nominal river flow of 40,000 cfs, the actual model flow was 48,000 cfs to increase suspended sediment concentration based on the previously discussed sensitivity testing. The water surface elevation was set at 183.00 ft. Modification 6 included a 700 ft long weir with a crest elevation of 170.00 ft. The weir satisfies the 2 ft/s velocity limitation during periods of low river flow. Figure 5-36 shows a plan view of the weir layout. To determine the efficacy of the weir it is necessary to test a baseline condition and a modification condition. Modification 6 was tested on July 8, and the baseline test was completed on July 12. Test results different from expectations, and both the modification and baseline test were repeated on July 27 and 29 respectively. The same test procedure was followed that was used in the baseline testing. Results for the baseline tests were previously presented in Section 5.2.2.

For the two Modification 6 tests, turbidity and SSC in the river are plotted as a function of time in Figure 5-37. SSC in the powerhouse flow is plotted as a function of time in Figure 5-38. Table 5-10 shows the measured SSC values for the baseline conditions with a nominal river flow of 40,000 cfs. For each test, the percentage of the river SSC transported to the power plant was computed.

Results from the first baseline and modification tests showed under baseline conditions about 50 percent of the suspended sediment in the river is transported to the power plant. With the modification about 92 percent of the suspended sediment concentration in the river is transported to the power plant. The test results imply that the weir increases the amount of sediment transported to the reservoir. This result is inconsistent with the previous testing. The suspended sediment concentration in the river varied between 8 and 23 mg/l during the baseline and modification test.

The baseline and modification tests were repeated. In the baseline test suspended sediment concentration to the reservoir was 92 percent of river concentration. In the modification test the suspended sediment concentration to the river was 166 percent of the river concentration. The river concentration was between 3.9 and 6.9 mg/l during the tests.

The sediment transport to the reservoir is necessarily normalized by the suspended sediment concentration in the river. Normalization allows comparing tests where the suspended sediment concentration in the river was different for the same test conditions. At very low river flows, the suspended sediment concentration in the river decreases both in the model and the real world. Therefore, normalizing the sediment concentration to the reservoir by the suspended sediment concentration in the river can result in problems as the concentration approaches zero. Further, the sediment transport to the reservoir includes bedload and suspended load, because 100 percent of the water to the plant is being sampled. In the river, suspended sediment samples are collected that do not include bed load. There is no practical way to measure bed load transport in the river. As the suspended load decreases the bed load becomes an increasingly important component of the total load. Because of the model limitations, and consistent results at low flows, further testing at low flows was not recommended. The results of low flow testing are further discussed in the analysis and conclusion.

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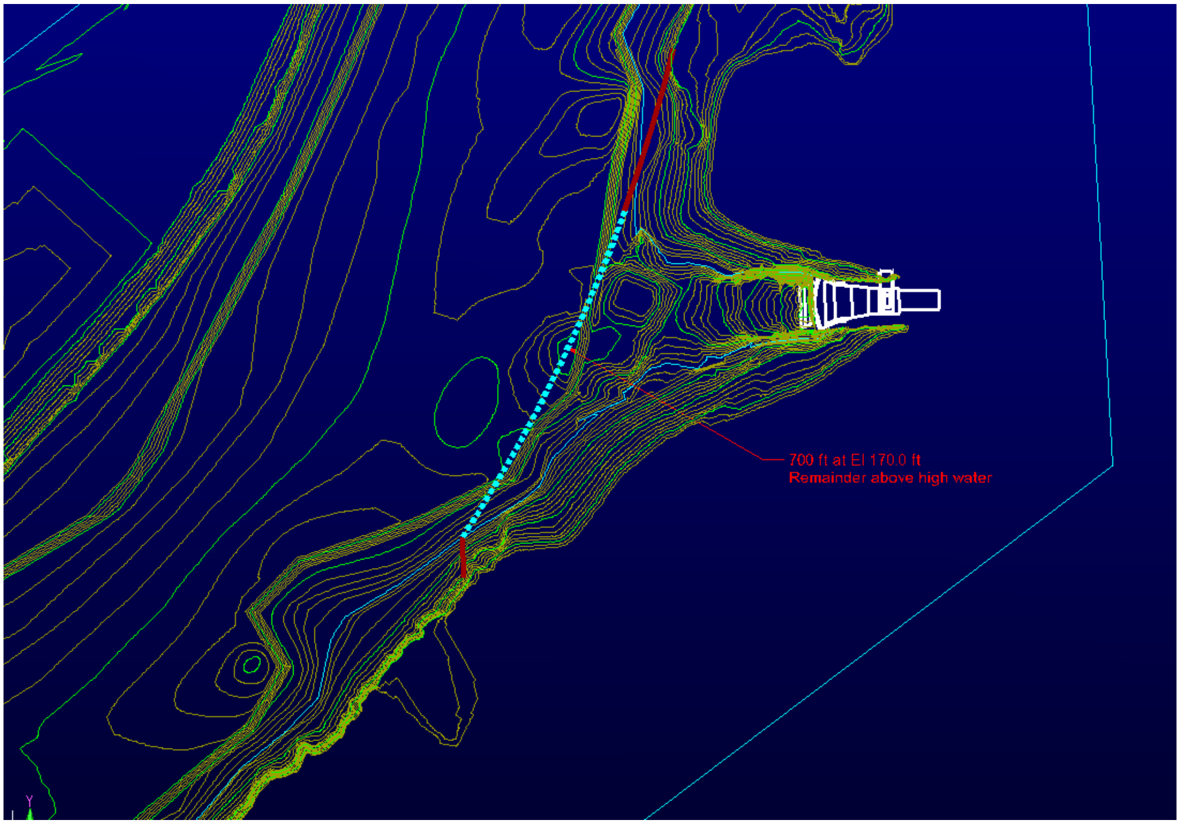

Figure 5-36: Modification 6 plan view drawings.

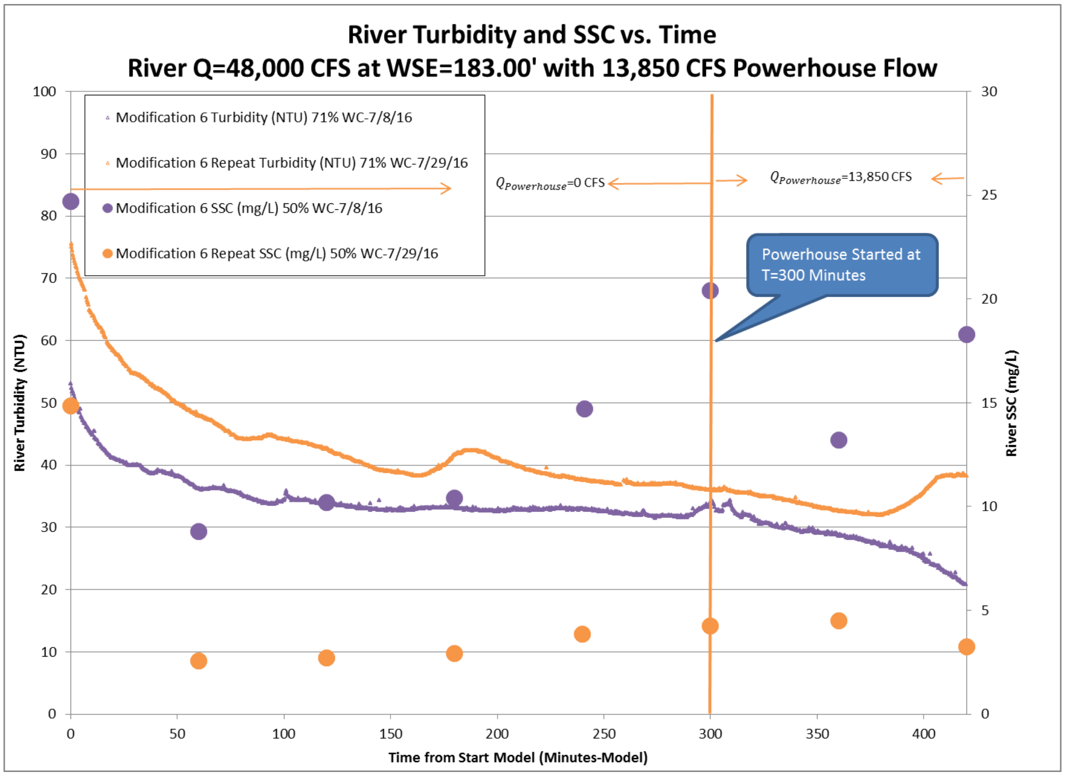

Figure 5-37: Modification 6 river turbidity and SSC, 40,000 cfs.

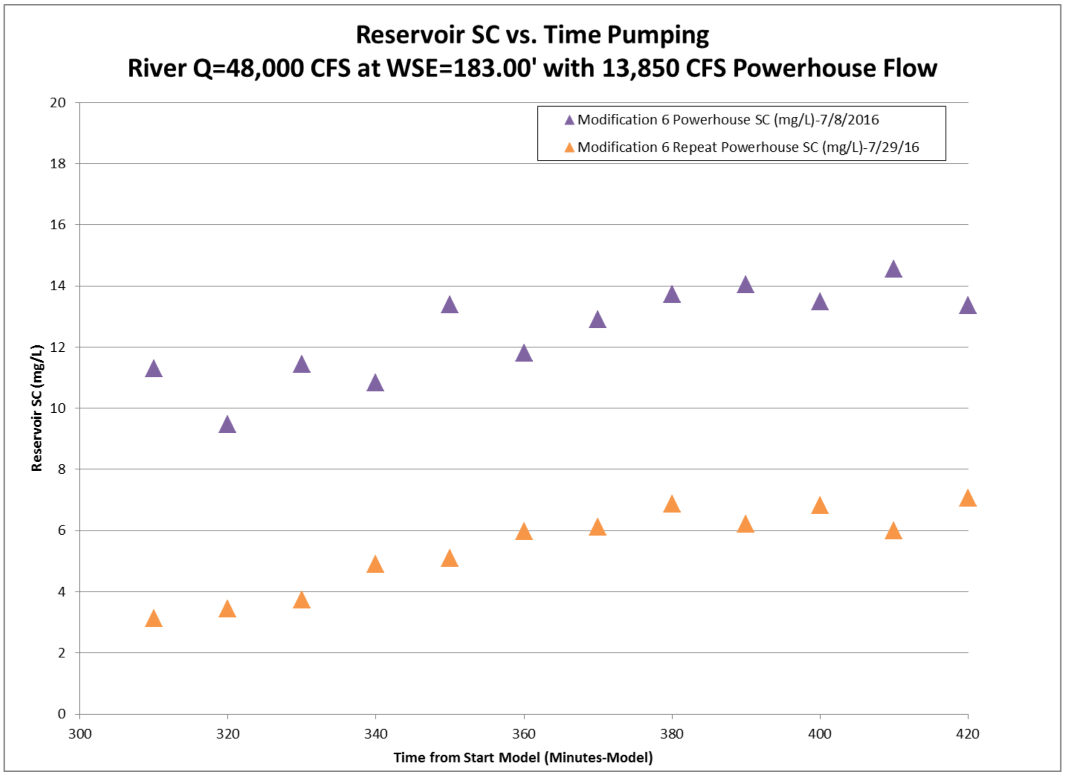

Figure 5-38: Modification 6 powerhouse SSC, 40,000 cfs.

Table 5-10: Measured SSC During Modification 6, 40,000 cfs

Time from Start of Test	River Flow SSC (mg/l)		Powerhouse Flow SC (mg/l)	
(Minutes)	Modification 6	Modification 6 Repeat	Modification 6	Modification 6 Repeat
360	15.5	4.5	11.8	6.0
370	-	-	12.9	6.1
380	-	-	13.7	6.9
390	-	-	14.0	6.2
400	-	-	13.5	6.8
410	-	-	14.5	6.0
420	20.5	3.2	13.3	7.1

6.0 Analysis and Conclusions

Every physical model involves compromise and tradeoffs in the model design, testing program, and results. Analysis and interpretation of the results is a critical component of each model study when trying to understand how a proposed modification might perform in the real world (prototype). The Northfield model was constructed at a 1:100 scale, making it possible to extend the model 2 miles upstream of the intake and 0.5 miles downstream of the intake. The exceptionally large domain ensures that the flow patterns approaching the intake are properly modeled and that secondary currents caused by upstream river bends are reproduced. The compromise however is that at a 1:100 scale the water depth in the model becomes very shallow and water velocities become very small, resulting in a low Reynolds number and distortion of the vertical velocity profile. The model scale also necessitates the use of very fine lightweight sediment. A spherical particle was used in the model after testing with an angular particle showed poor reproducibility of results. In theory the spherical particle may result in a suspended sediment concentration profile where the near bed concentration is sediment rich while the surface concentration is sediment poor. The following sections consider all of the model results and how the prototype system is expected to perform.

6.1 Effect of Spherical Particles

The physical model uses lightweight spherical particles while the real word has angular sand particles. When scaling sediment, the model and prototype Shields parameter and Rouse number should match. The Shields parameter is the ratio of the shear stress relative to the particle size (diameter and density). When the Shields parameter exceeds the critical Shields parameter, sediment transport begins. Therefore, it is important to match the model and prototype Shields parameter. Reducing particle size with the model length scale will, in principal, result in Shields parameter parity. In a 1:100 scale model, particle size cannot be reduced with length scale and light weight sediment is used to achieve Shields parameter parity.

The Rouse number is a ratio of the fall velocity to the shear velocity. Particle fall velocity is a function of particle diameter, density and shape. Fall velocity can be determined experimentally or analytically. Many papers have been written on computing particle fall velocity. Shear velocity is a function of the hydrodynamics, including the shear stress and the fluid density. Shear stress is a function of water depth and slope.

Spherical particles have a higher fall velocity than angular particles that have the same diameter and density. As a result, in the model, the particle fall velocity is ‘too high’ relative to the shear velocity. Consequently the suspended sediment concentration in the model is expected to be too low near the water surface and too high near the river bed. This can be quantified using the theoretical Rouse model for computing suspended sediment concentration profiles. Figure 6-1 shows the Rouse curves for three prototype particle diameters from the reservoir: The minimum D50, the average D50 and the maximum D50. For the maximum D50, one of the samples near the intake was not considered because it had a D50 of about 3mm, which is inconsistent with the of other samples. Figure 6-2 shows the sample locations and the D50 for each sample. All of the curves are steep, showing high suspended sediment concentration. The average D50 profile shows a mid-depth sediment concentration which is 70 percent of the near bed concentration. Figure 6-1 also shows two dashed lines: The red dashed line shows the Rouse curve as computed for the model using a spherical particle and the blue line shows the Rouse curve computed using an angular particle. An angular particle may have better matched the Rouse number in the prototype; however, at a 1:100 scale a cost effective particle with the correct density and angularity was not available. Analytical methods can be used to correct for the fall velocity. Figure 6-1 also shows Rouse curves for a Rouse number of one and two.

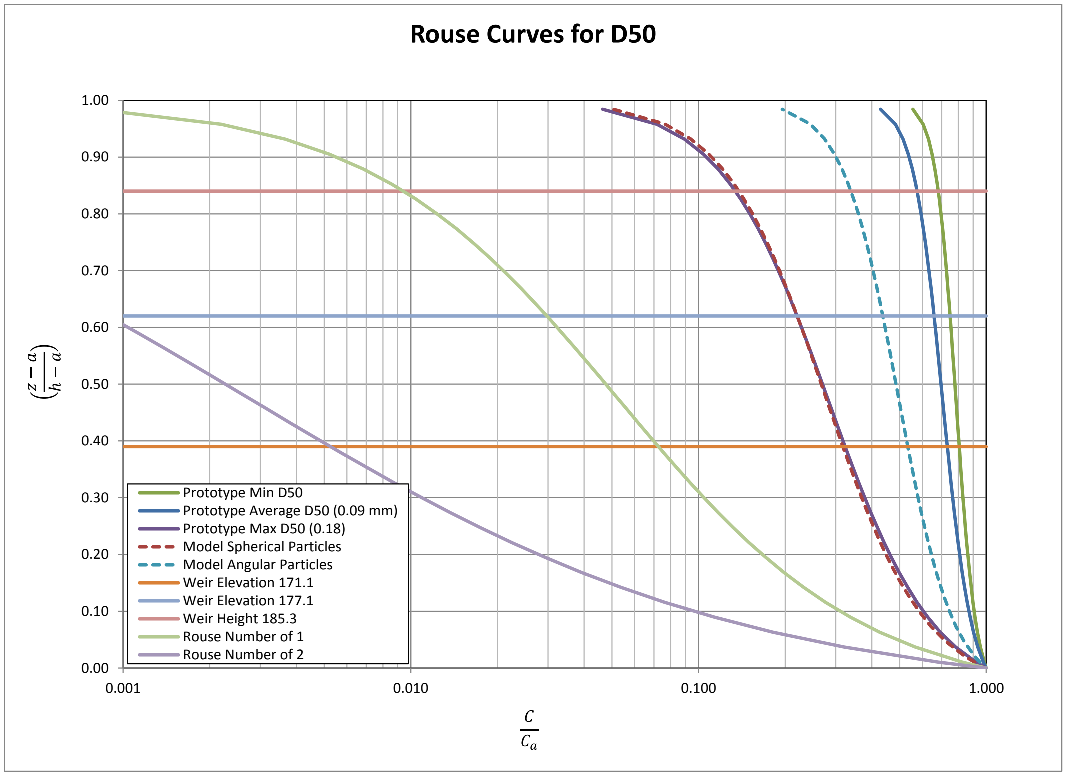

Figure 6-1: Rouse curves for nominal river flow of 70,000 cfs.

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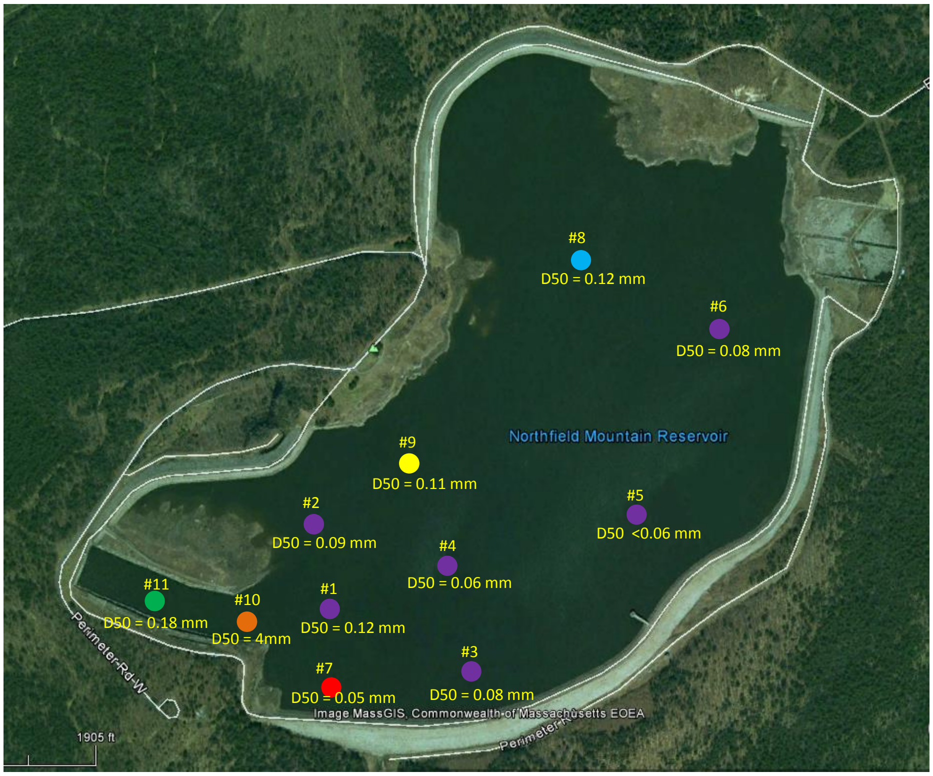

Figure 6-2: Measured D50 in reservoir samples.

Based on the sediment concentration profile shown in Figure 6-1, the reduction in sediment concentration to the reservoir can be computed as a function of weir crest elevation. The assumption is that all of the water and sediment entering the forebay must come from above the weir crest. The assumption is simplistic, but offers a method for determining how much the spherical particles in the model over predict the efficacy of the weir. For each Rouse curve shown in Figure 6-1, the percentage of sediment in the water column above and below a theoretical weir crest is computed. Results are shown in Figure 6-3. Figure 6-3 shows the weir crest elevation as a function of reduction in sediment entering the forebay. Three solid lines show the reduction for the minimum, average and maximum prototype D50. The two dashed lines show the reduction for spherical and angular particles in the model. Based on Figure 6-3, the spherical particles used in the physical model should result in about twice the efficacy that would be measured using angular particles.

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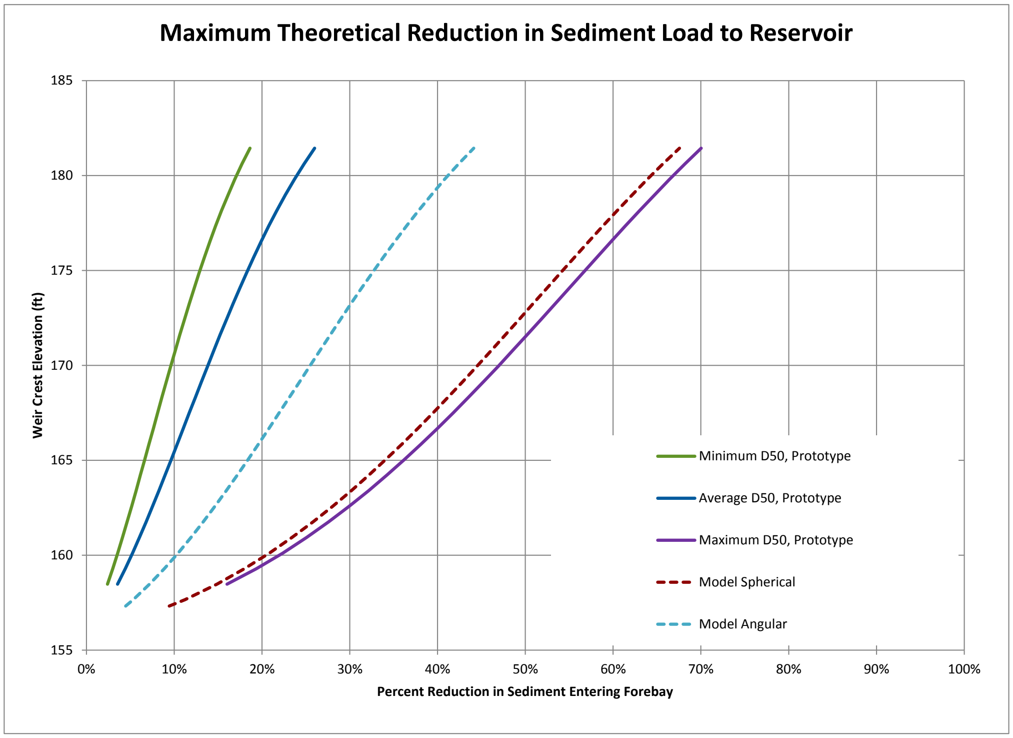

Figure 6-3: Theoretical exclusion of sediment as a function of weir height (70,000 cfs).

Results of the model tests are shown in Figure 6-4, showing the reduction in suspended sediment concentration entering the power plant relative to the suspended sediment concentration in the river. Figure 6-5 shows the results of the model tests corrected using the theoretical exclusion in Figure 6-3.

For a weir height of 169 feet, the difference between the angular and spherical particle size lines is about 58 percent. Therefore, only about 58 percent of the reduction measured in the physical model would probably have been realized if an angular particle was used. The correction is applied to each of the four modification results and shown in Figure 6-5.

The model test results show a system with good reproducibility. For a weir height of 177.1 ft and a river flow of 70,000 cfs, the lab data corrected for spherical particles shows a reduction of 30 percent in sediment transported to the reservoir. The lower weir elevation of 171 ft shows a reduction of about 10 percent. It is expected that the model is unable to achieve the theoretical reductions because some water will lift up and over the weir.

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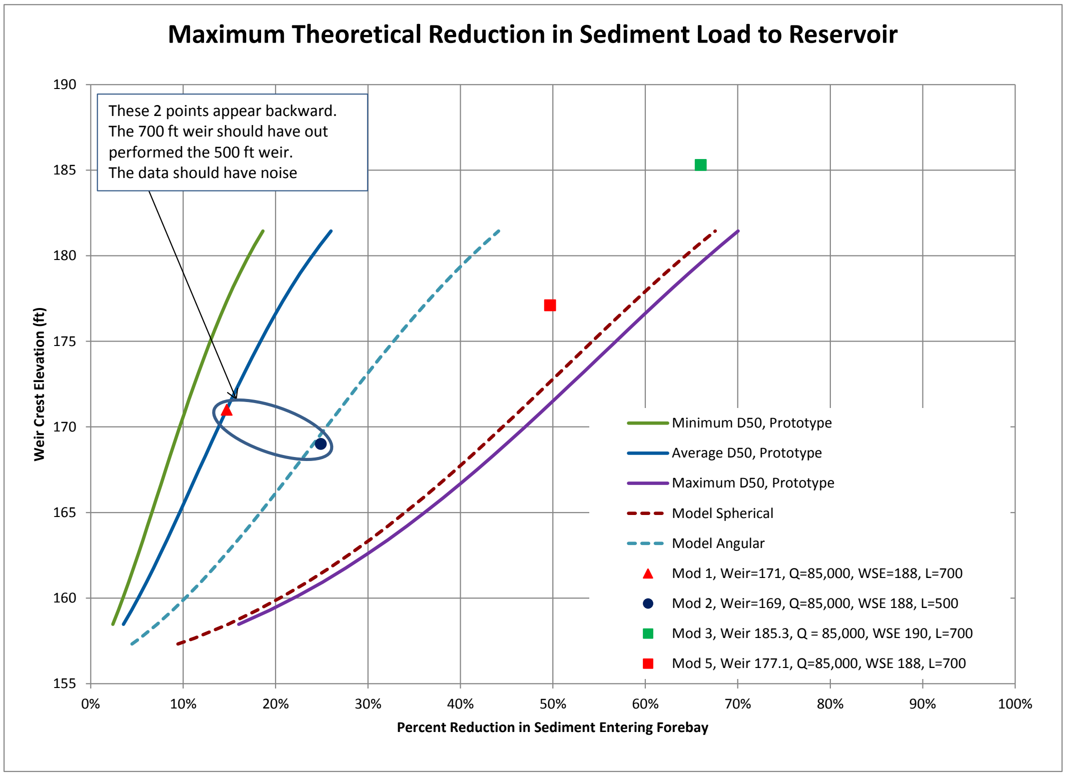

Figure 6-4: Reduction in SSC for range of weir crest elevations.

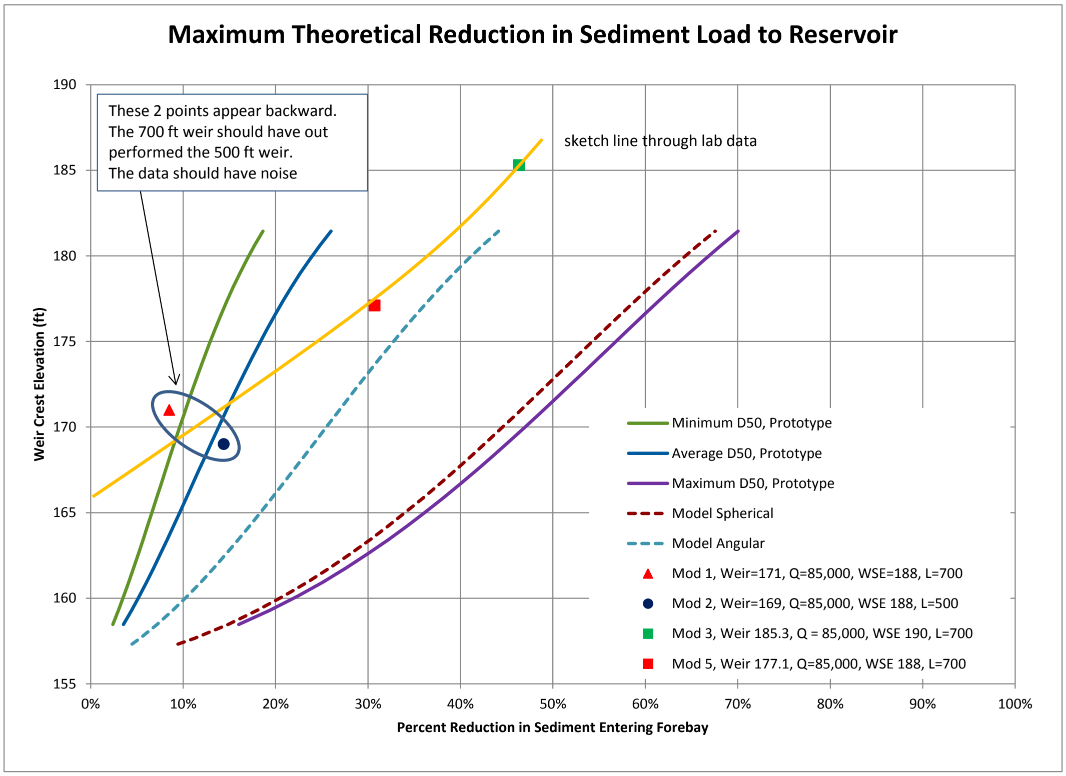

Figure 6-5: Reduction in SSC for range of weir crest elevations with correction.

The analysis using the Rouse curves relies on the assumption that the fall velocity of the spherical particles is higher than that of the angular particles, resulting in higher near bed sediment concentration and lower concentrations near the water surface. During the May 13 and May 17 physical model tests, turbidity meters were placed at three depths at the middle sampling location, results are shown in Figure 6-6.

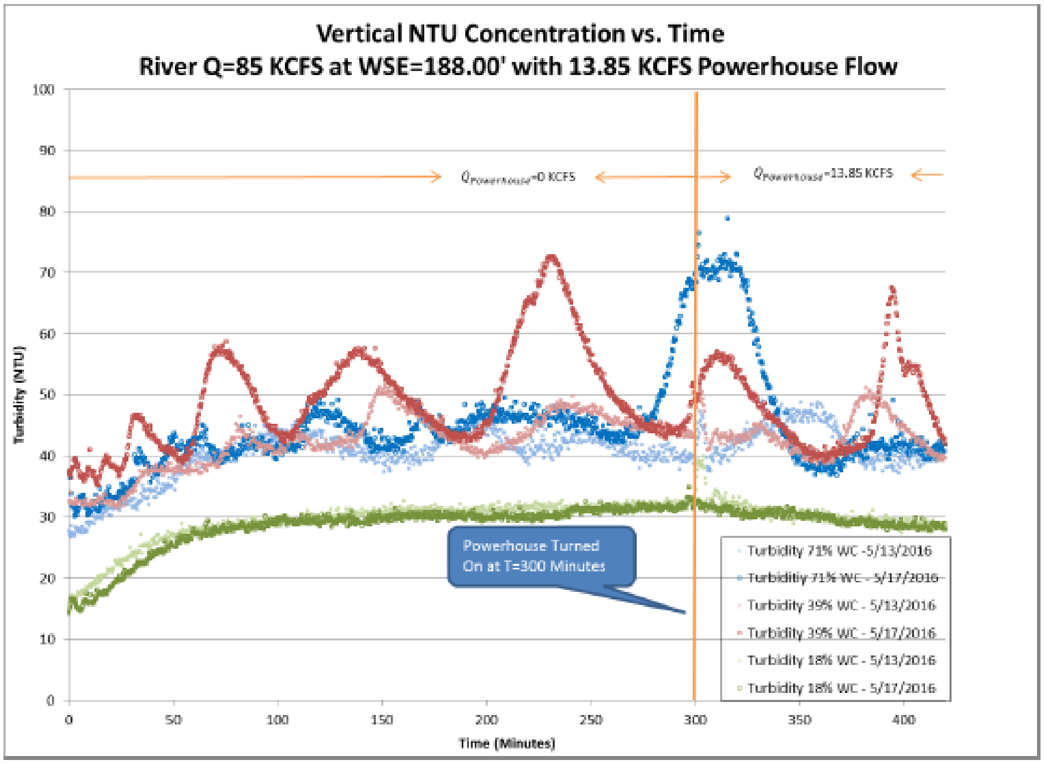

Figure 6-6: Turbidity at three depths during May 13 and May 17 testing.

Results of the turbidity meters can be used in combination with model data that relates turbidity to SSC to determine the suspended sediment concentration profile in the model. Figure 6-7 shows suspended sediment concentration is approximately linearly related to turbidity. Based on the linear relationship between turbidity and SSC, the turbidity values from May 13 and May 17 can be plotted in combination with the Rouse curves. Some subjectivity is required in determining the turbidity between T=360 and T=420 in Figure 6-6. The turbidity in the top of the water column is very constant, while the turbidity near the bed is strongly influenced the passing of bed forms. Figure 6-8 shows that despite the particles being spherical in shape, the concentration profile measured in the model is consistent with the that for angular particles. The three tan squares in Figure 6-8 more closely match the dashed blue line (the theoretical curve for angular particles) than the dashed red line (the theoretical curve for spherical particles). The model concentration profile is less uniform than the theoretical profile for the prototype (solid blue line). However, the turbidity measurements show that the weir may perform better than expected from Figure 6-5.

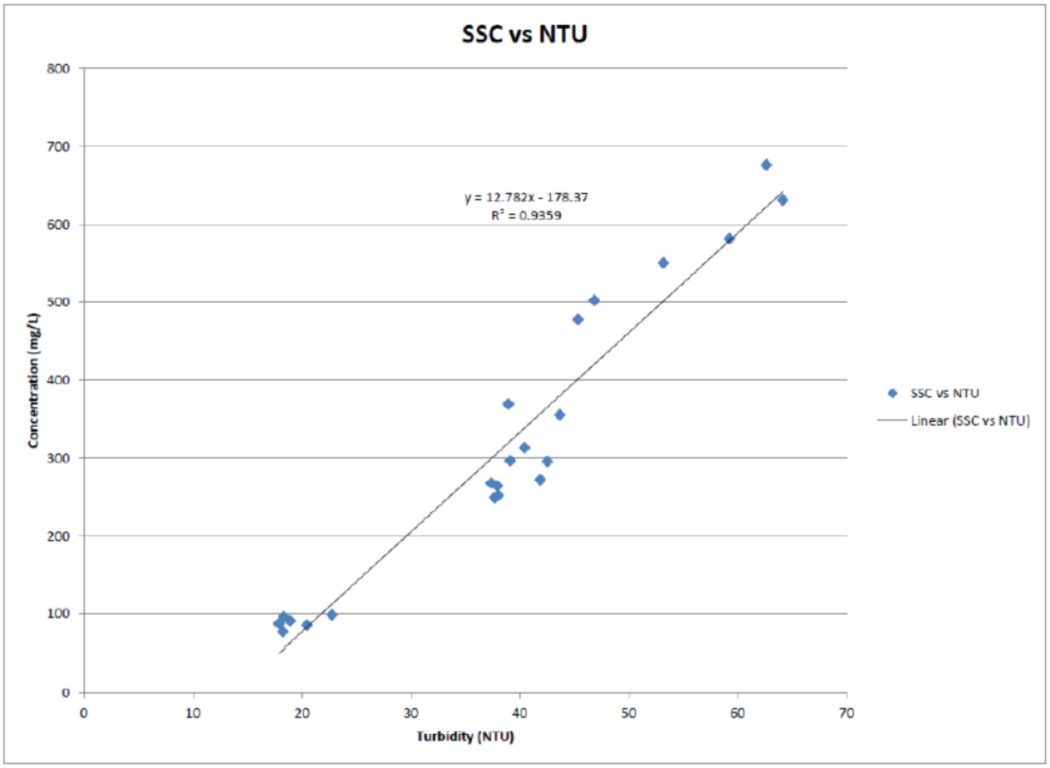

Figure 6-7: Suspended sediment concentration as function of Turbidity.

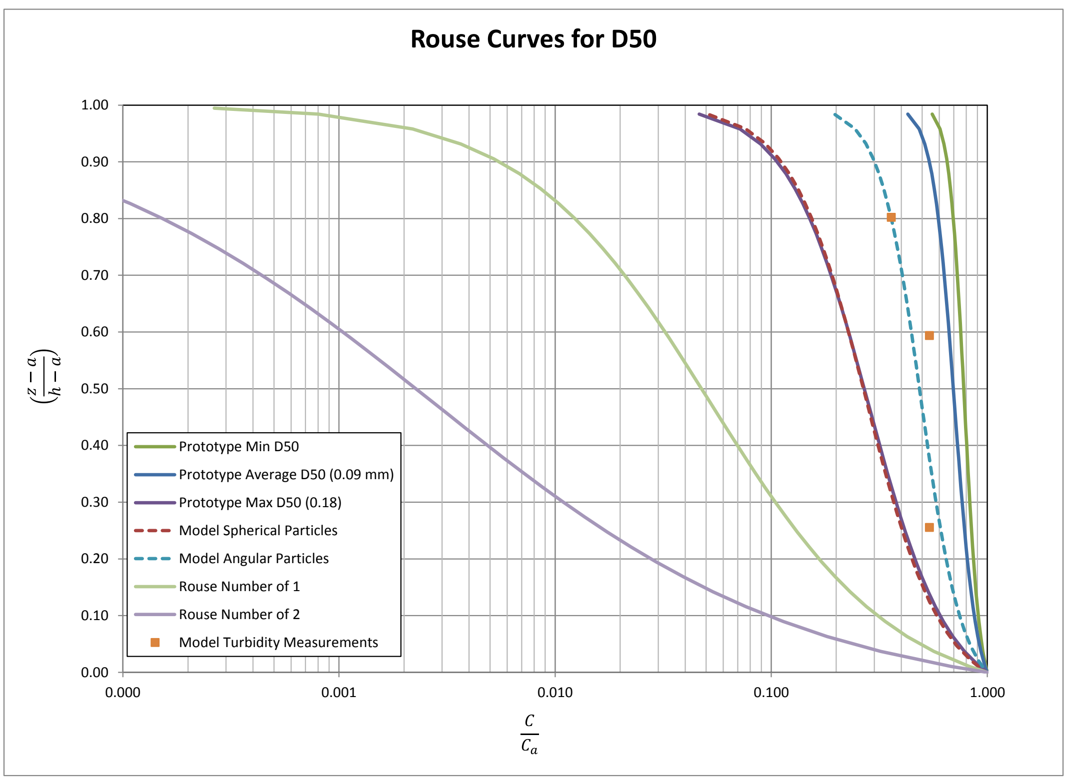

Figure 6-8: Measured concentration profile with Rouse curves.

6.2 Expected Performance at Low River Flows

Predicting the performance of the weir at low flow is difficult. At low flows, bedload can be transported to the forebay where it is transported to the reservoir. Based on the field data collected by Alden the suspended sediment concentration profiles at low flows is highly uniform as shown in Figure 6-9. The uniformity is a result of the particle sizes being transported. The D_{50} of the suspended sediment samples collected by Alden is between 0.01 and 0.02 mm. Most of the material accumulated in the reservoir is much coarser, suggesting that the material in the reservoir is not suspended load from periods of low flow. The suspended load measurements made by Alden are very consistent with the data collected by streamside sampling from 2012 to 2015. Figure 6-10 shows the measured sediment suspended sediment concentration from 2012 to 2015 and the Alden measurements. The data shows that the sediment accumulating in the reservoir is not suspended load from periods of low flow.

The physical model testing showed an increase in the amount of sediment transported to the reservoir for the first pair of baseline and modification tests. The baseline test showed a sediment load of 10.3 mg/l going to the reservoir while the Modification 6 test showed a concentration of 13.4 mg/l. For the repeat test the concentration of sediment going to the reservoir was about the same with and without the modification; 6.3 mg/l (baseline) and 6.4 mg/l (Modification 6). Based on the model results, there is no predicted decrease in the sediment load to the reservoir at low flows. This result may be overly conservative, because a weir should be very effective at excluding bedload.

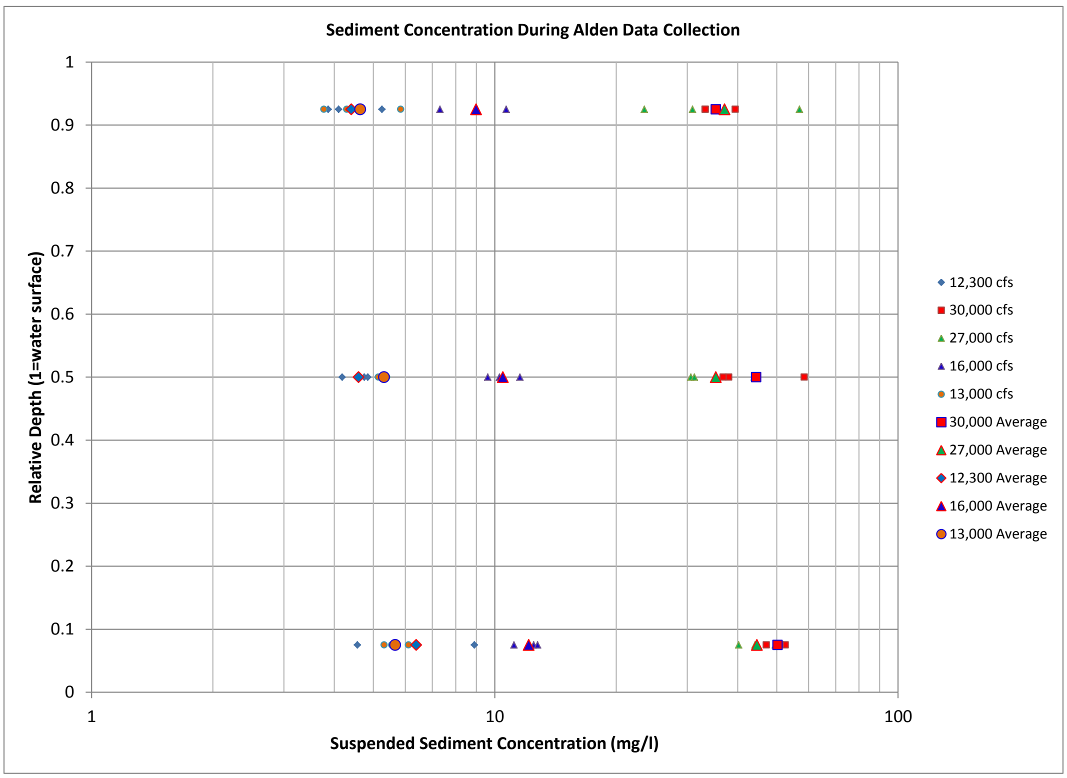

Figure 6-9: Prototype suspended sediment concentration.

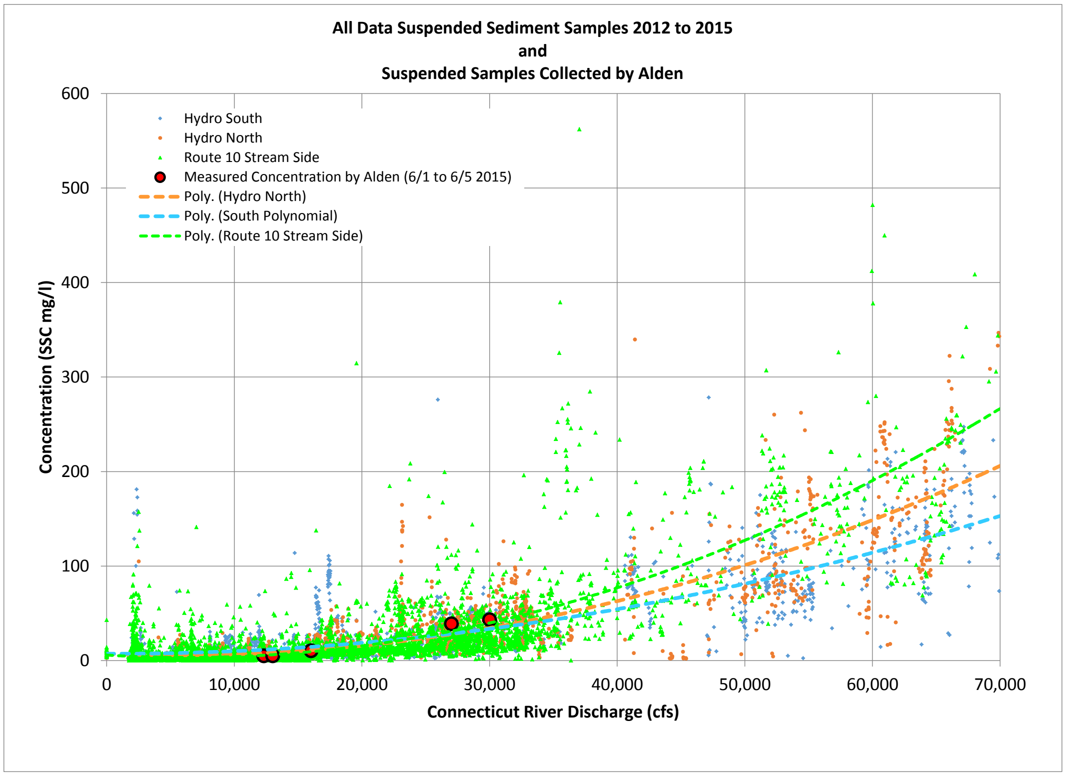

Figure 6-10: Suspended sediment concentration measurements by Alden.

6.3 Expected Performance over Range of Flows

The physical model testing evaluated the efficacy of the weir at a nominal flow of 70,000 cfs. At a nominal flow of 70,000 cfs, a weir with a crest elevation of 170 reduces the sediment load to the reservoir by 10 to 20 percent. For a crest elevation of 177, the reduction in sediment transport to the reservoir is 30 to 50 percent. For flows less than 40,000 cfs, the physical model showed no reduction in the sediment transport to the reservoir. The result is counter intuitive and may be an artifact of how the reduction in sediment transport to the reservoir is computed. In principal the weir should be very effective at excluding bedload from entering the forebay area.

The sediment transport to the reservoir was normalized by dividing the sediment concentration to the reservoir by the sediment concentration in the river. The resulting value describes how much lower the sediment load to the reservoir is than the sediment load in the river. The sediment load in the river is only quantified by the suspended load and does not include the bedload, which cannot be measured. At low river flows, the suspended load in the river becomes small and the measurement uncertainty increases. In addition, the percentage of the total load that is transported as bedload increases and may not be negligible. It is therefore reasonable to consider using only the measured sediment load to the reservoir in determining the efficacy of the weir. In the first set of Modification 6 tests, the average baseline transport to the reservoir was 10.2 mg/l while the with weir option had a transport of 13.4 mg/l. The second test showed a baseline transport of 6.3 mg/l to the reservoir and 6.4 mg/l when the weir was installed. The variability between baseline tests is greater than the change in transport resulting from the weir. This suggests the test uncertainty exceeds the effect of the weir.

Based on the flow duration curve from 2000 to 2010 (Section 2.3) it is understood that flow is equal or greater than 70,000 cfs 0.1 percent of the time. Flow is greater than 50,000 cfs 2.5 percent of the time and flow is greater than 40,000 cfs 5 percent of the time. On average, there are 40 times more days where the flow is less than 50,000 cfs than greater than 50,000 cfs. Based on the physical model, at a flow of 70,000 cfs the sediment concentration to the reservoir is about 170 mg/l (178 mg/l in test 1 and 166 mg/l in test 2). Dividing the 170 mg/l by 40 (because there are 40 times more days where the flow is less than 50,000 cfs than greater) yields a concentration of 4.25 mg/l. If the low river flow sediment concentration to the reservoir is greater than about 4 mg/l then the significance of low period is not negligible. The physical model testing showed concentrations of 5 to 10 mg/l.

When estimating the benefits of the weir over a range of flows, it is reasonable to assume a reduction in sediment load to the reservoir of 10 to 20 percent for flow greater than 50,000 cfs. This assumes that for flows down to 50,000 cfs the benefits of the weir are similar to those tested in the model at 70,000 cfs. For periods of river flow less than 50,000 cfs, two bounding assumptions could be made: 1) There is no reduction in sediment transport to the reservoir. 2) Bedload transport is eliminated and the very fine suspended load does not accumulate, making the weir 100 percent effective. What remains unknown however is contribution of sediment to the reservoir during periods of low flow relative to periods of high river flow. As a result, the benefits of the weir over a range of flows cannot be calculated because of missing prototype data. We could assume that 15 percent of the sediment load during high river flows is removed and 100 percent of the sediment load during periods of low river flow is removed but the relative load to the reservoir at low flows and high flows is unknown.

A reasonable estimate for the reduction in sediment load to the reservoir is to assume that the benefits realized at 70,000 cfs will also be realized at lower flows. This would result in a reduction of sediment of 10 to 20 percent for a fixed weir and 30 to 50 percent for a moving weir. However, it must be recognized that the physical model does not support this estimate at lower flows.

6.4 Recommendations

Based on the physical model test results, the following considerations and recommendations are offered:

1) Consider using field data to better estimate the amount of sediment transported to the reservoir during periods of low river flow relative to periods of high river flow.
    a. Review the historic bathymetric surveys and determine the volume of sediment deposited in the reservoir between surveys.
    b. Develop a flow duration curve for each period between hydrographic surveys.
    c. Develop a function that relates mg/l pumped to the reservoir as a function of river flow. The physical model can help predict what the form of the relationship. The function must be tuned by applying it to the flow duration curves between hydrographic surveys and comparing the predicted and measured sediment accumulation.

2) More fully investigate the construction and constructability aspects of a moving weir with a vendor that could manufacture one. The model shows that a moving weir will be much more effective at removing sediment than a fixed weir. At flows of 70,000 cfs the sediment reduction is increased from 10 to 20 percent for a fixed weir to 30 to 50 percent for a moving weir. Alden is not aware of any moving weirs of this type and size that have been constructed for sediment exclusion purposes. Bidirectional flow will need to be considered in the design of the moving weir.

3) All of the physical model tests were for a pumping configuration. Alden recommends that the model be operated in generating mode to determine the effects of the weir on generation.
   a. The tests should determine if the weir raises tailwater levels at the plant discharge. An increase in the resistance to discharge will reduce power production.
   b. Determine how sediment that accumulates in the forebay is removed by generating flows. The testing to date assumed that during generation, the forebay is 'cleaned' of sediment. This was simulated by using a clean forebay at the beginning of each test.
   c. The weir will increase surface velocity in the river during generation. Tests during generation will show how flow patterns and sediment movement in the river are changed due to the weir.

4) The physical model considered the benefits of a weir. The weir, in part, depends on secondary currents to reduce the amount of sediment entrained by the plant. It may be possible to install bendway weirs upstream of the power plant to enhance secondary currents and improve performance. This could be tested in the physical model.

6.5 Conclusions

A 1:100 scale physical model of the Connecticut river was constructed to determine the efficacy of a proposed weir in reducing the sediment transport to the Northfield Reservoir. Twenty one tests were conducted to test both the reproducibility of the model tests and the benefits of the weir. Most of the testing focused on a river flow of 70,000 cfs and three units pumping.

Multiple weir alignments and crest elevations were tested. Based on fisheries requirements, the maximum velocity over the weir crest is 2 ft/s. With four pumps in operation, the velocity limit can be satisfied with a weir at elevation 170 feet when the water level is greater than 181.00 ft. Water levels greater than 181.00 ft occur about 90 % of the time. With three pumps in operation and a weir crest elevation of 170 feet, the velocity limit is satisfied when the water level is greater than 178.00 ft, which occurs about 99 percent of time. Alternatively, a moving weir can be constructed that remains at least 11 feet below the water surface

Based on the physical model tests, a fixed weir at elevation 170 feet will result in a reduction of sediment transported to the reservoir of 10 to 20 percent for a river flow of 70,000 cfs. Model results at lower flows were inconclusive but the weir performance should not be worse at low flows than high flows. The physical model also showed that a moving weir could reduce the sediment load to the reservoir by 30 to 50 percent. The constructability of a moving weir was not investigated.

Appendix A Flow Analysis Supporting Material

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Table A- 1: Frequency Factors K for Log-Pearson Type III Distribution (Haan, 1977)

	Recurrence Interval In Years							
	1.0101	2	5	10	25	50	100	200
SKEW COEFFICIENT	Percent Chance (>=) = 1-F							
Cs	99	50	20	10	4	2	1	0.5
3	-0.667	-0.396	0.42	1.18	2.278	3.152	4.051	4.97
2.9	-0.69	-0.39	0.44	1.195	2.277	3.134	4.013	4.904
2.8	-0.714	-0.384	0.46	1.21	2.275	3.114	3.973	4.847
2.7	-0.74	-0.376	0.479	1.224	2.272	3.093	3.932	4.783
2.6	-0.769	-0.368	0.499	1.238	2.267	3.071	3.889	4.718
2.5	-0.799	-0.36	0.518	1.25	2.262	3.048	3.845	4.652
2.4	-0.832	-0.351	0.537	1.262	2.256	3.023	3.8	4.584
2.3	-0.867	-0.341	0.555	1.274	2.248	2.997	3.753	4.515
2.2	-0.905	-0.33	0.574	1.284	2.24	2.97	3.705	4.444
2.1	-0.946	-0.319	0.592	1.294	2.23	2.942	3.656	4.372
2	-0.99	-0.307	0.609	1.302	2.219	2.912	3.605	4.298
1.9	-1.037	-0.294	0.627	1.31	2.207	2.881	3.553	4.223
1.8	-1.087	-0.282	0.643	1.318	2.193	2.848	3.499	4.147
1.7	-1.14	-0.268	0.66	1.324	2.179	2.815	3.444	4.069
1.6	-1.197	-0.254	0.675	1.329	2.163	2.78	3.388	3.99
1.5	-1.256	-0.24	0.69	1.333	2.146	2.743	3.33	3.91
1.4	-1.318	-0.225	0.705	1.337	2.128	2.706	3.271	3.828
1.3	-1.383	-0.21	0.719	1.339	2.108	2.666	3.211	3.745
1.2	-1.449	-0.195	0.732	1.34	2.087	2.626	3.149	3.661
1.1	-1.518	-0.18	0.745	1.341	2.066	2.585	3.087	3.575
1	-1.588	-0.164	0.758	1.34	2.043	2.542	3.022	3.489
0.9	-1.66	-0.148	0.769	1.339	2.018	2.498	2.957	3.401
0.8	-1.733	-0.132	0.78	1.336	1.993	2.453	2.891	3.312
0.7	-1.806	-0.116	0.79	1.333	1.967	2.407	2.824	3.223
0.6	-1.88	-0.099	0.8	1.328	1.939	2.359	2.755	3.132
0.5	-1.955	-0.083	0.808	1.323	1.91	2.311	2.686	3.041
0.4	-2.029	-0.066	0.816	1.317	1.88	2.261	2.615	2.949
0.3	-2.104	-0.05	0.824	1.309	1.849	2.211	2.544	2.856
0.2	-2.178	-0.033	0.83	1.301	1.818	2.159	2.472	2.763
0.1	-2.252	-0.017	0.836	1.292	1.785	2.107	2.4	2.67
0	-2.326	0	0.842	1.282	1.751	2.054	2.326	2.576
-0.1	-2.4	0.017	0.846	1.27	1.716	2	2.252	2.482
-0.2	-2.472	0.033	0.85	1.258	1.68	1.945	2.178	2.388
-0.3	-2.544	0.05	0.853	1.245	1.643	1.89	2.104	2.294
-0.4	-2.615	0.066	0.855	1.231	1.606	1.834	2.029	2.201
-0.5	-2.686	0.083	0.856	1.216	1.567	1.777	1.955	2.108
-0.6	-2.755	0.099	0.857	1.2	1.528	1.72	1.88	2.016
-0.7	-2.824	0.116	0.857	1.183	1.488	1.663	1.806	1.926
-0.8	-2.891	0.132	0.856	1.166	1.448	1.606	1.733	1.837
-0.9	-2.957	0.148	0.854	1.147	1.407	1.549	1.66	1.749
-1	-3.022	0.164	0.852	1.128	1.366	1.492	1.588	1.664
-1.1	-3.087	0.18	0.848	1.107	1.324	1.435	1.518	1.581
-1.2	-3.149	0.195	0.844	1.086	1.282	1.379	1.449	1.501
-1.3	-3.211	0.21	0.838	1.064	1.24	1.324	1.383	1.424
-1.4	-3.271	0.225	0.832	1.041	1.198	1.27	1.318	1.351
-1.5	-3.33	0.24	0.825	1.018	1.157	1.217	1.256	1.282
-1.6	-3.88	0.254	0.817	0.994	1.116	1.166	1.197	1.216
-1.7	-3.444	0.268	0.808	0.97	1.075	1.116	1.14	1.155
-1.8	-3.499	0.282	0.799	0.945	1.035	1.069	1.087	1.097
-1.9	-3.553	0.294	0.788	0.92	0.996	1.023	1.037	1.044
-2	-3.605	0.307	0.777	0.895	0.959	0.98	0.99	0.995
-2.1	-3.656	0.319	0.765	0.869	0.923	0.939	0.946	0.949
-2.2	-3.705	0.33	0.752	0.844	0.888	0.9	0.905	0.907
-2.3	-3.753	0.341	0.739	0.819	0.855	0.864	0.867	0.869
-2.4	-3.8	0.351	0.725	0.795	0.823	0.83	0.832	0.833
-2.5	-3.845	0.36	0.711	0.711	0.793	0.798	0.799	0.8
-2.6	-3.899	0.368	0.696	0.747	0.764	0.768	0.769	0.769
-2.7	-3.932	0.376	0.681	0.724	0.738	0.74	0.74	0.741
-2.8	-3.973	0.384	0.666	0.702	0.712	0.714	0.714	0.714
-2.9	-4.013	0.39	0.651	0.681	0.683	0.689	0.69	0.69
-3	-4.051	0.396	0.636	0.66	0.666	0.666	0.667	0.667

Appendix B Sediment Sample Analysis

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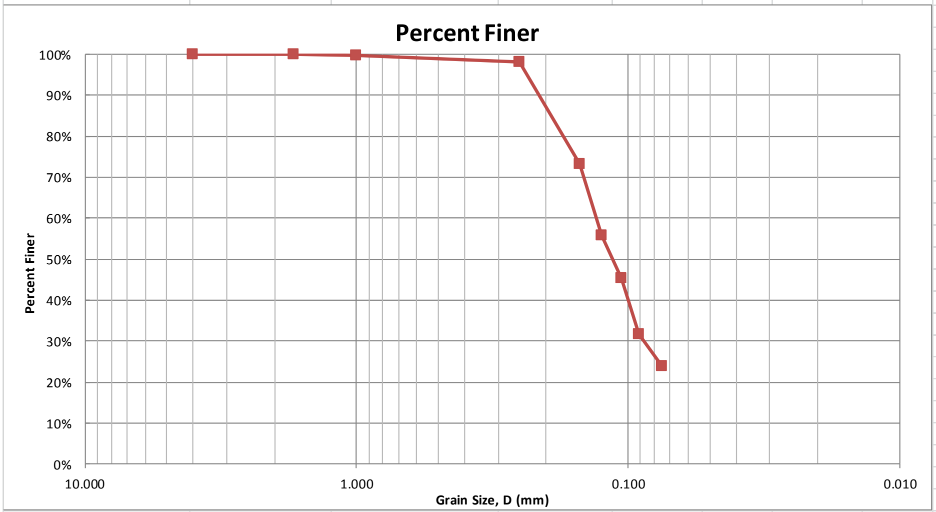
Target Number	15:15	Date	10-Jun-15
Description of sediment	Silt		
Sample number	15:15	Tested by	DE
Nominal size (mm)		Mass can (g)	12
Mass + sediment (wet) (g)		Mass sediment (wet)(g)	
Mass + sediment (dry) (g)	474	Mass sediment (dry)(g)	462
Mass Moisture (g)		Moisture Content (%)	

Sieve Number	Sieve Opening (mm)	Sieve Mass (g)	Sediment (g)	Mass sediment retained (g)	Percent Retained on sieve	Cumulative Percent Retained	Percent Finer
5	4.000	734.1	734.1	0	0%	0%	100%
12	1.700	453.9	453.9	0	0%	0%	100%
18	1.000	435.5	436.3	0.8	0%	0%	100%
60	0.250	373.6	381.6	8	2%	2%	98%
100	0.150	355.5	469.6	114.1	25%	27%	73%
120	0.125	356.5	436	79.5	17%	44%	56%
140	0.106	355	403.8	48.8	11%	55%	45%
170	0.091	330.2	393.2	63	14%	68%	32%
200	0.075	318.8	354.3	35.5	8%	76%	24%
Pan	0.000	726.7	836	109.3	24%	100%	0%

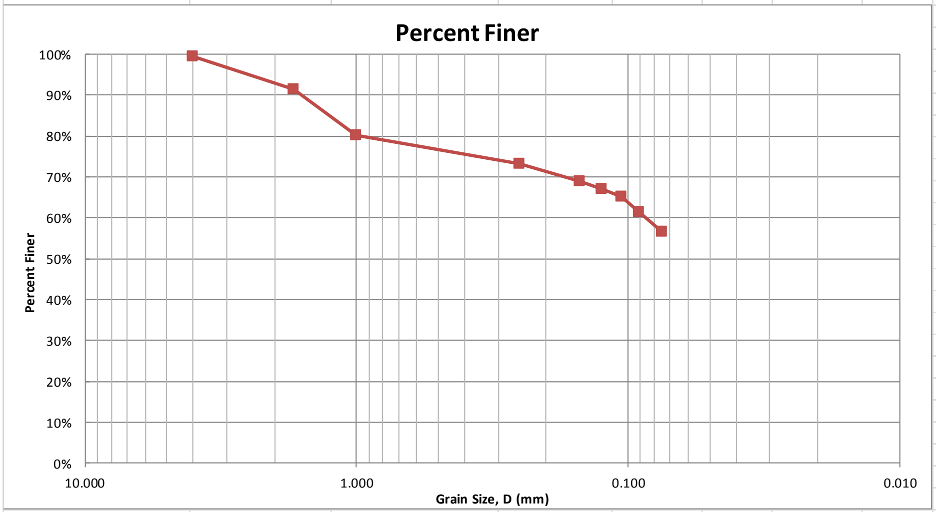
Total retained	459	g	D50		
Mass Lost during sieve analysis	3	g		50%	114 micron
Percent Lost during sieve analysis	0.7%	%			



Target Number	15:16	Date	10-Jun-15
Description of sediment	Silt		
Sample number	15:16	Tested by	DE
Nominal size (mm)		Mass can (g)	11.7
Mass + sediment (wet) (g)		Mass sediment (wet)(g)	
Mass + sediment (dry) (g)	337.2	Mass sediment (dry)(g)	325.5
Mass Moisture (g)		Moisture Content (%)	

Sieve Number	Sieve Opening (mm)	Sieve Mass (g)	Sediment (g)	Mass sediment retained (g)	Percent Retained on sieve	Cumulative Percent Retained	Percent Finer
5	4.000	733	734.7	1.7	1%	1%	99%
12	1.700	452.5	477.8	25.3	8%	8%	92%
18	1.000	434.3	470.4	36.1	11%	20%	80%
60	0.250	373.6	395.5	21.9	7%	27%	73%
100	0.150	355.6	369.1	13.5	4%	31%	69%
120	0.125	356.5	362.9	6.4	2%	33%	67%
140	0.106	355	360.7	5.7	2%	35%	65%
170	0.091	330.3	342.7	12.4	4%	39%	61%
200	0.075	318.7	333.5	14.8	5%	43%	57%
Pan	0.000	726.7	906.8	180.1	57%	100%	0%

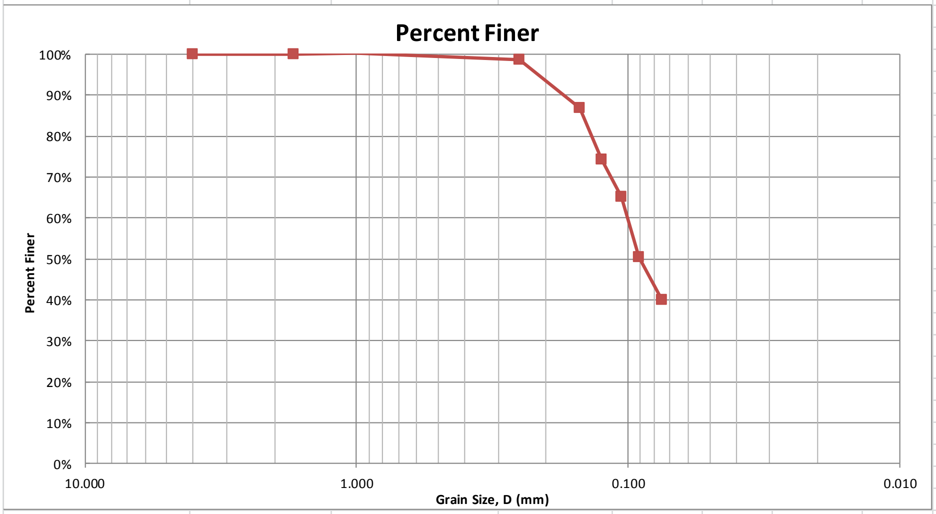
Total retained	317.9	g	D50		
Mass Lost during sieve analysis	7.6	g	50%	66 micron	
Percent Lost during sieve analysis	2.4%	%			



Target Number	15:19	Date	10-Jun-15
Description of sediment	Silt		
Sample number	15:19	Tested by	DE
Nominal size (mm)		Mass Tray (g)	11.9
Mass + sediment (wet) (g)		Mass sediment (wet)(g)	
Mass + sediment (dry) (g)	363.2	Mass sediment (dry)(g)	351.3
Mass Moisture (g)		Moisture Content (%)	

Sieve Number	Sieve Opening (mm)	Sieve Mass (g)	Sediment (g)	Mass sediment retained (g)	Percent Retained on sieve	Cumulative Percent Retained	Percent Finer
5	4.000	733.2	733.3	0.1	0%	0%	100%
12	1.700	452.6	452.7	0.1	0%	0%	100%
18	1.000	435.4	434.6	-0.8	0%	0%	100%
60	0.250	372.6	378	5.4	2%	1%	99%
100	0.150	354.8	396.1	41.3	12%	13%	87%
120	0.125	355.2	399.7	44.5	13%	26%	74%
140	0.106	353.6	385.1	31.5	9%	35%	65%
170	0.091	329.3	381.8	52.5	15%	50%	50%
200	0.075	318.1	354.6	36.5	10%	60%	40%
Pan	0.000	726.8	867.6	140.8	40%	100%	0%

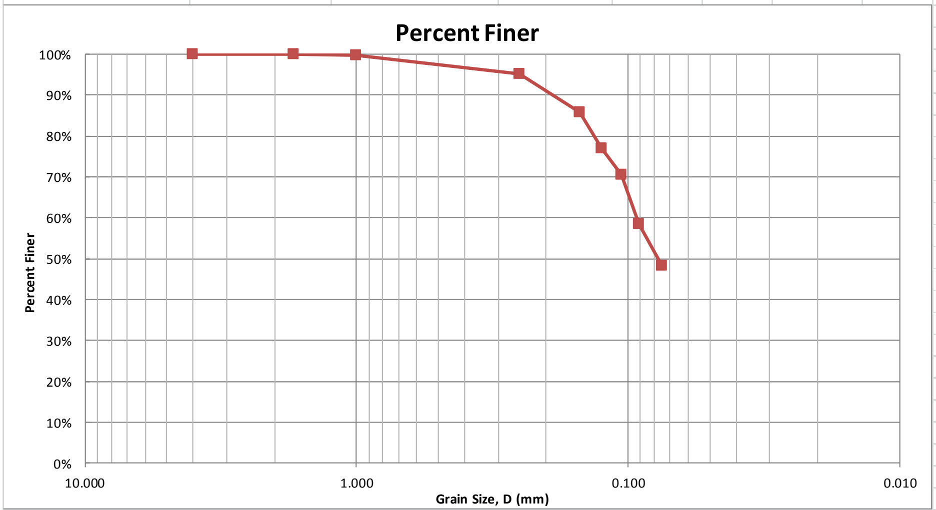
Total retained	351.9	g	D50	linear interpolation
Mass Lost during sieve analysis	-0.6	g	50%	94 micron
Percent Lost during sieve analysis	-0.2%	%		



Target Number	15:36	Date	11-Jun-15
Description of sediment	Silt		
Sample number	15:36	Tested by	DE
Nominal size (mm)		Mass Tray (g)	11.7
Mass + sediment (wet) (g)		Mass sediment (wet)(g)	
Mass + sediment (dry) (g)	585.5	Mass sediment (dry)(g)	573.8
Mass Moisture (g)		Moisture Content (%)	

Sieve Number	Sieve Opening (mm)	Sieve Mass (g)	Sediment (g)	Mass sediment retained (g)	Percent Retained on sieve	Cumulative Percent Retained	Percent Finer
5	4.000	733.1	733.2	0.1	0%	0%	100%
12	1.700	453.8	454	0.2	0%	0%	100%
18	1.000	435.4	435.9	0.5	0%	0%	100%
60	0.250	373.6	400.4	26.8	5%	5%	95%
100	0.150	355.5	408.8	53.3	9%	14%	86%
120	0.125	356.5	408.1	51.6	9%	23%	77%
140	0.106	354.9	391.5	36.6	6%	29%	71%
170	0.091	330.3	399.8	69.5	12%	42%	58%
200	0.075	318.8	376.6	57.8	10%	52%	48%
Pan	0.000	726.7	1003.6	276.9	48%	100%	0%

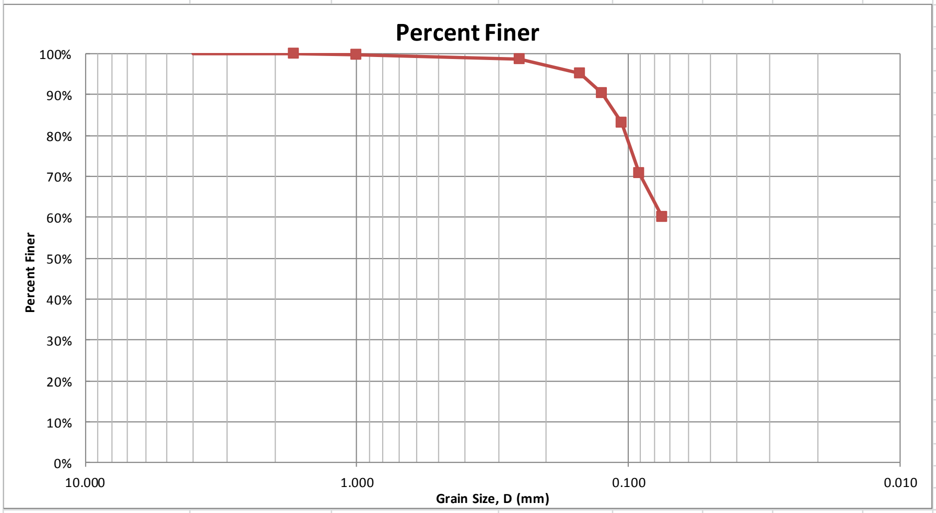
Total retained	573.3	g	D50	linear interpolation
Mass Lost during sieve analysis	0.5	g	50%	78 micron
Percent Lost during sieve analysis	0.1%	%		



Target Number	15:41	Date	11-Jun-15
Description of sediment	Silt		
Sample number	15:41	Tested by	DE
Nominal size (mm)		Mass Tray (g)	11.6
Mass + sediment (wet) (g)		Mass sediment (wet)(g)	
Mass + sediment (dry) (g)	207.3	Mass sediment (dry)(g)	195.7
Mass Moisture (g)		Moisture Content (%)	

Sieve Number	Sieve Opening (mm)	Sieve Mass (g)	Sediment (g)	Mass sediment retained (g)	Percent Retained on sieve	Cumulative Percent Retained	Percent Finer
5	4.000	733.1	733	-0.1	0%	0%	100%
12	1.700	453.8	453.9	0.1	0%	0%	100%
18	1.000	435.5	436	0.5	0%	0%	100%
60	0.250	373.6	375.7	2.1	1%	1%	99%
100	0.150	355.5	362.5	7	4%	5%	95%
120	0.125	356.4	365.8	9.4	5%	10%	90%
140	0.106	354.8	368.6	13.8	7%	17%	83%
170	0.091	330.2	354.1	23.9	12%	29%	71%
200	0.075	318.6	339.6	21	11%	40%	60%
Pan	0.000	726.8	843.7	116.9	60%	100%	0%

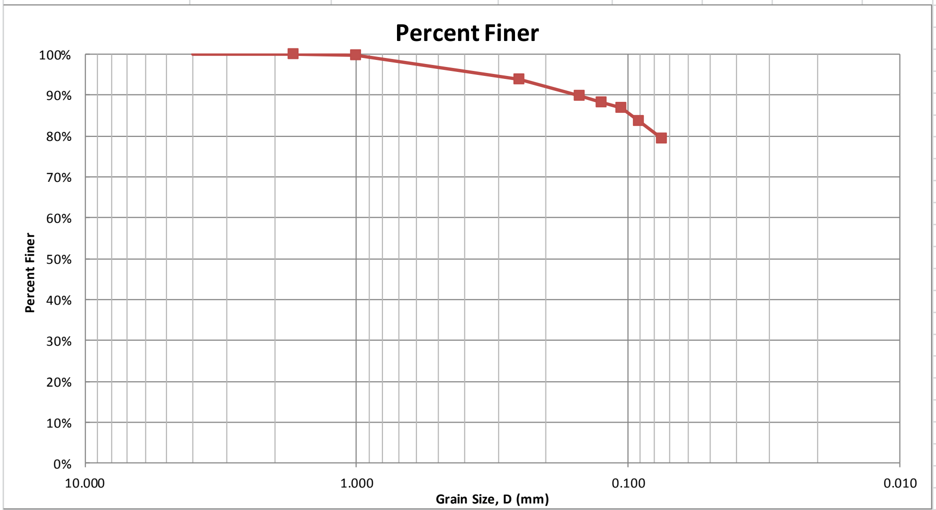
Total retained	194.6	g	D50	linear interpolation
Mass Lost during sieve analysis	1.1	g	50%	62 micron
Percent Lost during sieve analysis	0.6%	%		



Target Number	15:50	Date	11-Jun-15
Description of sediment	Silt		
Sample number	15:50	Tested by	DE
Nominal size (mm)		Mass Tray (g)	12
Mass + sediment (wet) (g)		Mass sediment (wet)(g)	
Mass + sediment (dry) (g)	360.7	Mass sediment (dry)(g)	348.7
Mass Moisture (g)		Moisture Content (%)	

Sieve Number	Sieve Opening (mm)	Sieve Mass (g)	Sediment (g)	Mass sediment retained (g)	Percent Retained on sieve	Cumulative Percent Retained	Percent Finer
5	4.000	733.4	733.3	-0.1	0%	0%	100%
12	1.700	453.8	454.2	0.4	0%	0%	100%
18	1.000	435.4	435.8	0.4	0%	0%	100%
60	0.250	373.6	394.5	20.9	6%	6%	94%
100	0.150	355.4	369	13.6	4%	10%	90%
120	0.125	356.5	362.8	6.3	2%	12%	88%
140	0.106	354.9	359.1	4.2	1%	13%	87%
170	0.091	330.2	341.7	11.5	3%	16%	84%
200	0.075	318.8	333.8	15	4%	21%	79%
Pan	0.000	726.7	1003.8	277.1	79%	100%	0%

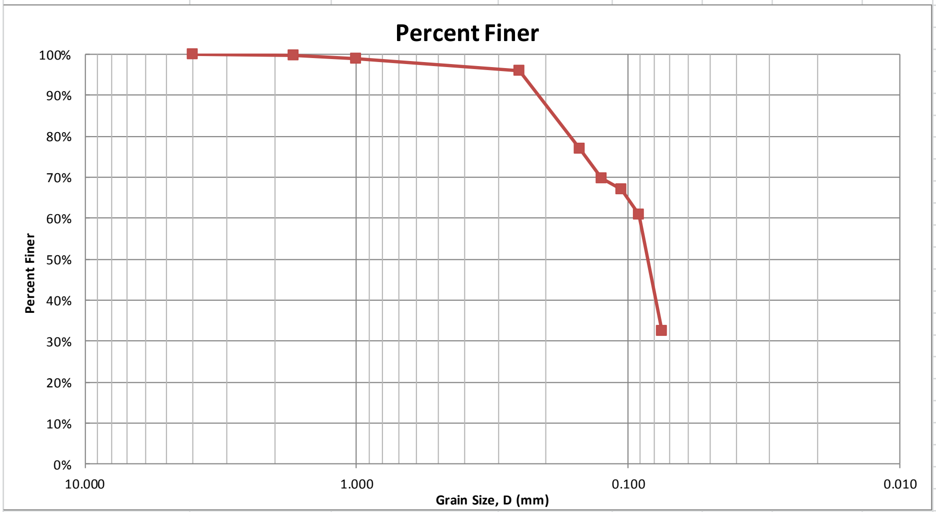
Total retained	349.3	g	D50	linear interpolation
Mass Lost during sieve analysis	-0.6	g	50%	47 micron
Percent Lost during sieve analysis	-0.2%	%		



Target Number	15:58	Date	11-Jun-15
Description of sediment	silt		
Sample number	15:58	Tested by	DE
Nominal size (mm)		Mass Tray (g)	12.5
Mass + sediment (wet) (g)		Mass sediment (wet)(g)	
Mass + sediment (dry) (g)	465	Mass sediment (dry)(g)	452.5
Mass Moisture (g)		Moisture Content (%)	

Sieve Number	Sieve Opening (mm)	Sieve Mass (g)	Sediment (g)	Mass sediment retained (g)	Percent Retained on sieve	Cumulative Percent Retained	Percent Finer
5	4.000	733	733.5	0.5	0%	0%	100%
12	1.700	453.7	454.7	1	0%	0%	100%
18	1.000	435.4	438.5	3.1	1%	1%	99%
60	0.250	373.6	386.1	12.5	3%	4%	96%
100	0.150	355.5	439.8	84.3	19%	23%	77%
120	0.125	356.4	388.8	32.4	7%	30%	70%
140	0.106	354.9	366.4	11.5	3%	33%	67%
170	0.091	330.2	357.4	27.2	6%	39%	61%
200	0.075	318.6	444.3	125.7	28%	68%	32%
Pan	0.000	728	871.5	143.5	32%	100%	0%

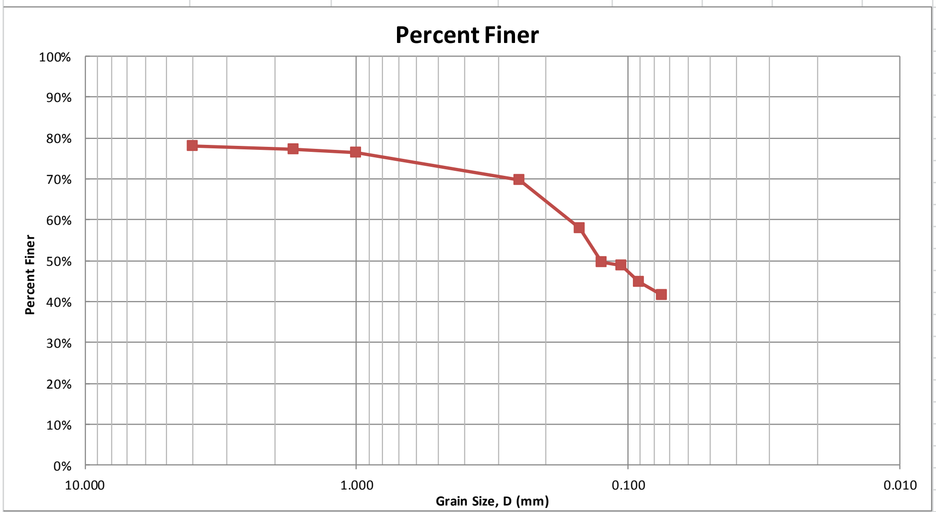
Total retained	441.7	g	D50	linear interpolation
Mass Lost during sieve analysis	10.8	g	50%	85 micron
Percent Lost during sieve analysis	2.5%	%		



Target Number	16:07	Date	11-Jun-15
Description of sediment	Silt with small rocks		
Sample number	16:07	Tested by	DE
Nominal size (mm)		Mass Tray (g)	11.6
Mass + sediment (wet) (g)		Mass sediment (wet)(g)	
Mass + sediment (dry) (g)	278	Mass sediment (dry)(g)	266.4
Mass Moisture (g)		Moisture Content (%)	

Sieve Number	Sieve Opening (mm)	Sieve Mass (g)	Sediment (g)	Mass sediment retained (g)	Percent Retained on sieve	Cumulative Percent Retained	Percent Finer
5	4.000	733	793.1	60.1	22%	22%	78%
12	1.700	452.6	454.5	1.9	1%	23%	77%
18	1.000	434	436.4	2.4	1%	24%	76%
60	0.250	372.5	390.9	18.4	7%	30%	70%
100	0.150	355.4	387.7	32.3	12%	42%	58%
120	0.125	355.2	377.6	22.4	8%	50%	50%
140	0.106	353.6	356.2	2.6	1%	51%	49%
170	0.091	329.1	340.2	11.1	4%	55%	45%
200	0.075	318.7	327.1	8.4	3%	58%	42%
Pan	0.000	727.9	841.6	113.7	42%	100%	0%

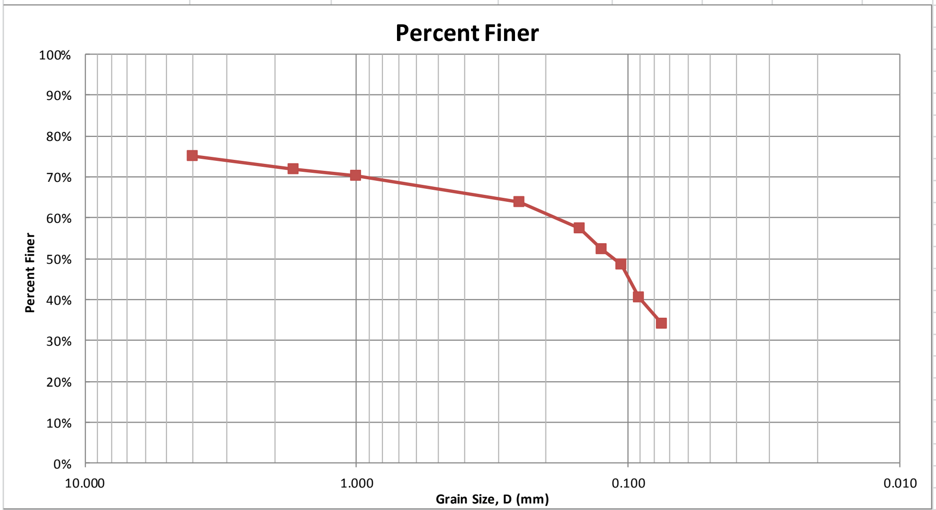
Total retained	273.3	g	D50	linear interpolation
Mass Lost during sieve analysis	-6.9	g	50%	109 micron
Percent Lost during sieve analysis	-2.5%	%		



Target Number	16:20	Date	11-Jun-15
Description of sediment	Silt with small rocks		
Sample number	16:20	Tested by	DE
Nominal size (mm)		Mass Tray (g)	11.7
Mass + sediment (wet) (g)		Mass sediment (wet)(g)	
Mass + sediment (dry) (g)	286	Mass sediment (dry)(g)	274.3
Mass Moisture (g)		Moisture Content (%)	

Sieve Number	Sieve Opening (mm)	Sieve Mass (g)	Sediment (g)	Mass sediment retained (g)	Percent Retained on sieve	Cumulative Percent Retained	Percent Finer
5	4.000	734.4	801.6	67.2	25%	25%	75%
12	1.700	453.6	461.7	8.1	3%	28%	72%
18	1.000	435.4	439.8	4.4	2%	30%	70%
60	0.250	373.7	390.9	17.2	6%	36%	64%
100	0.150	354.5	371.8	17.3	6%	43%	57%
120	0.125	356.4	370	13.6	5%	48%	52%
140	0.106	354.8	365.4	10.6	4%	52%	48%
170	0.091	330.2	351.6	21.4	8%	60%	40%
200	0.075	318.6	335.9	17.3	6%	66%	34%
Pan	0.000	728	819.3	91.3	34%	100%	0%

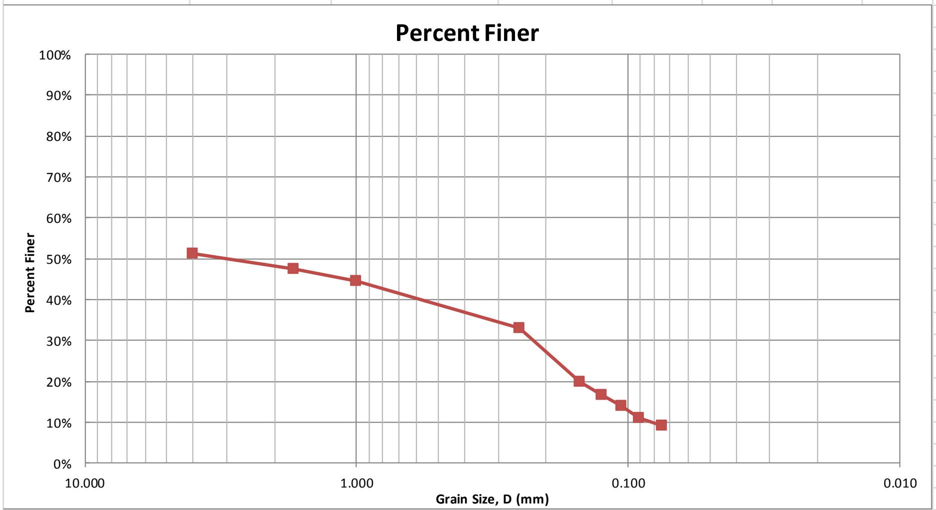
Total retained	268.4	g	D50	linear interpolation
Mass Lost during sieve analysis	5.9	g	50%	110 micron
Percent Lost during sieve analysis	2.2%	%		



Target Number	16:26	Date	11-Jun-15
Description of sediment	Silt with small rocks		
Sample number	16:26	Tested by	DE
Nominal size (mm)		Mass Tray (g)	11.7
Mass + sediment (wet) (g)		Mass sediment (wet)(g)	
Mass + sediment (dry) (g)	595.8	Mass sediment (dry)(g)	584.1
Mass Moisture (g)		Moisture Content (%)	

Sieve Number	Sieve Opening (mm)	Sieve Mass (g)	Sediment (g)	Mass sediment retained (g)	Percent Retained on sieve	Cumulative Percent Retained	Percent Finer
5	4.000	733	999.2	266.2	49%	49%	51%
12	1.700	453.7	474.2	20.5	4%	52%	48%
18	1.000	435.4	451.7	16.3	3%	55%	45%
60	0.250	373.6	437.1	63.5	12%	67%	33%
100	0.150	355.4	426.3	70.9	13%	80%	20%
120	0.125	356.5	374.1	17.6	3%	83%	17%
140	0.106	354.9	370	15.1	3%	86%	14%
170	0.091	330.2	345.9	15.7	3%	89%	11%
200	0.075	318.8	329.4	10.6	2%	91%	9%
Pan	0.000	727.9	777.6	49.7	9%	100%	0%

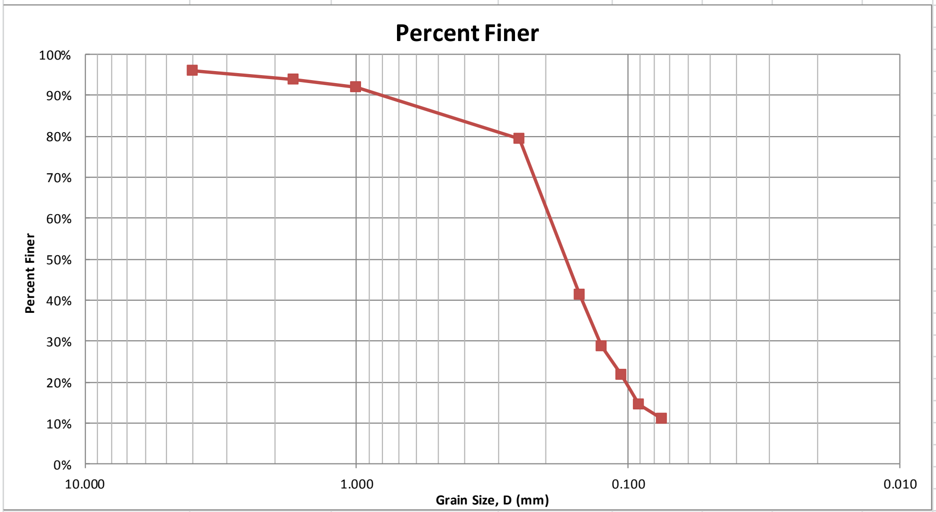
Total retained	546.1	g	D50		linear interpolation
Mass Lost during sieve analysis	38	g		50%	4363 micron
Percent Lost during sieve analysis	7.5%	%			



Target Number	16:29	Date	11-Jun-15
Description of sediment	Silt		
Sample number	16:29	Tested by	DE
Nominal size (mm)		Mass Tray (g)	12.1
Mass + sediment (wet) (g)		Mass sediment (wet)(g)	
Mass + sediment (dry) (g)	421.9	Mass sediment (dry)(g)	409.8
Mass Moisture (g)		Moisture Content (%)	

Sieve Number	Sieve Opening (mm)	Sieve Mass (g)	Sediment (g)	Mass sediment retained (g)	Percent Retained on sieve	Cumulative Percent Retained	Percent Finer
5	4.000	733.1	749.2	16.1	4%	4%	96%
12	1.700	453.8	462.8	9	2%	6%	94%
18	1.000	435.4	443.3	7.9	2%	8%	92%
60	0.250	373.7	424.4	50.7	12%	21%	79%
100	0.150	355.5	510.6	155.1	38%	59%	41%
120	0.125	356.4	407.9	51.5	13%	71%	29%
140	0.106	354.9	383.4	28.5	7%	78%	22%
170	0.091	330.2	359.4	29.2	7%	85%	15%
200	0.075	318.7	333.1	14.4	4%	89%	11%
Pan	0.000	728	773.2	45.2	11%	100%	0%

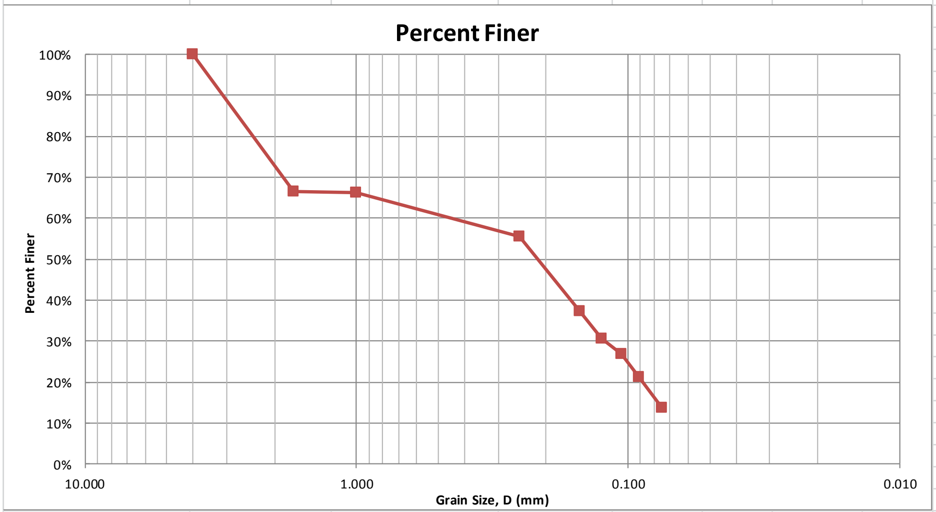
Total retained	407.6	g	D50	linear interpolation
Mass Lost during sieve analysis	2.2	g	50%	206 micron
Percent Lost during sieve analysis	0.5%	%		



Target Number	RT10 S1	Date	12-Jun-15
Description of sediment	Silt		
Sample number	RT10 S1	Tested by	DE
Nominal size (mm)		Mass Tray (g)	12
Mass + sediment (wet) (g)		Mass sediment (wet)(g)	
Mass + sediment (dry) (g)	570.4	Mass sediment (dry)(g)	558.4
Mass Moisture (g)		Moisture Content (%)	

Sieve Number	Sieve Opening (mm)	Sieve Mass (g)	Sediment (g)	Mass sediment retained (g)	Percent Retained on sieve	Cumulative Percent Retained	Percent Finer
5	4.000	732.8	733.6	0.8	0%	0%	100%
12	1.700	453.7	754.2	300.5	34%	34%	66%
18	1.000	435.4	436	0.6	0%	34%	66%
60	0.250	374	471.2	97.2	11%	45%	55%
100	0.150	355.5	517.5	162	18%	63%	37%
120	0.125	356.4	417.7	61.3	7%	69%	31%
140	0.106	354.8	386.9	32.1	4%	73%	27%
170	0.091	330.2	382.5	52.3	6%	79%	21%
200	0.075	318.7	384.5	65.8	7%	86%	14%
Pan	0.000	726.6	850.4	123.8	14%	100%	0%

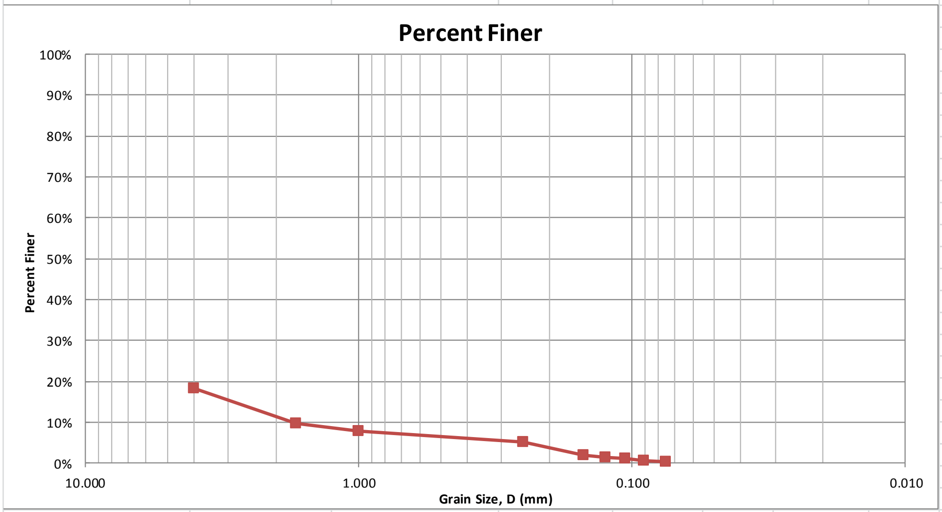
Total retained	896.4	g	D50	linear interpolation
Mass Lost during sieve analysis	-338	g	50%	324 micron
Percent Lost during sieve analysis	-27.4%	%		



Target Number	RT10 S2	Date	12-Jun-15
Description of sediment	1/8-3/8 rock		
Sample number	RT10 S2	Tested by	DE
Nominal size (mm)		Mass Tray (g)	11.6
Mass + sediment (wet) (g)		Mass sediment (wet)(g)	
Mass + sediment (dry) (g)	745.2	Mass sediment (dry)(g)	733.6
Mass Moisture (g)		Moisture Content (%)	

Sieve Number	Sieve Opening (mm)	Sieve Mass (g)	Sediment (g)	Mass sediment retained (g)	Percent Retained on sieve	Cumulative Percent Retained	Percent Finer
5	4.000	734.2	1332.8	598.6	82%	82%	18%
12	1.700	453.7	516.1	62.4	9%	90%	10%
18	1.000	435.3	448.3	13	2%	92%	8%
60	0.250	373.7	393	19.3	3%	95%	5%
100	0.150	355.7	379.9	24.2	3%	98%	2%
120	0.125	356.5	359.9	3.4	0%	99%	1%
140	0.106	354.9	358.1	3.2	0%	99%	1%
170	0.091	330.2	333.1	2.9	0%	99%	1%
200	0.075	318.7	320.7	2	0%	100%	0%
Pan	0.000	727.9	730.3	2.4	0%	100%	0%

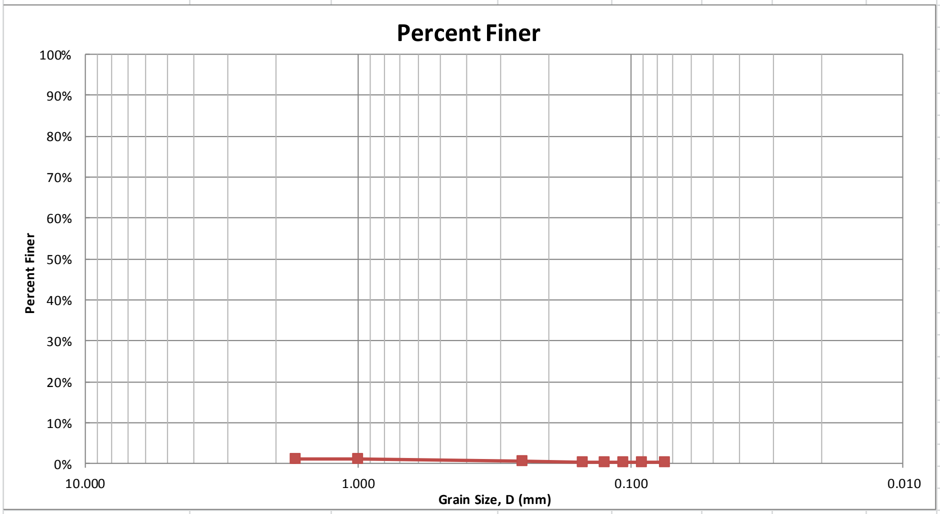
Total retained	731.4	g	D50	linear interpolation
Mass Lost during sieve analysis	2.2	g	50%	11428 micron
Percent Lost during sieve analysis	0.3%	%		



Target Number	RT10 S3	Date	12-Jun-15
Description of sediment	1/4-1 1/2 rock		
Sample number	RT10 S3	Tested by	DE
Nominal size (mm)		Mass Tray (g)	11.6
Mass + sediment (wet) (g)		Mass sediment (wet)(g)	
Mass + sediment (dry) (g)	666	Mass sediment (dry)(g)	.
Mass Moisture (g)		Moisture Content (%)	

Sieve Number	Sieve Opening (mm)	Sieve Mass (g)	Sediment (g)	Mass sediment retained (g)	Percent Retained on sieve	Cumulative Percent Retained	Percent Finer
5	4.000	733.2	1382.9	649.7	182%	182%	-82%
12	1.700	753.7	455.9	-297.8	-84%	99%	1%
18	1.000	435.2	436	0.8	0%	99%	1%
60	0.250	373.8	375.3	1.5	0%	99%	1%
100	0.150	355.6	356.4	0.8	0%	100%	0%
120	0.125	356.5	356.5	0	0%	100%	0%
140	0.106	354.9	354.8	-0.1	0%	100%	0%
170	0.091	330.2	330.2	0	0%	100%	0%
200	0.075	318.6	318.7	0.1	0%	100%	0%
Pan	0.000	726.6	727.9	1.3	0%	100%	0%

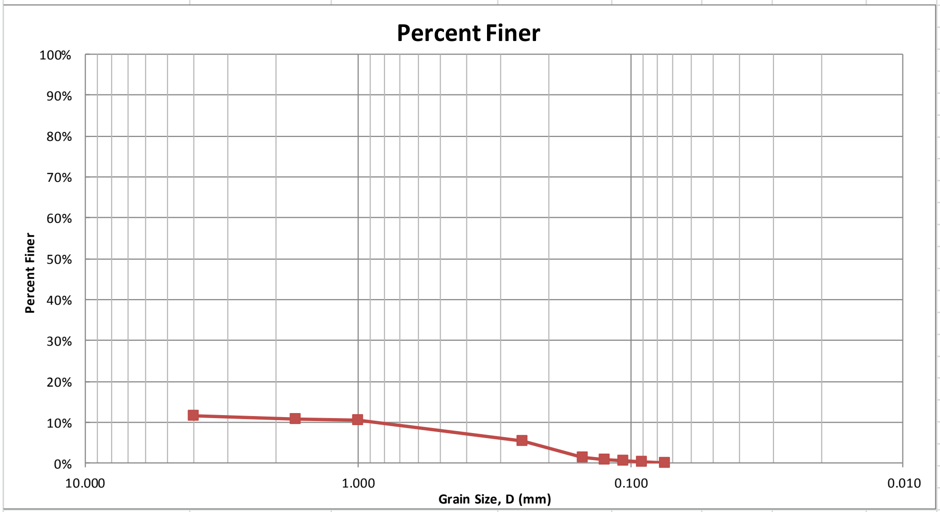
Total retained	356.3	g	D50	linear interpolation
Mass Lost during sieve analysis	#VALUE!	g	50%	10278 micron
Percent Lost during sieve analysis	#VALUE!	%		



Target Number	RT10 S4	Date	12-Jun-15
Description of sediment	Silt with 1/4-1 1/2 rock		
Sample number	RT10 S4	Tested by	DE
Nominal size (mm)		Mass Tray (g)	12.1
Mass + sediment (wet) (g)		Mass sediment (wet)(g)	
Mass + sediment (dry) (g)	695.6	Mass sediment (dry)(g)	683.5
Mass Moisture (g)		Moisture Content (%)	

Sieve Number	Sieve Opening (mm)	Sieve Mass (g)	Sediment (g)	Mass sediment retained (g)	Percent Retained on sieve	Cumulative Percent Retained	Percent Finer
5	4.000	743.7	1339.8	596.1	89%	89%	11%
12	1.700	453.6	458.8	5.2	1%	89%	11%
18	1.000	435.2	436.9	1.7	0%	90%	10%
60	0.250	373.7	407.8	34.1	5%	95%	5%
100	0.150	355.5	382.9	27.4	4%	99%	1%
120	0.125	356.4	359.5	3.1	0%	99%	1%
140	0.106	354.9	357.2	2.3	0%	99%	1%
170	0.091	330.3	332	1.7	0%	100%	0%
200	0.075	318.8	319.6	0.8	0%	100%	0%
Pan	0.000	727.9	728.8	0.9	0%	100%	0%

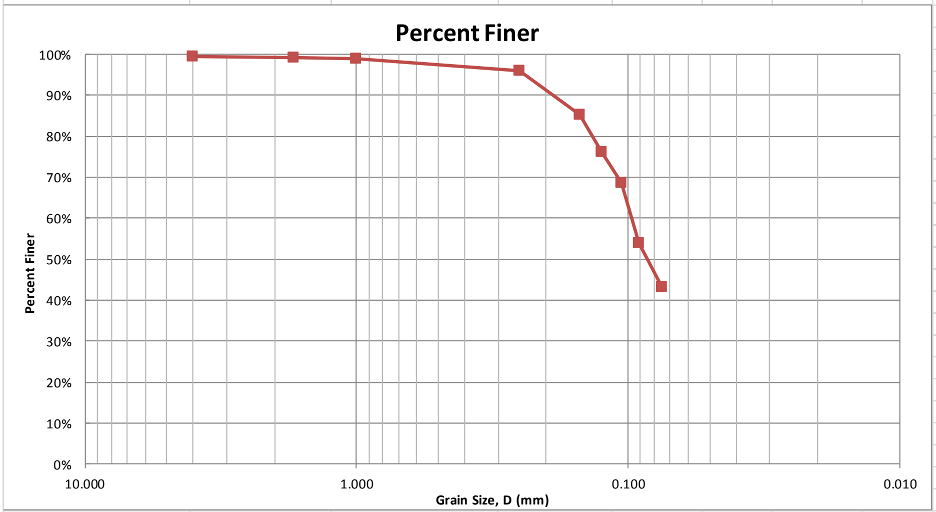
Total retained	673.3	g	D50	linear interpolation
Mass Lost during sieve analysis	10.2	g	50%	28054 micron
Percent Lost during sieve analysis	1.5%	%		



Target Number	RT10 S5	Date	12-Jun-15
Description of sediment	Silt		
Sample number	RT10 S5	Tested by	DE
Nominal size (mm)		Mass Tray (g)	10.9
Mass + sediment (wet) (g)		Mass sediment (wet)(g)	
Mass + sediment (dry) (g)	337.3	Mass sediment (dry)(g)	326.4
Mass Moisture (g)		Moisture Content (%)	

Sieve Number	Sieve Opening (mm)	Sieve Mass (g)	Sediment (g)	Mass sediment retained (g)	Percent Retained on sieve	Cumulative Percent Retained	Percent Finer
5	4.000	732.9	735	2.1	1%	1%	99%
12	1.700	453.6	454.3	0.7	0%	1%	99%
18	1.000	435.2	435.8	0.6	0%	1%	99%
60	0.250	373.7	383.4	9.7	3%	4%	96%
100	0.150	355.6	390.6	35	11%	15%	85%
120	0.125	356.5	387.2	30.7	9%	24%	76%
140	0.106	354.9	379.3	24.4	7%	31%	69%
170	0.091	330.4	378.3	47.9	15%	46%	54%
200	0.075	318.7	354.3	35.6	11%	57%	43%
Pan	0.000	727.9	870	142.1	43%	100%	0%

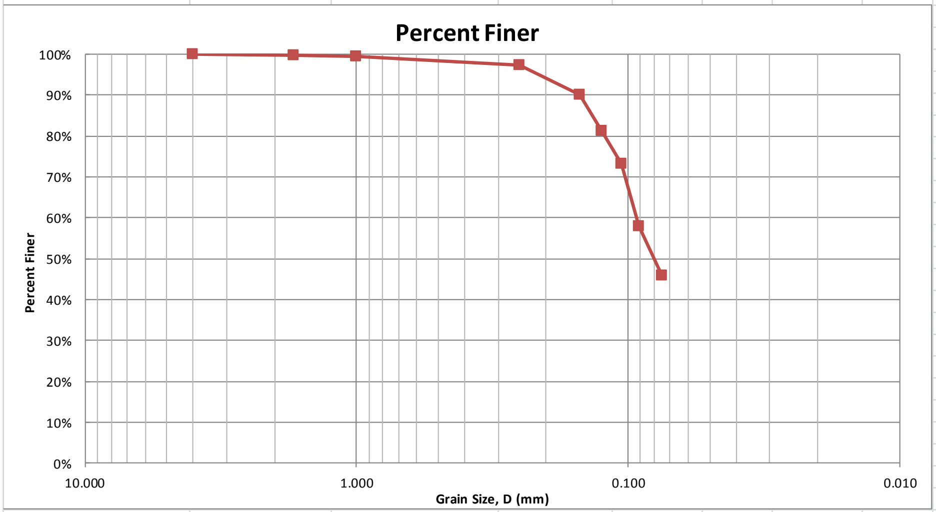
Total retained	328.8	g	D50	linear interpolation
Mass Lost during sieve analysis	-2.4	g	50%	85 micron
Percent Lost during sieve analysis	-0.7%	%		



Target Number	S1	Date	12-Jun-15
Description of sediment	Silt		
Sample number	S1	Tested by	DE
Nominal size (mm)		Mass Tray (g)	11.7
Mass + sediment (wet) (g)		Mass sediment (wet)(g)	
Mass + sediment (dry) (g)	374.3	Mass sediment (dry)(g)	362.6
Mass Moisture (g)		Moisture Content (%)	

Sieve Number	Sieve Opening (mm)	Sieve Mass (g)	Sediment (g)	Mass sediment retained (g)	Percent Retained on sieve	Cumulative Percent Retained	Percent Finer
5	4.000	734.4	734.8	0.4	0%	0%	100%
12	1.700	453.7	454.6	0.9	0%	0%	100%
18	1.000	435.3	436	0.7	0%	1%	99%
60	0.250	373.6	380.8	7.2	2%	3%	97%
100	0.150	355.6	382.8	27.2	7%	10%	90%
120	0.125	356.5	388.2	31.7	9%	19%	81%
140	0.106	354.9	384.5	29.6	8%	27%	73%
170	0.091	330.3	385.2	54.9	15%	42%	58%
200	0.075	318.7	362.8	44.1	12%	54%	46%
Pan	0.000	726.7	893	166.3	46%	100%	0%

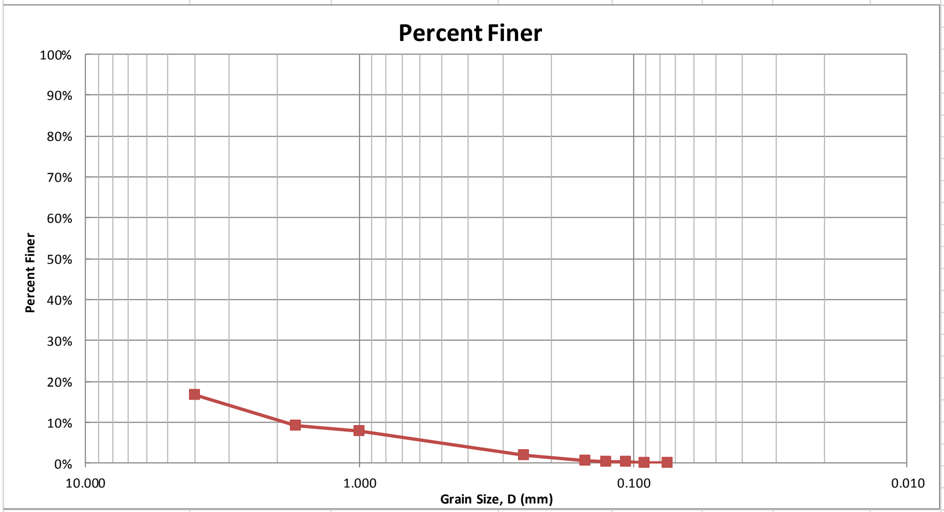
Total retained	363	g	D50	linear interpolation
Mass Lost during sieve analysis	-0.4	g	50%	81 micron
Percent Lost during sieve analysis	-0.1%	%		



Target Number	S2	Date	12-Jun-15
Description of sediment	1/8-3/4 rock		
Sample number	S2	Tested by	DE
Nominal size (mm)		Mass Tray (g)	11.6
Mass + sediment (wet) (g)		Mass sediment (wet)(g)	
Mass + sediment (dry) (g)	820.8	Mass sediment (dry)(g)	809.2
Mass Moisture (g)		Moisture Content (%)	

Sieve Number	Sieve Opening (mm)	Sieve Mass (g)	Sediment (g)	Mass sediment retained (g)	Percent Retained on sieve	Cumulative Percent Retained	Percent Finer
5	4.000	734.4	1410.5	676.1	83%	83%	17%
12	1.700	452.5	514.1	61.6	8%	91%	9%
18	1.000	435.4	446	10.6	1%	92%	8%
60	0.250	373.8	421.8	48	6%	98%	2%
100	0.150	355.6	366	10.4	1%	99%	1%
120	0.125	356.4	358	1.6	0%	100%	0%
140	0.106	354.9	355.8	0.9	0%	100%	0%
170	0.091	330.4	330.8	0.4	0%	100%	0%
200	0.075	318.8	318.9	0.1	0%	100%	0%
Pan	0.000	726.8	728.2	1.4	0%	100%	0%

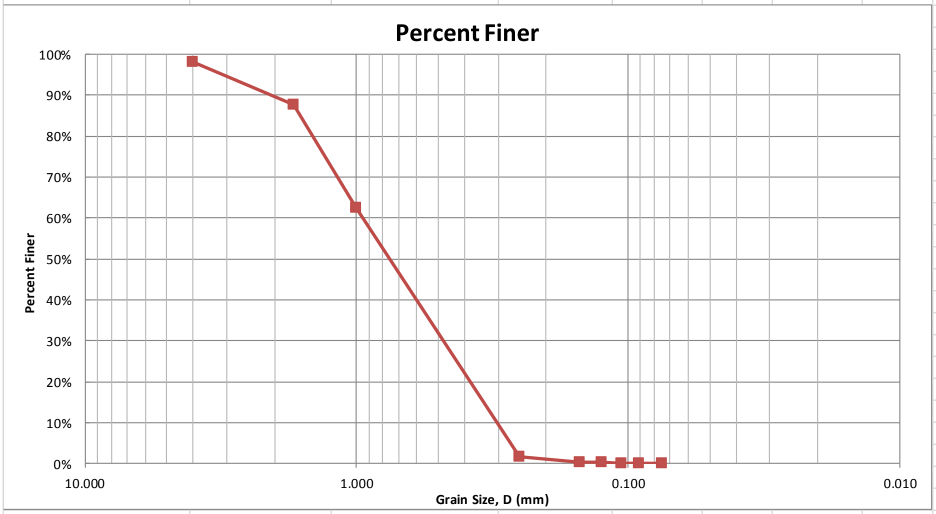
Total retained	811.1	g	D50	linear interpolation
Mass Lost during sieve analysis	-1.9	g	50%	21726 micron
Percent Lost during sieve analysis	-0.2%	%		



Target Number	S3	Date	12-Jun-15
Description of sediment	Sand		
Sample number	S3	Tested by	DE
Nominal size (mm)		Mass Tray (g)	11.7
Mass + sediment (wet) (g)		Mass sediment (wet)(g)	
Mass + sediment (dry) (g)	608.8	Mass sediment (dry)(g)	597.1
Mass Moisture (g)		Moisture Content (%)	

Sieve Number	Sieve Opening (mm)	Sieve Mass (g)	Sediment (g)	Mass sediment retained (g)	Percent Retained on sieve	Cumulative Percent Retained	Percent Finer
5	4.000	734.5	746.2	11.7	2%	2%	98%
12	1.700	453.8	515.4	61.6	10%	12%	88%
18	1.000	435.4	585.4	150	25%	38%	62%
60	0.250	373.7	734.6	360.9	61%	98%	2%
100	0.150	355.6	363.1	7.5	1%	100%	0%
120	0.125	356.5	357.3	0.8	0%	100%	0%
140	0.106	354.9	355.4	0.5	0%	100%	0%
170	0.091	330.4	330.6	0.2	0%	100%	0%
200	0.075	318.8	318.9	0.1	0%	100%	0%
Pan	0.000	727.9	728.4	0.5	0%	100%	0%

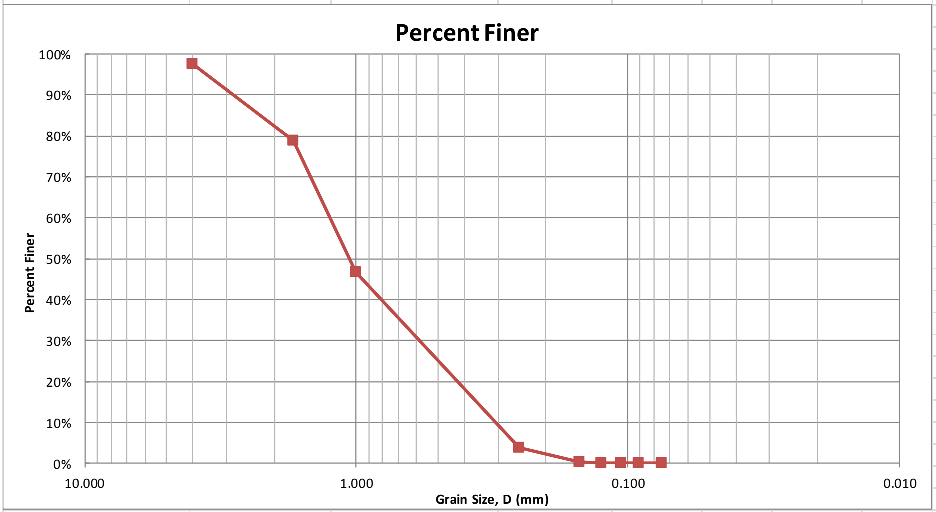
Total retained	593.8	g	D50	linear interpolation
Mass Lost during sieve analysis	3.3	g	50%	847 micron
Percent Lost during sieve analysis	0.6%	%		



Target Number	S4	Date	12-Jun-15
Description of sediment	Sand		
Sample number	S4	Tested by	DE
Nominal size (mm)		Mass Tray (g)	12.9
Mass + sediment (wet) (g)		Mass sediment (wet)(g)	
Mass + sediment (dry) (g)	687.9	Mass sediment (dry)(g)	675
Mass Moisture (g)		Moisture Content (%)	

Sieve Number	Sieve Opening (mm)	Sieve Mass (g)	Sediment (g)	Mass sediment retained (g)	Percent Retained on sieve	Cumulative Percent Retained	Percent Finer
5	4.000	734.3	750.2	15.9	2%	2%	98%
12	1.700	453.7	575.4	121.7	19%	21%	79%
18	1.000	435.5	645.1	209.6	32%	53%	47%
60	0.250	373.7	653.8	280.1	43%	96%	4%
100	0.150	355.5	378.5	23	4%	100%	0%
120	0.125	356.5	358.2	1.7	0%	100%	0%
140	0.106	354.9	355.4	0.5	0%	100%	0%
170	0.091	330.3	330.4	0.1	0%	100%	0%
200	0.075	318.8	318.8	0	0%	100%	0%
Pan	0.000	727.9	728.1	0.2	0%	100%	0%

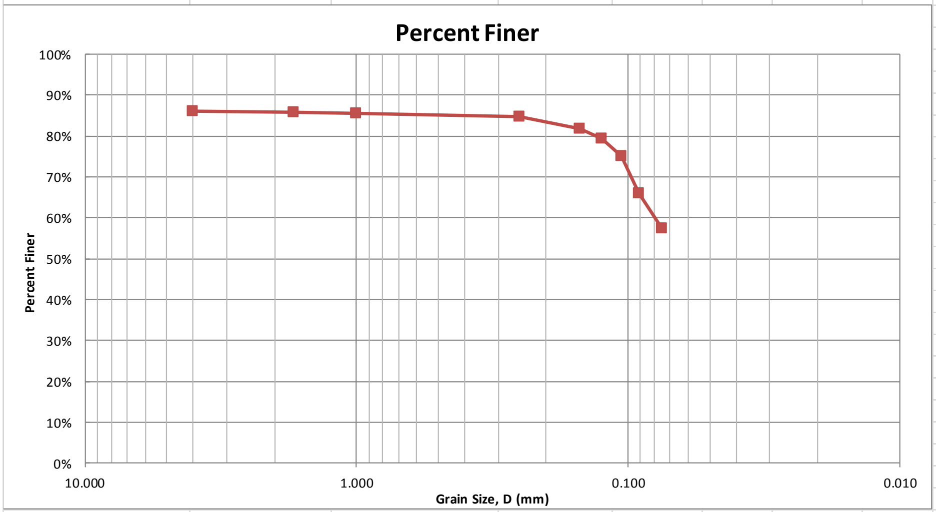
Total retained	652.8	g	D50	linear interpolation
Mass Lost during sieve analysis	22.2	g	50%	1069 micron
Percent Lost during sieve analysis	3.5%	%		



Target Number	S5	Date	12-Jun-15
Description of sediment	Silt		
Sample number	S5	Tested by	DE
Nominal size (mm)		Mass Tray (g)	11.7
Mass + sediment (wet) (g)		Mass sediment (wet)(g)	
Mass + sediment (dry) (g)	514.9	Mass sediment (dry)(g)	503.2
Mass Moisture (g)		Moisture Content (%)	

Sieve Number	Sieve Opening (mm)	Sieve Mass (g)	Sediment (g)	Mass sediment retained (g)	Percent Retained on sieve	Cumulative Percent Retained	Percent Finer
5	4.000	743.3	811	67.7	14%	14%	86%
12	1.700	453.7	455.3	1.6	0%	14%	86%
18	1.000	435	435.5	0.5	0%	14%	86%
60	0.250	373.8	379	5.2	1%	15%	85%
100	0.150	355.5	369	13.5	3%	18%	82%
120	0.125	356.5	369.1	12.6	3%	21%	79%
140	0.106	355	374.9	19.9	4%	25%	75%
170	0.091	330.3	375.1	44.8	9%	34%	66%
200	0.075	318.7	360.6	41.9	9%	43%	57%
Pan	0.000	726.6	1006.2	279.6	57%	100%	0%

Total retained	487.3	g	D50	linear interpolation	
Mass Lost during sieve analysis	15.9	g	50%	65 micron	
Percent Lost during sieve analysis	3.4%	%			



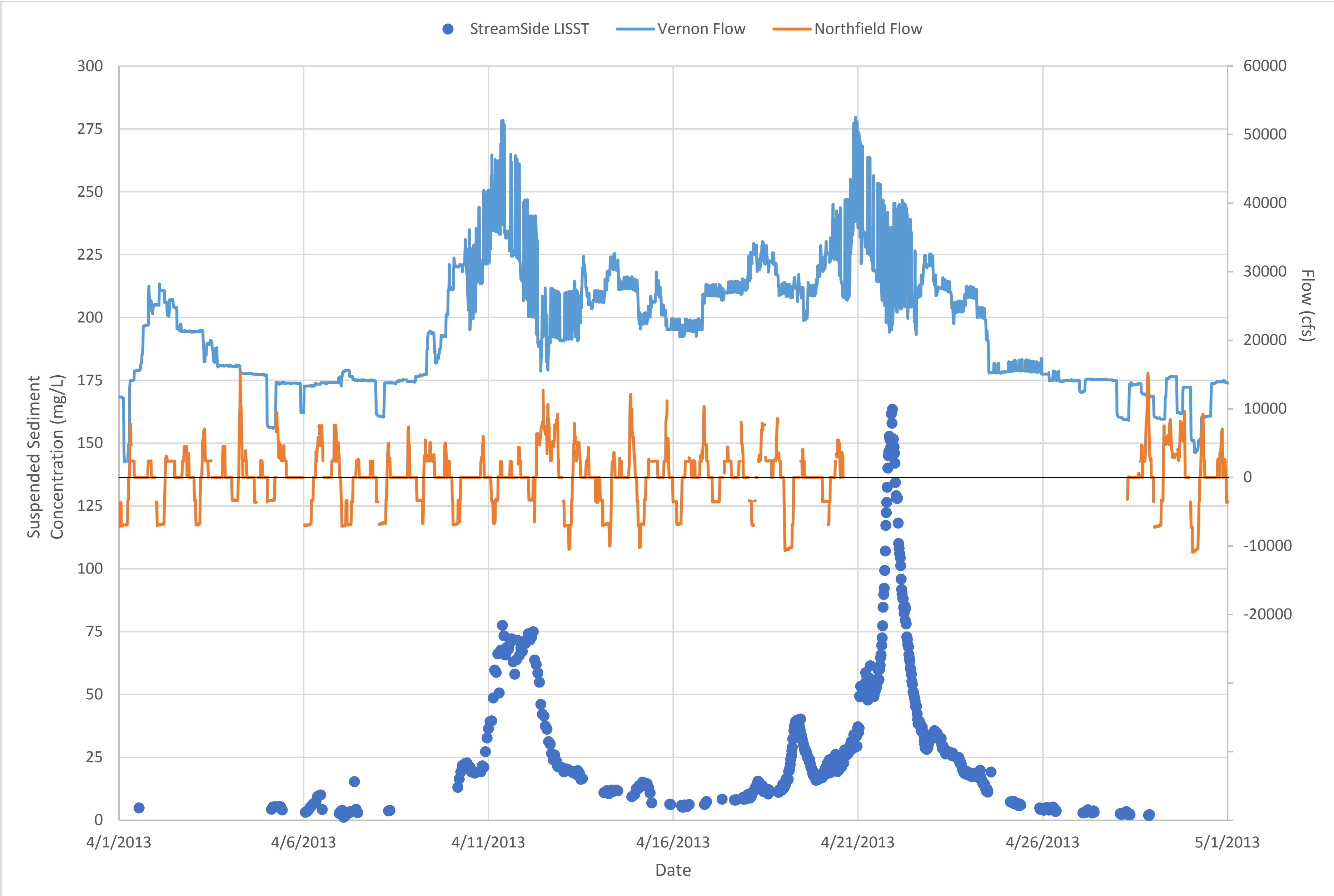
Appendix C Test Video

Test video is included on attached Blu-ray disks.

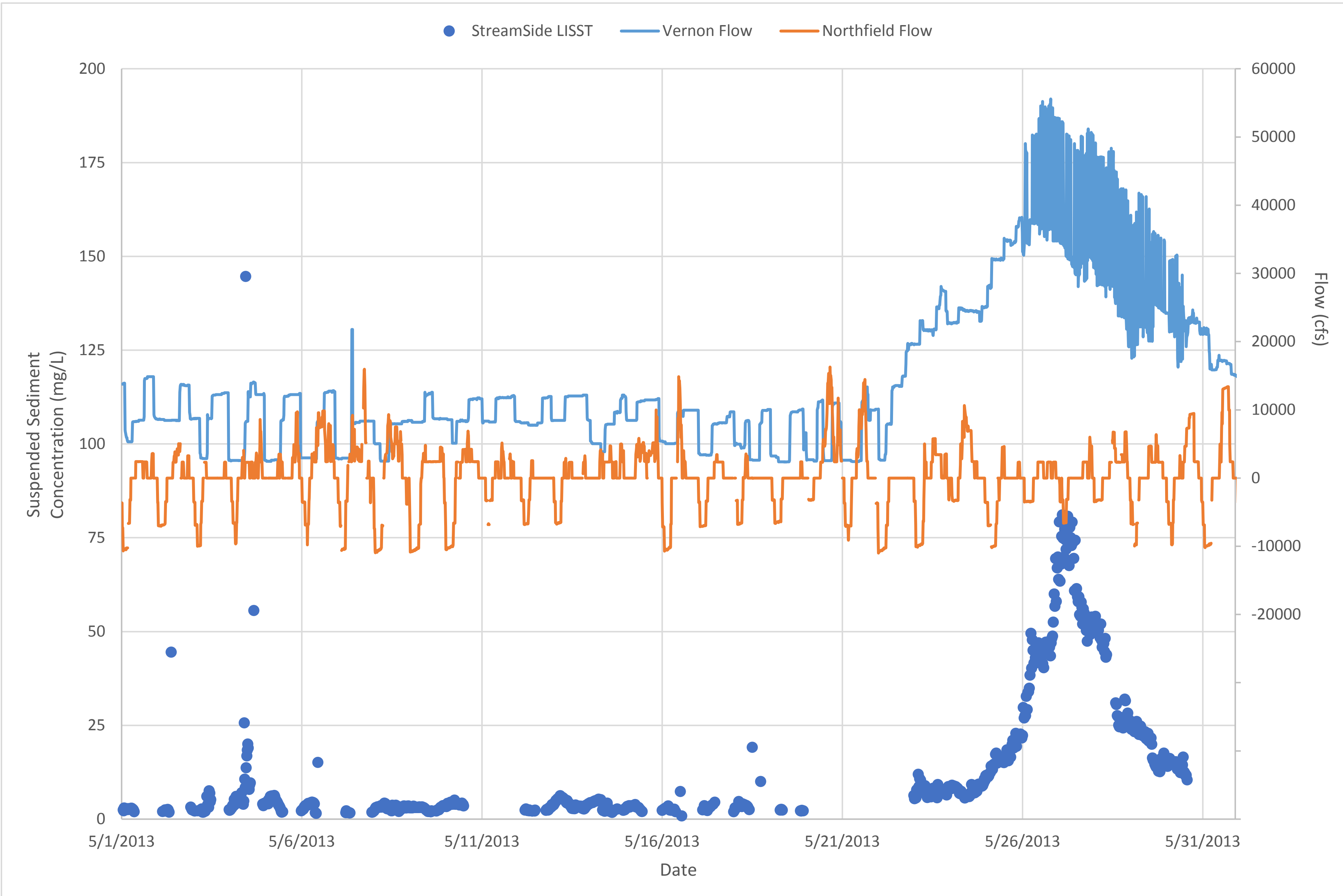
APPENDIX D – CONTINUOUS SSC, FLOW, AND PROJECT OPERATIONS TIMESERIES PLOTS – MG/L (2013-2015)[25]

[25] When reviewing the plots contained in this Appendix it is important to note that: 1) the y-axis may vary from plot to plot, and 2) gaps observed in the LISST data represent periods of time when the instruments were offline due to equipment malfunctions or data that was removed from the final dataset during the QA/QC process.

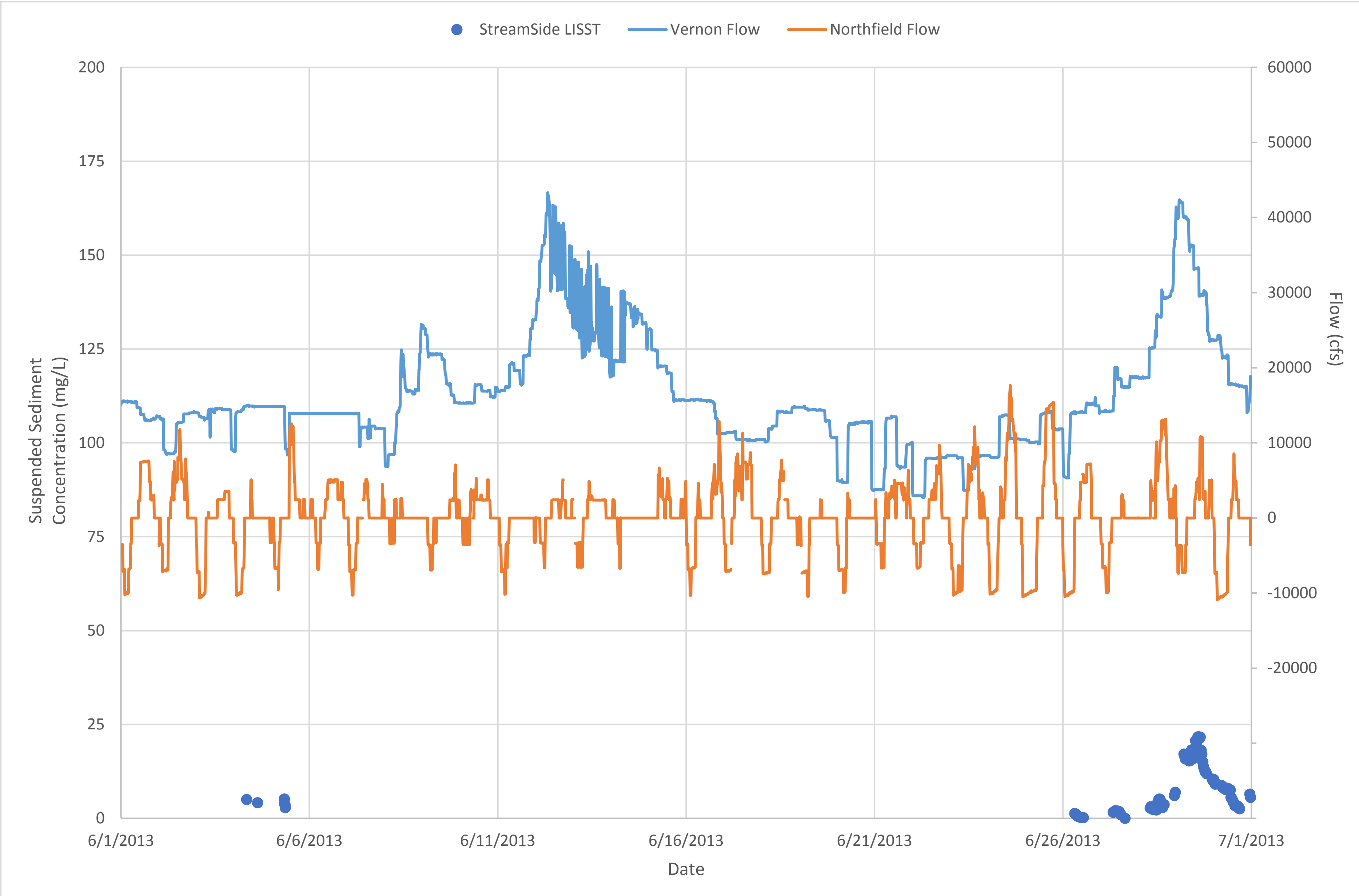
2013 CONTINUOUS LISST INSTRUMENT TIMESERIES-MONTHLY



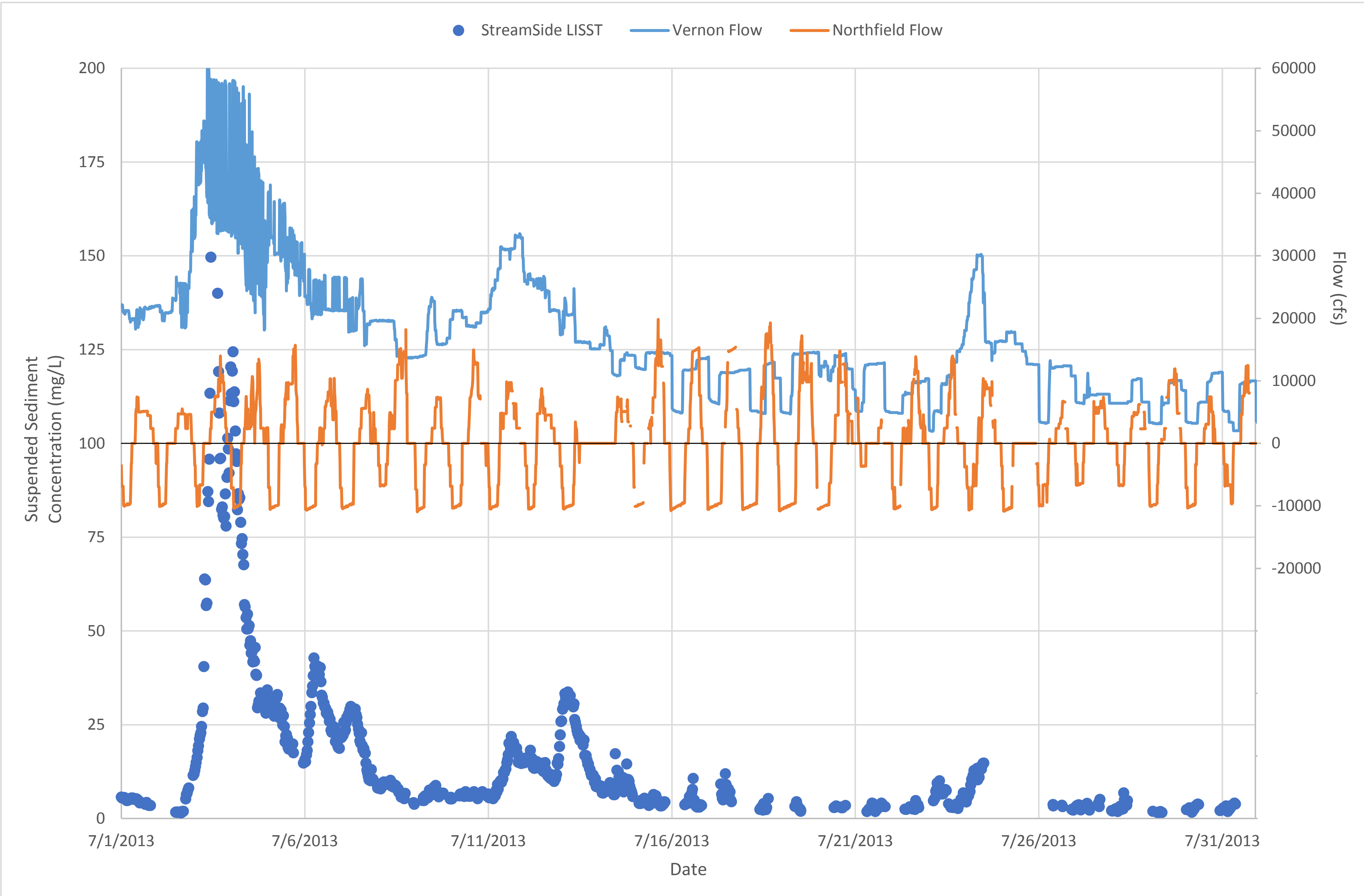
StreamSide LISST
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
300
275
250
225
200
175
150
125
100
75
50
25
0
Flow (cfs)
60000
50000
40000
30000
20000
10000
0
-10000
-20000
4/1/2013
4/6/2013
4/11/2013
4/16/2013
4/21/2013
4/26/2013
5/1/2013
Date



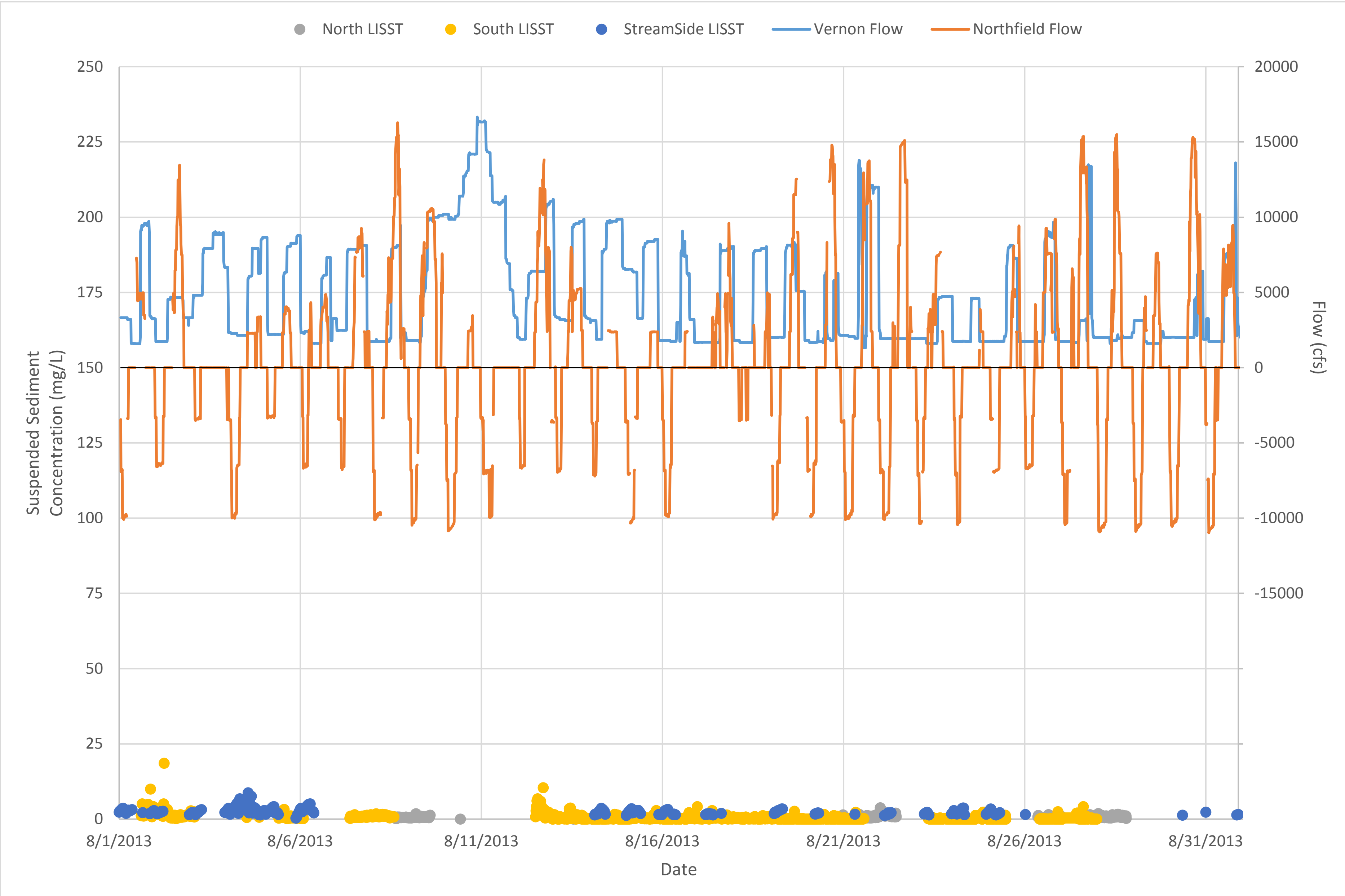
StreamSide LISST
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
Flow (cfs)
Date
200
175
150
125
100
75
50
25
0
60000
50000
40000
30000
20000
10000
0
-10000
-20000
5/1/2013
5/6/2013
5/11/2013
5/16/2013
5/21/2013
5/26/2013
5/31/2013



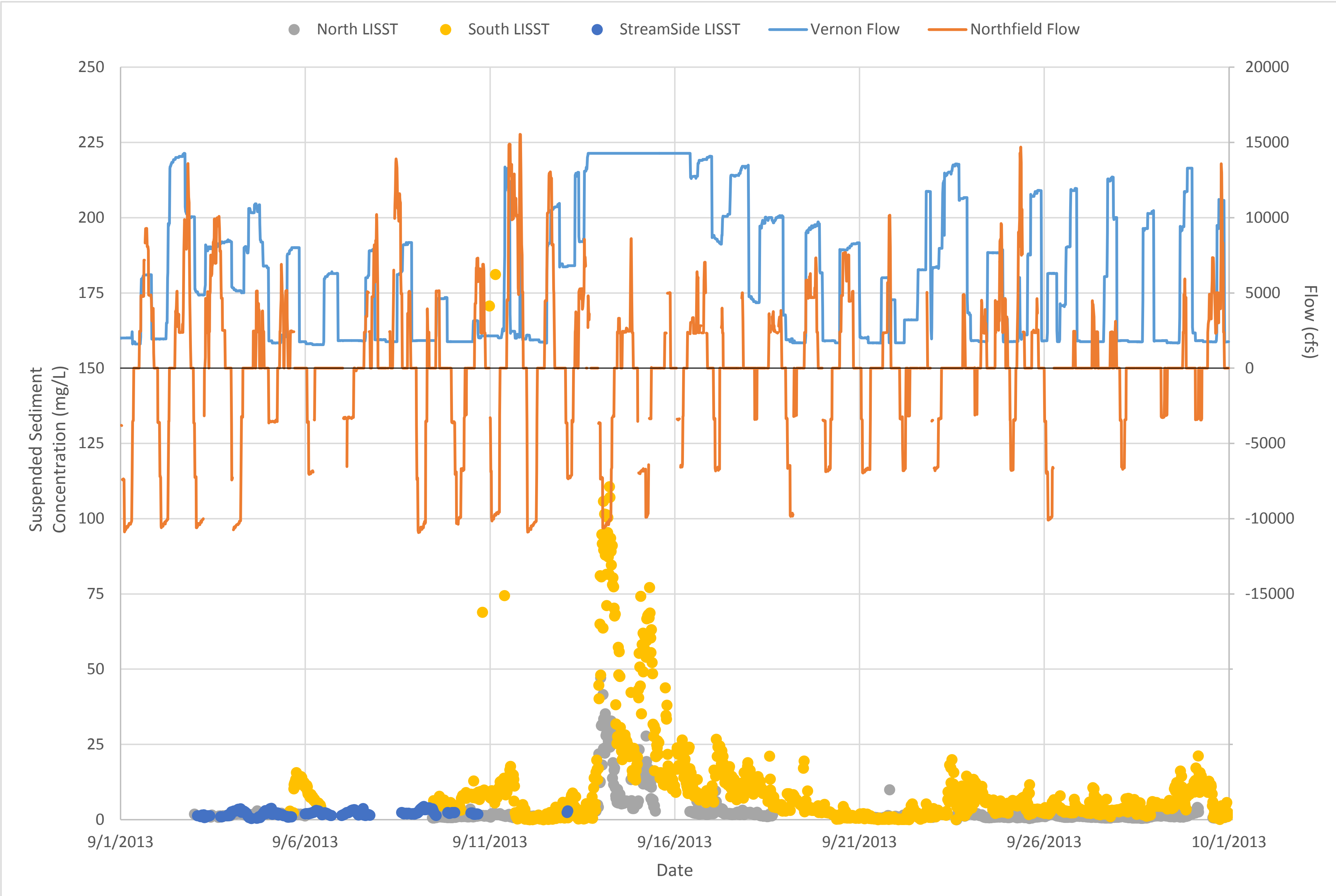
StreamSide LISST
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
Flow (cfs)
Date
200
175
150
125
100
75
50
25
0
60000
50000
40000
30000
20000
10000
0
-10000
-20000
6/1/2013
6/6/2013
6/11/2013
6/16/2013
6/21/2013
6/26/2013
7/1/2013

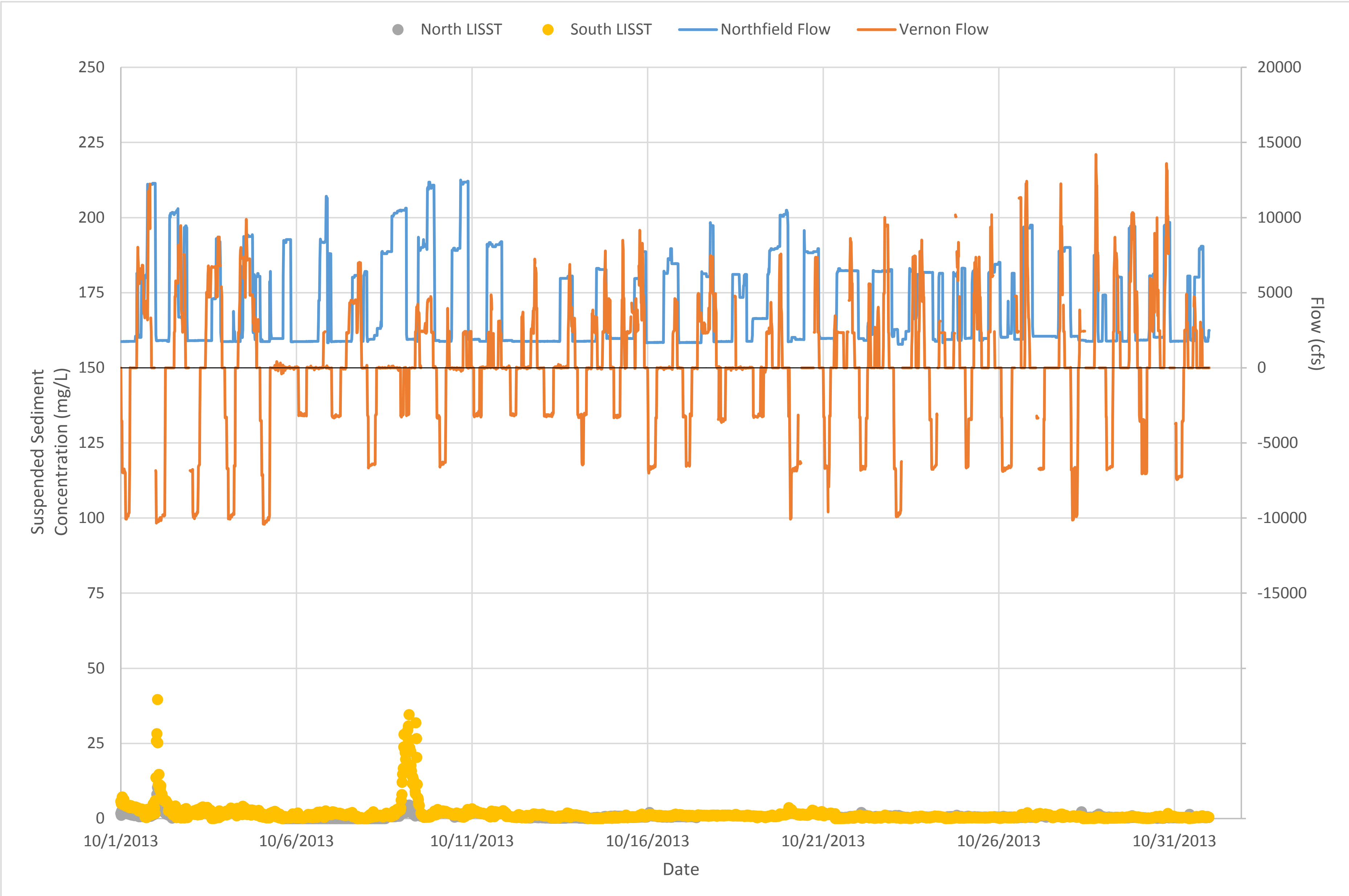


StreamSide LISST
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
Flow (cfs)
Date
0
25
50
75
100
125
150
175
200
60000
50000
40000
30000
20000
10000
0
-10000
-20000
7/1/2013
7/6/2013
7/11/2013
7/16/2013
7/21/2013
7/26/2013
7/31/2013

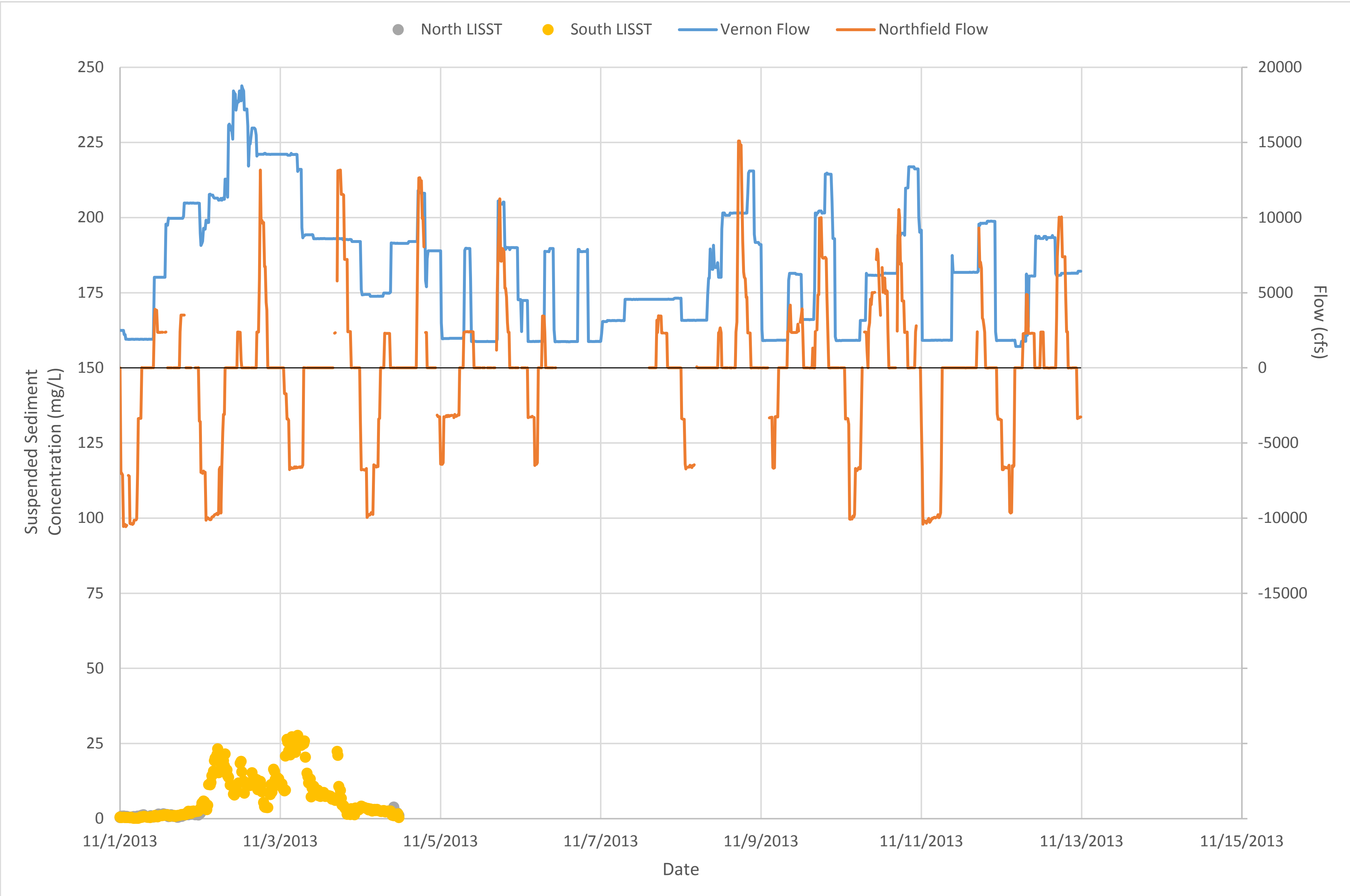


North LISST
South LISST
StreamSide LISST
Vernon Flow
Northfield Flow
250
225
200
175
150
125
100
75
50
25
0
20000
15000
10000
5000
0
-5000
-10000
-15000
Suspended Sediment Concentration (mg/L)
Flow (cfs)
8/1/2013
8/6/2013
8/11/2013
8/16/2013
8/21/2013
8/26/2013
8/31/2013
Date


North LISST
South LISST
StreamSide LISST
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
250
225
200
175
150
125
100
75
50
25
0
Flow (cfs)
20000
15000
10000
5000
0
-5000
-10000
-15000
9/1/2013
9/6/2013
9/11/2013
9/16/2013
9/21/2013
9/26/2013
10/1/2013
Date

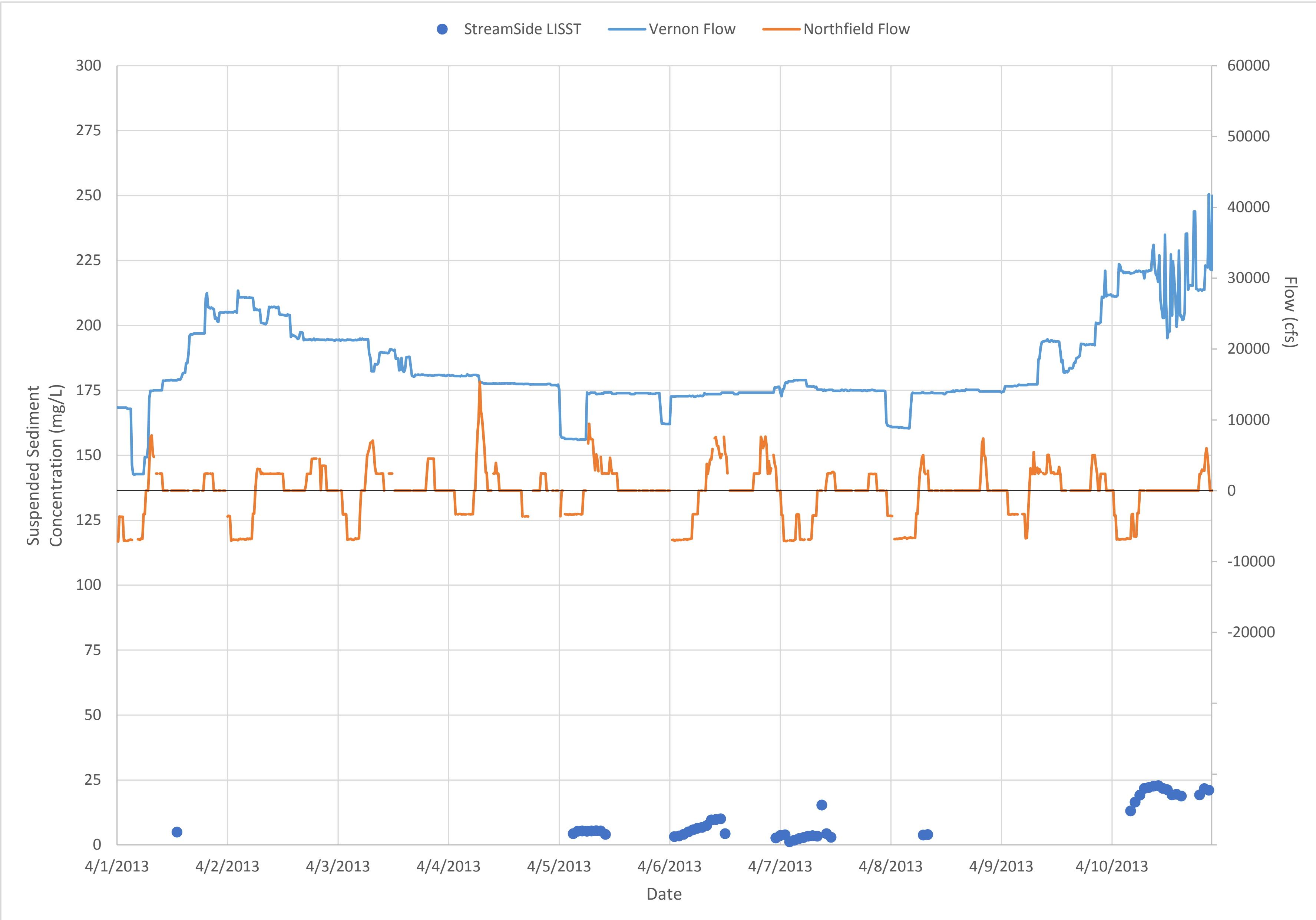


North LISST
South LISST
Northfield Flow
Vernon Flow
Suspended Sediment Concentration (mg/L)
250
225
200
175
150
125
100
75
50
25
0
Flow (cfs)
20000
15000
10000
5000
0
-5000
-10000
-15000
10/1/2013
10/6/2013
10/11/2013
10/16/2013
10/21/2013
10/26/2013
10/31/2013
Date

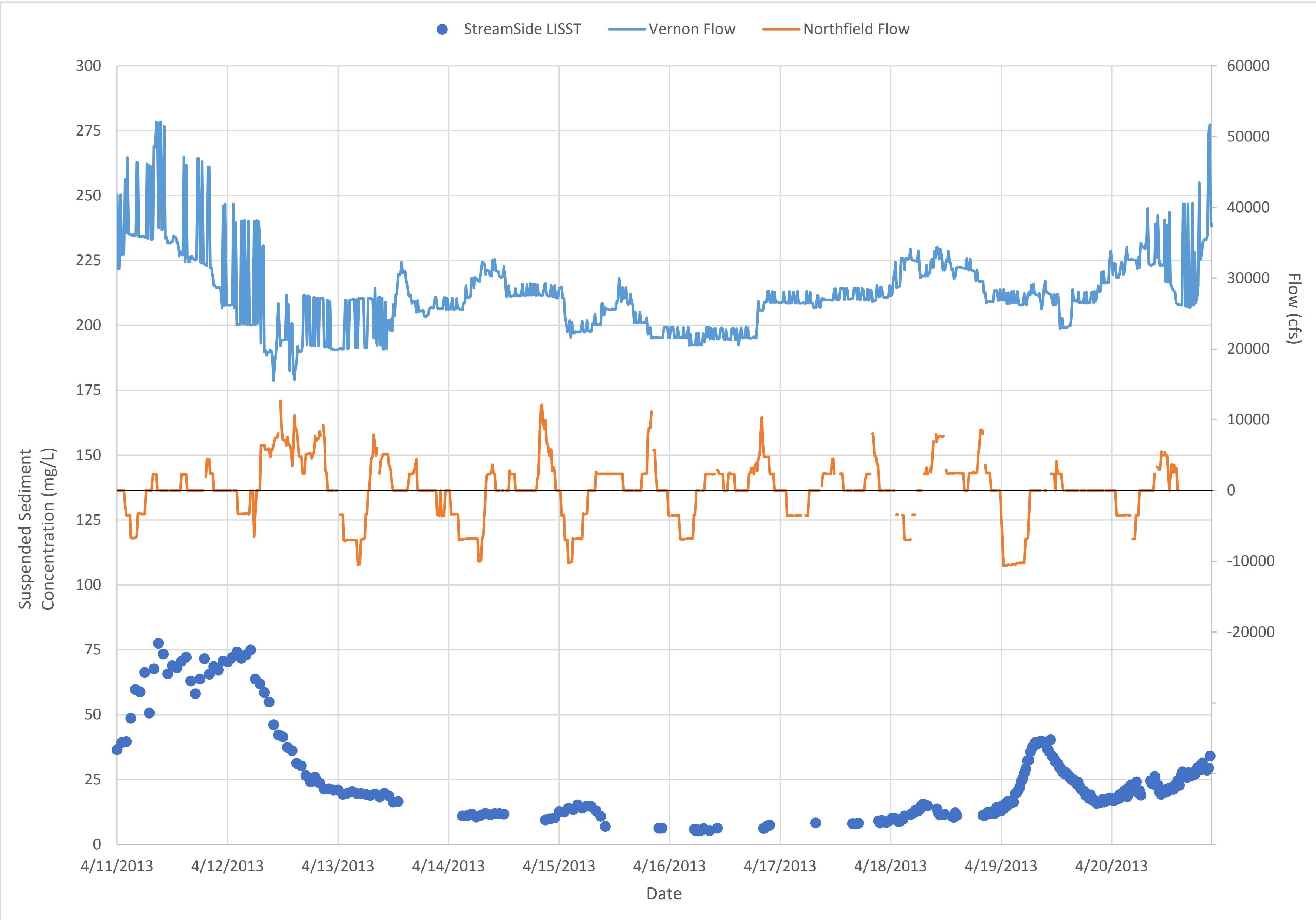


North LISST
South LISST
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
Flow (cfs)
Date
250
225
200
175
150
125
100
75
50
25
0
20000
15000
10000
5000
0
-5000
-10000
-15000
11/1/2013
11/3/2013
11/5/2013
11/7/2013
11/9/2013
11/11/2013
11/13/2013
11/15/2013

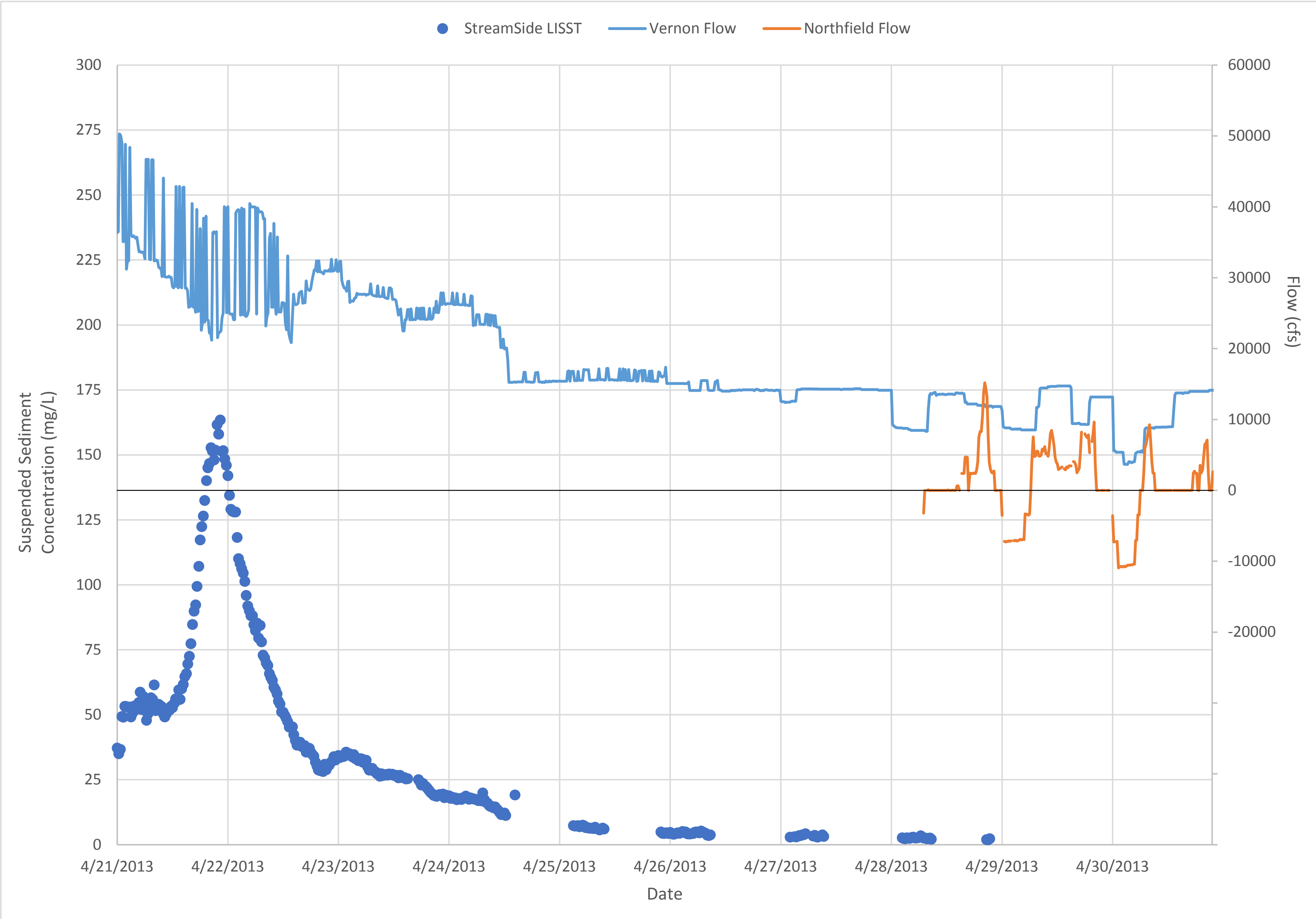
2013 CONTINUOUS LISST INSTRUMENT TIMESERIES-10 DAY



StreamSide LISST
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
Flow (cfs)
Date
0
25
50
75
100
125
150
175
200
225
250
275
300
60000
50000
40000
30000
20000
10000
0
-10000
-20000
4/1/2013
4/2/2013
4/3/2013
4/4/2013
4/5/2013
4/6/2013
4/7/2013
4/8/2013
4/9/2013
4/10/2013



StreamSide LISST
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
Flow (cfs)
Date
300
275
250
225
200
175
150
125
100
75
50
25
0
60000
50000
40000
30000
20000
10000
0
-10000
-20000
4/11/2013
4/12/2013
4/13/2013
4/14/2013
4/15/2013
4/16/2013
4/17/2013
4/18/2013
4/19/2013
4/20/2013



StreamSide LISST
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
Flow (cfs)
Date
300
275
250
225
200
175
150
125
100
75
50
25
0
60000
50000
40000
30000
20000
10000
0
-10000
-20000
4/21/2013
4/22/2013
4/23/2013
4/24/2013
4/25/2013
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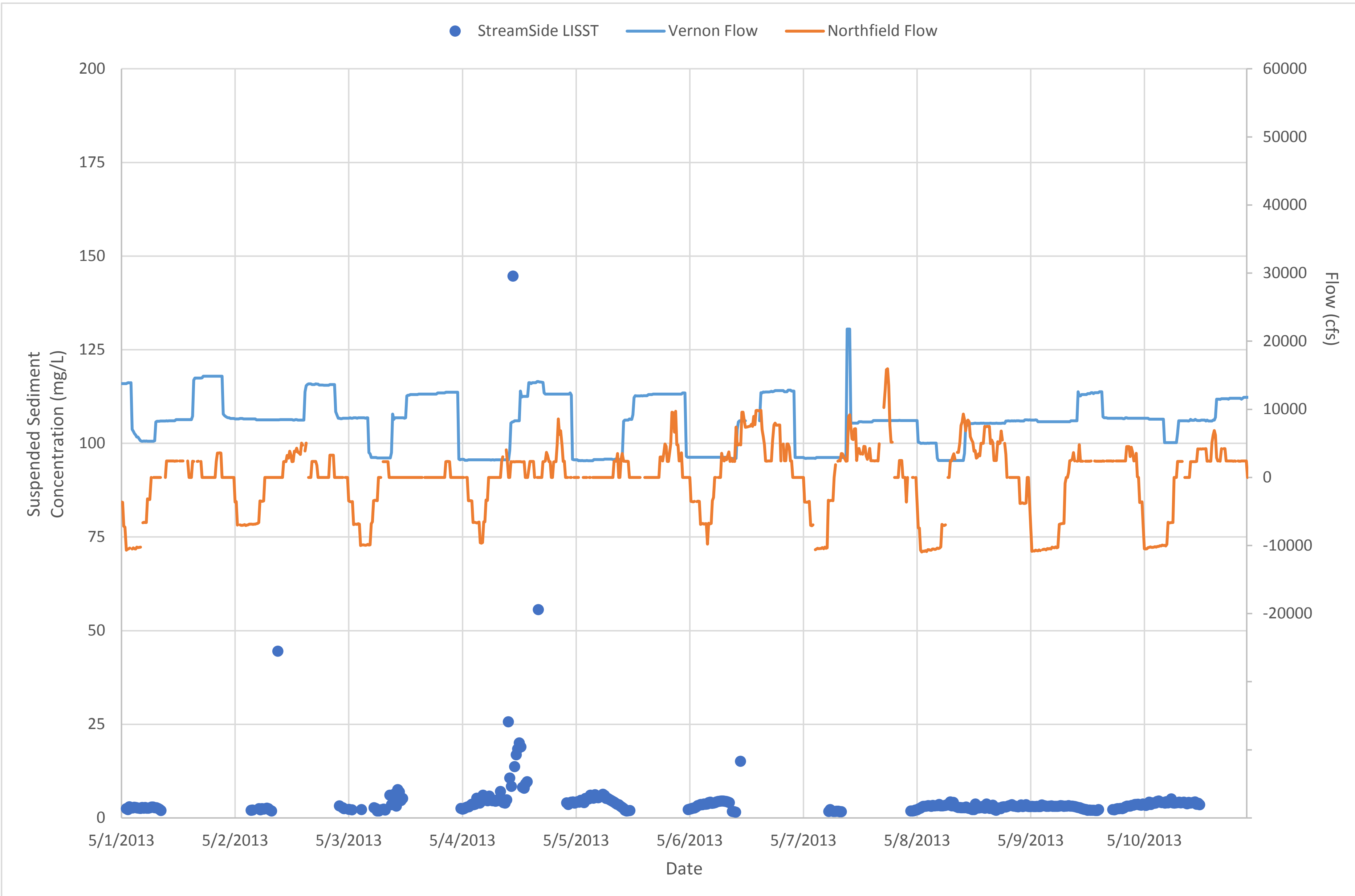
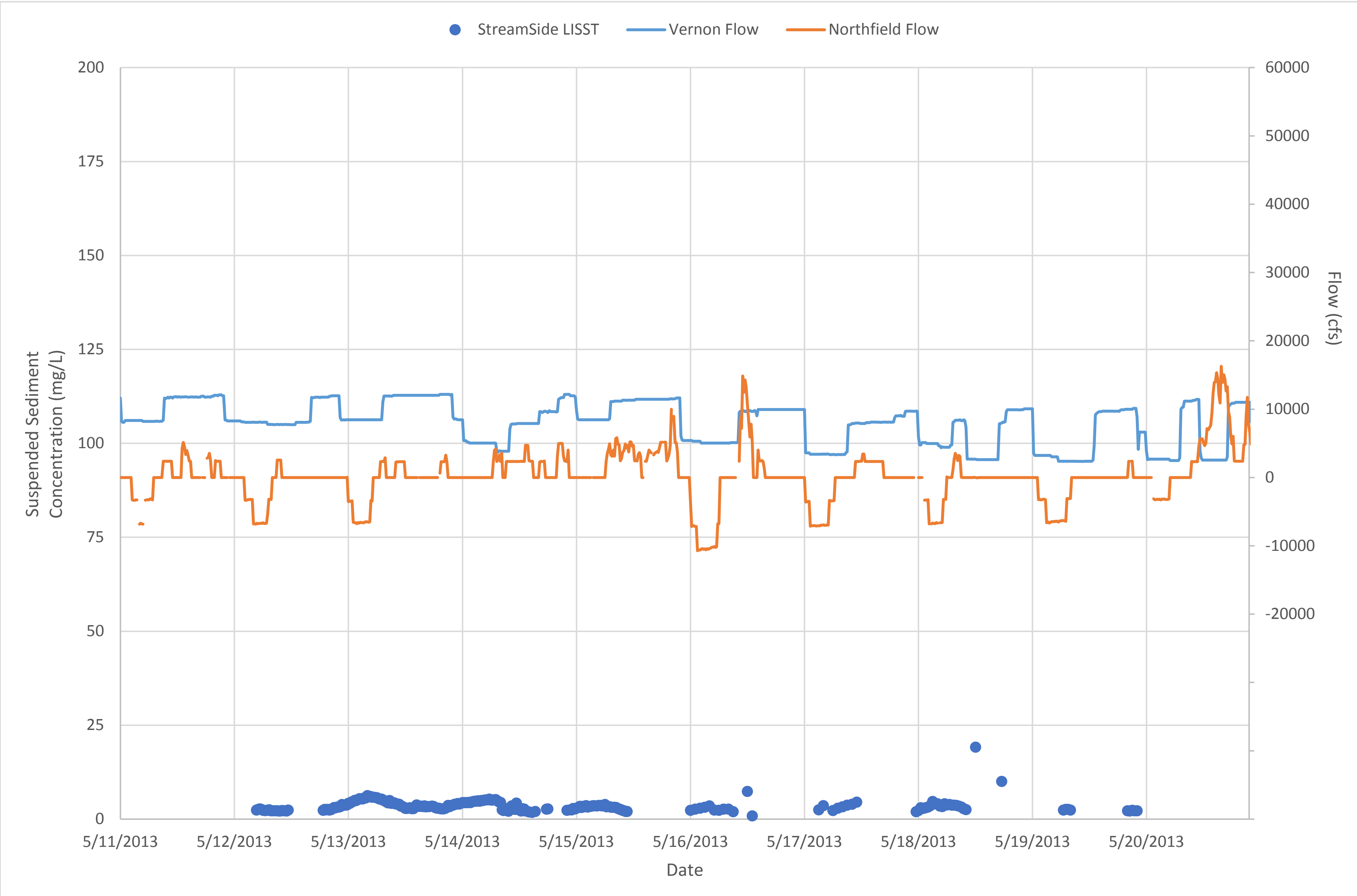
4/29/2013
4/30/2013



StreamSide LISST
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
Flow (cfs)
Date
200
175
150
125
100
75
50
25
0
60000
50000
40000
30000
20000
10000
0
-10000
-20000
5/1/2013
5/2/2013
5/3/2013
5/4/2013
5/5/2013
5/6/2013
5/7/2013
5/8/2013
5/9/2013
5/10/2013



StreamSide LISST
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
Flow (cfs)
Date
200
175
150
125
100
75
50
25
0
60000
50000
40000
30000
20000
10000
0
-10000
-20000
5/11/2013
5/12/2013
5/13/2013
5/14/2013
5/15/2013
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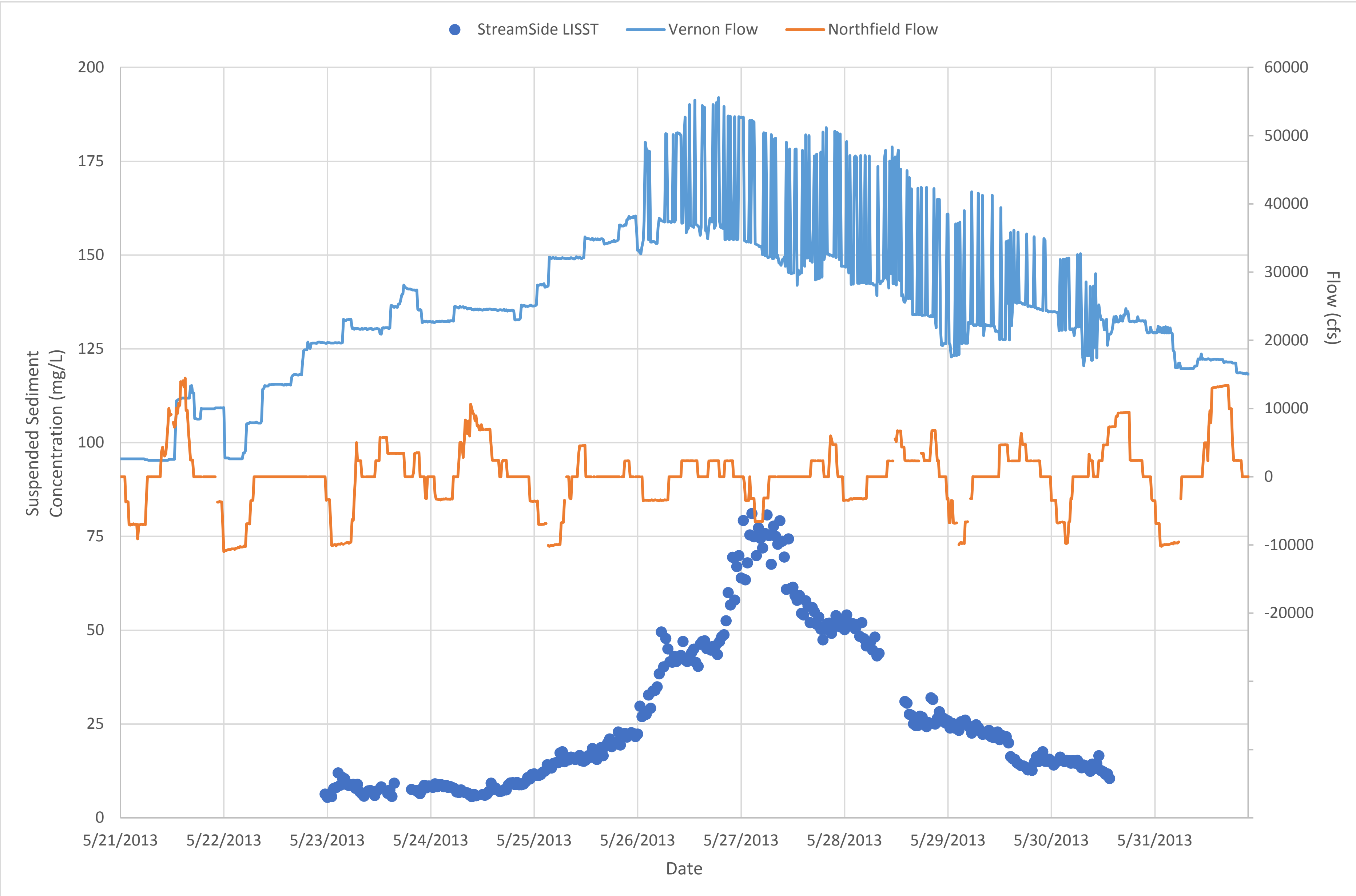
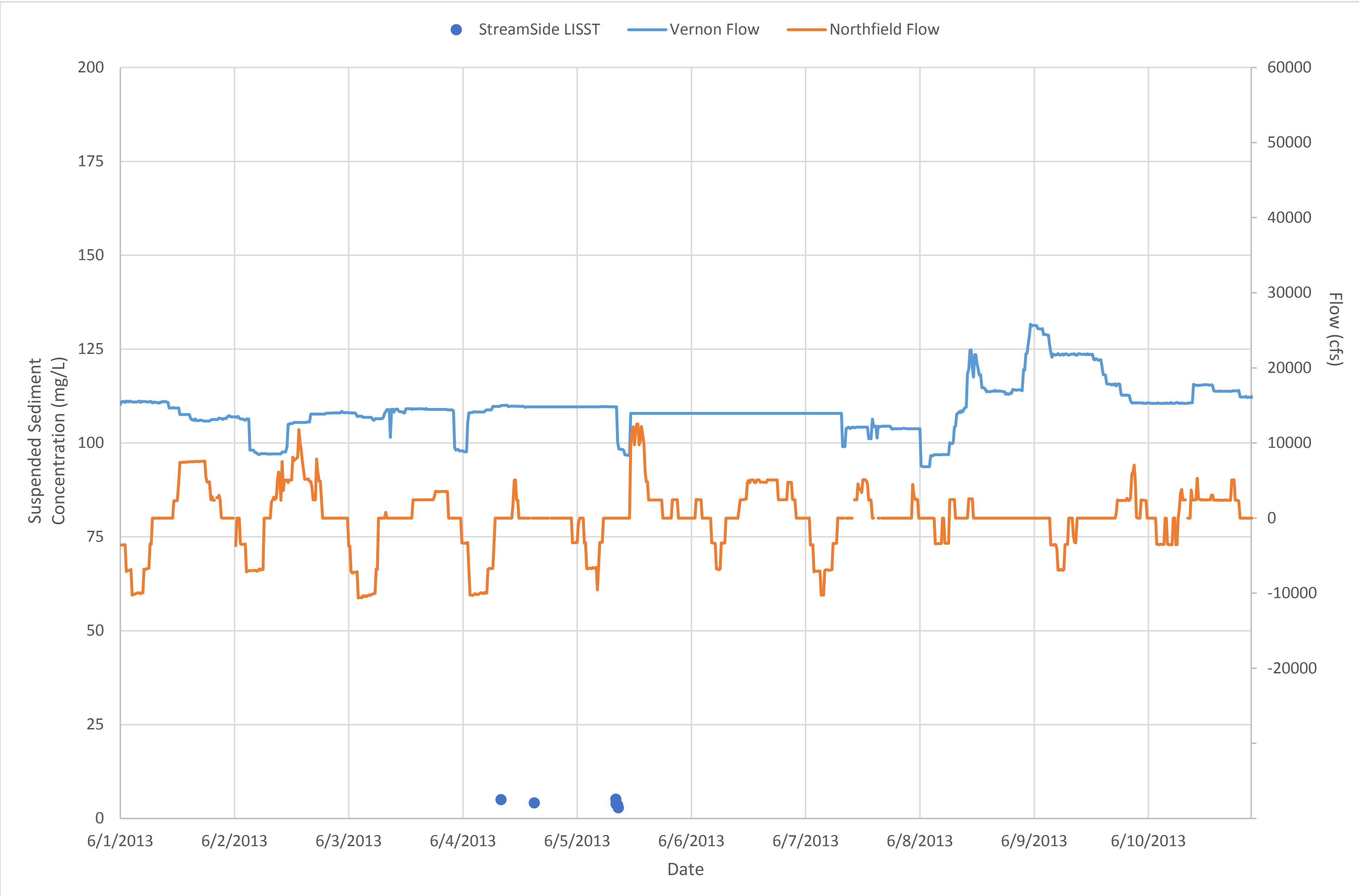
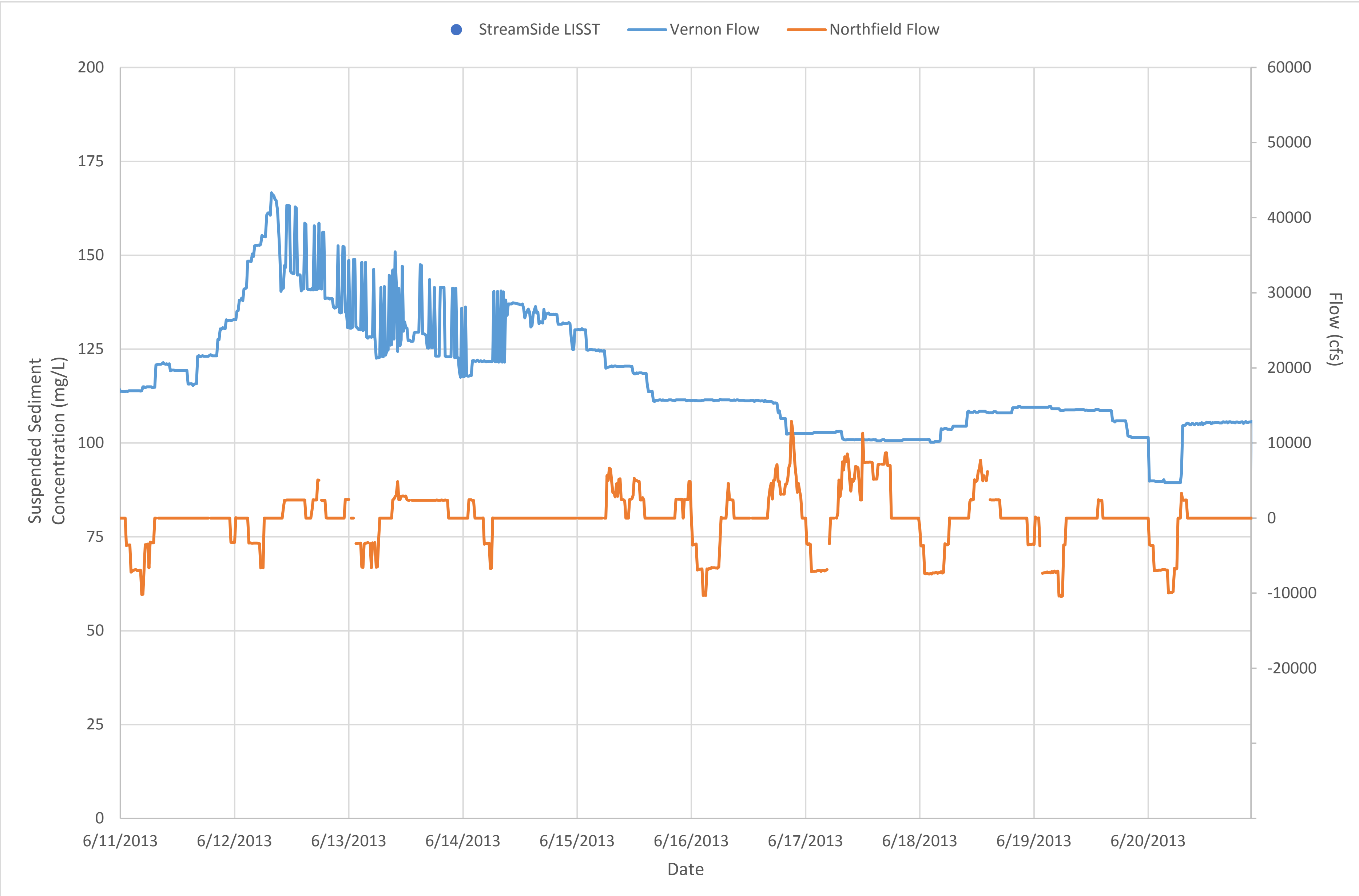
5/19/2013
5/20/2013


StreamSide LISST
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
200
175
150
125
100
75
50
25
0
60000
50000
40000
30000
20000
10000
0
-10000
-20000
Flow (cfs)
5/21/2013
5/22/2013
5/23/2013
5/24/2013
5/25/2013
5/26/2013
5/27/2013
5/28/2013
5/29/2013
5/30/2013
5/31/2013
Date



StreamSide LISST
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
200
175
150
125
100
75
50
25
0
Flow (cfs)
60000
50000
40000
30000
20000
10000
0
-10000
-20000
6/1/2013
6/2/2013
6/3/2013
6/4/2013
6/5/2013
6/6/2013
6/7/2013
6/8/2013
6/9/2013
6/10/2013
Date



StreamSide LISST
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
Flow (cfs)
Date
200
175
150
125
100
75
50
25
0
60000
50000
40000
30000
20000
10000
0
-10000
-20000
6/11/2013
6/12/2013
6/13/2013
6/14/2013
6/15/2013
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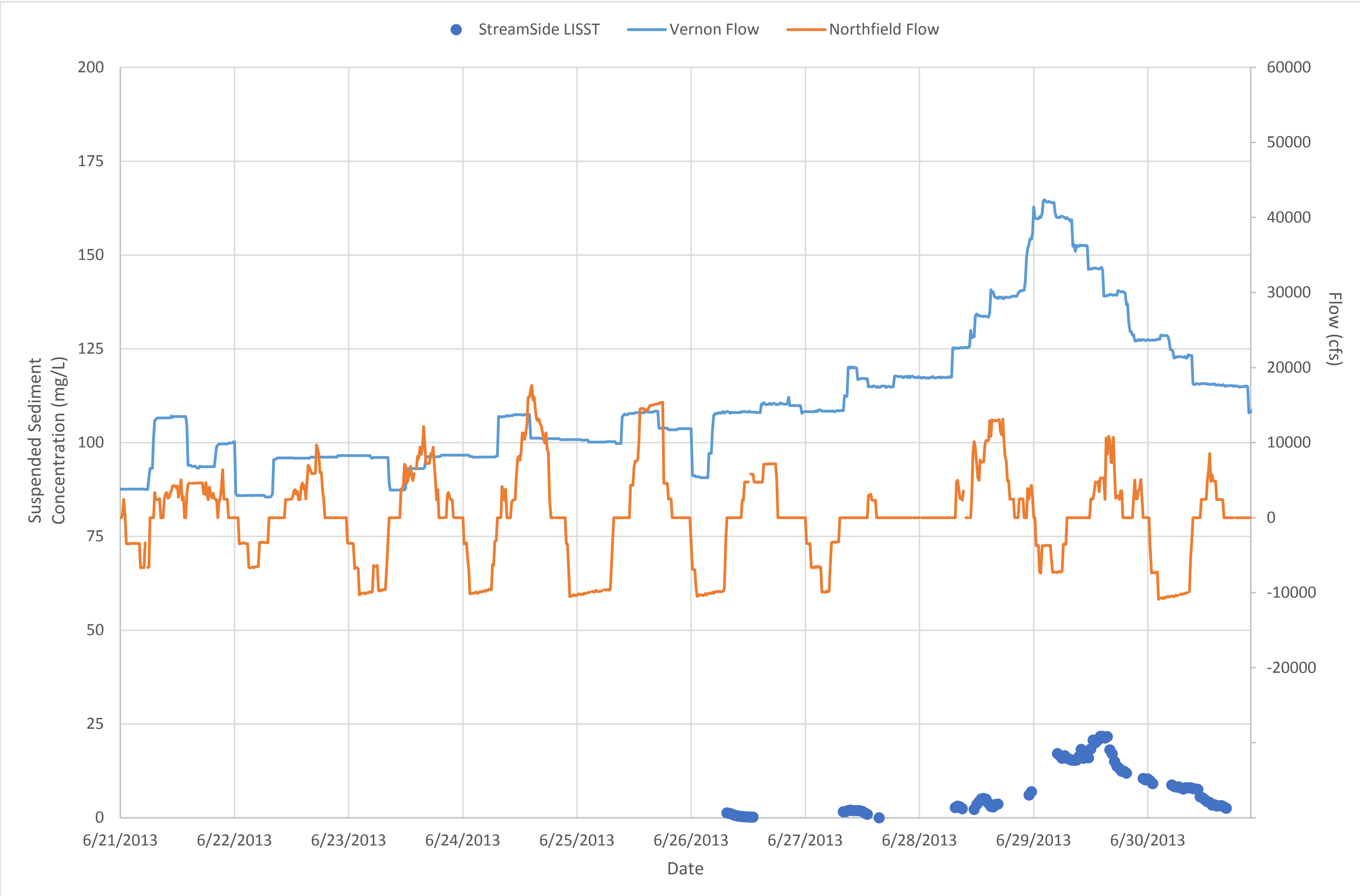
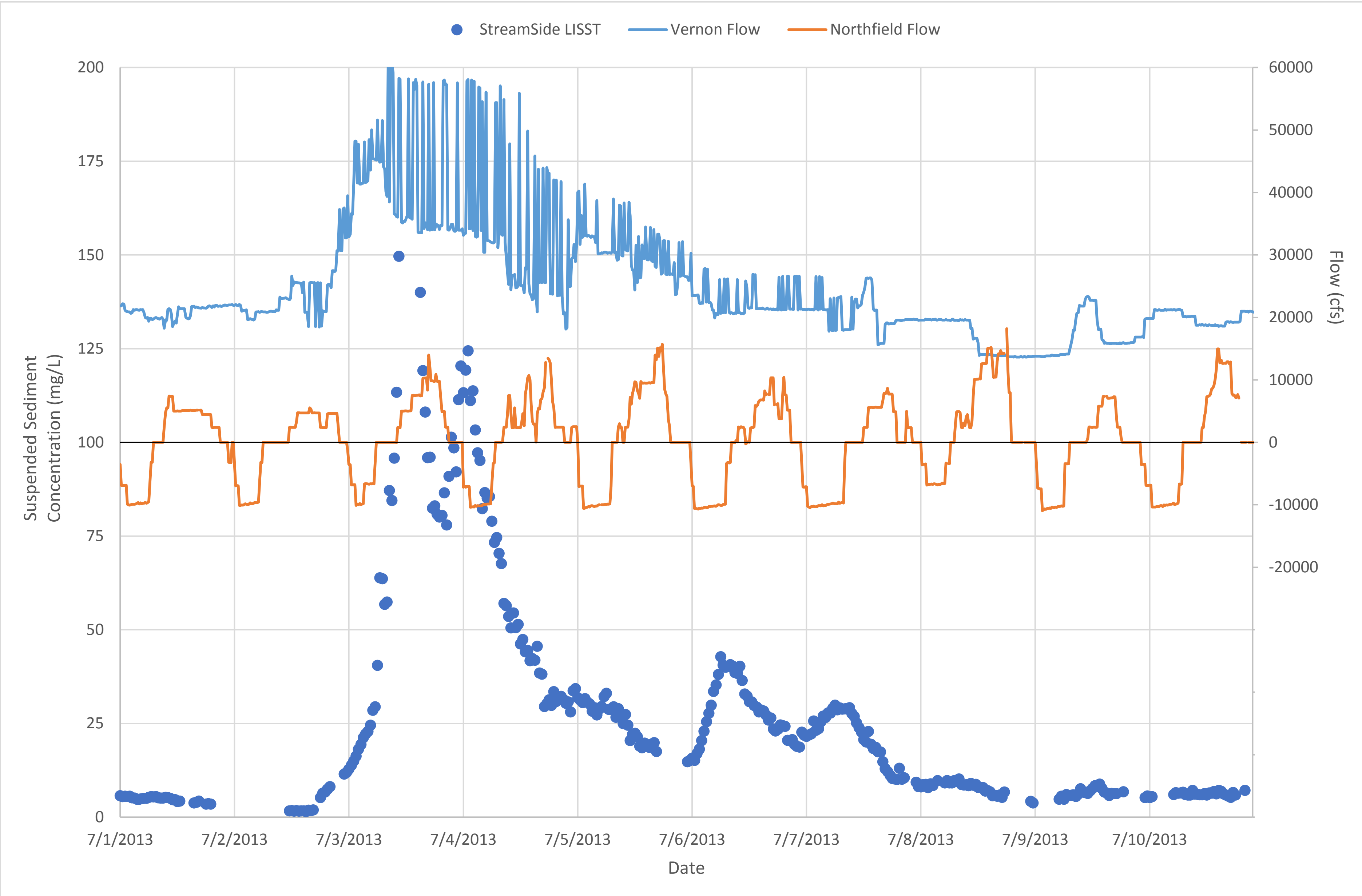
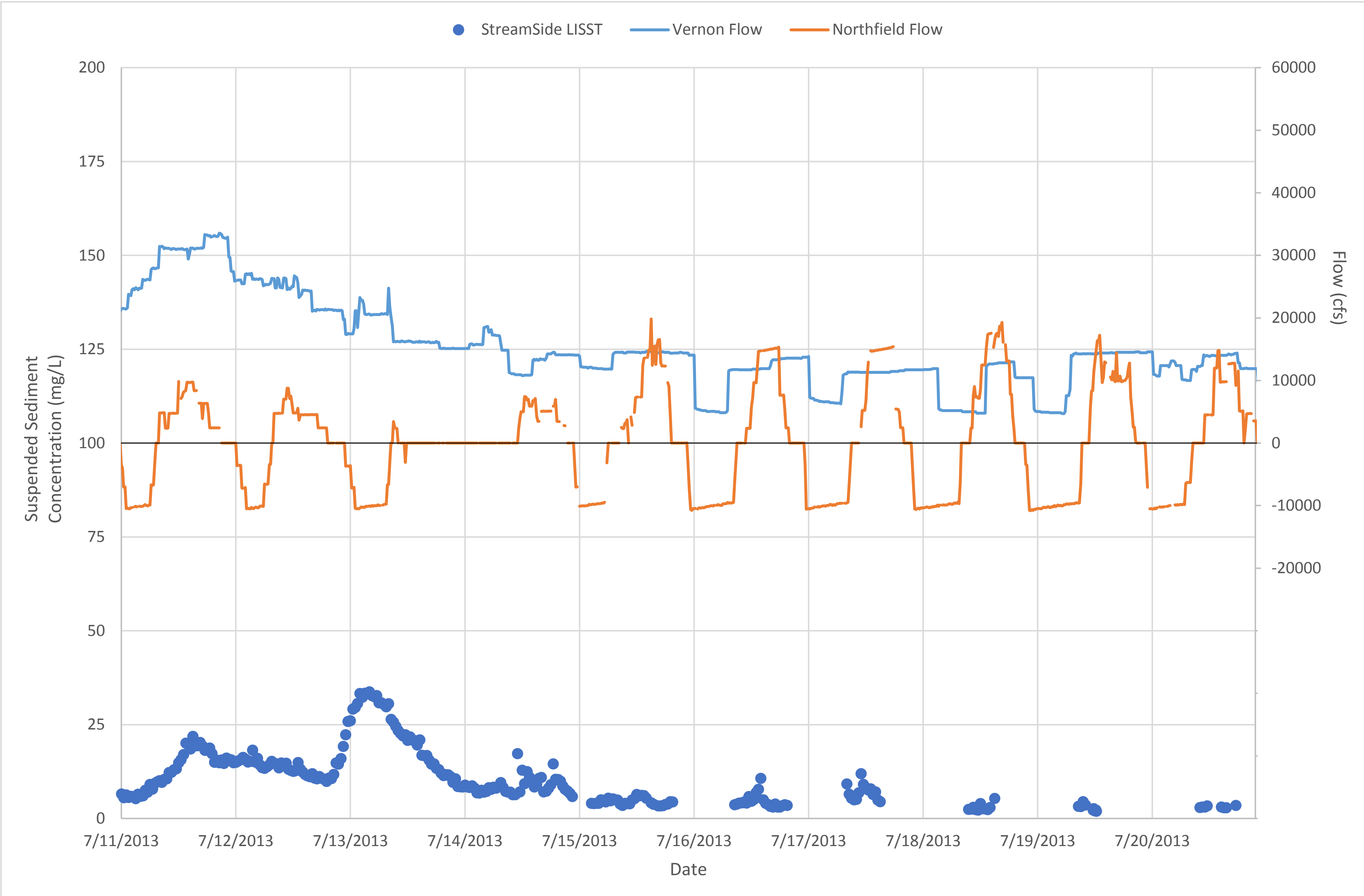
6/18/2013
6/19/2013
6/20/2013



StreamSide LISST
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
200
175
150
125
100
75
50
25
0
Flow (cfs)
60000
50000
40000
30000
20000
10000
0
-10000
-20000
6/21/2013
6/22/2013
6/23/2013
6/24/2013
6/25/2013
6/26/2013
6/27/2013
6/28/2013
6/29/2013
6/30/2013
Date


StreamSide LISST
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
Flow (cfs)
Date
200
175
150
125
100
75
50
25
0
60000
50000
40000
30000
20000
10000
0
-10000
-20000
7/1/2013
7/2/2013
7/3/2013
7/4/2013
7/5/2013
7/6/2013
7/7/2013
7/8/2013
7/9/2013
7/10/2013


StreamSide LISST
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
Flow (cfs)
Date
200
175
150
125
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75
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60000
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7/11/2013
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7/14/2013
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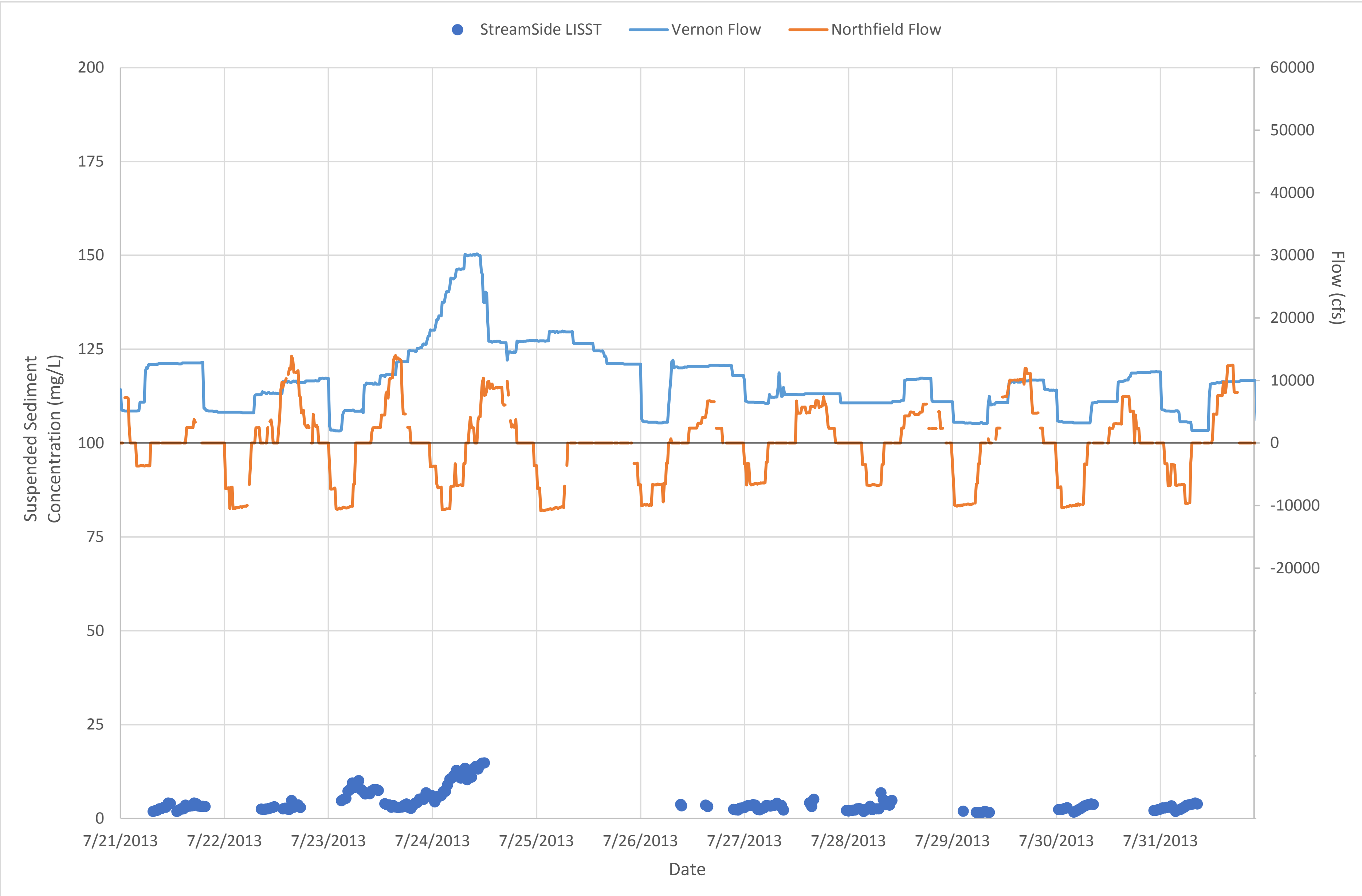
7/17/2013
7/18/2013
7/19/2013
7/20/2013


StreamSide LISST
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
Flow (cfs)
Date
200
175
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125
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75
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7/21/2013
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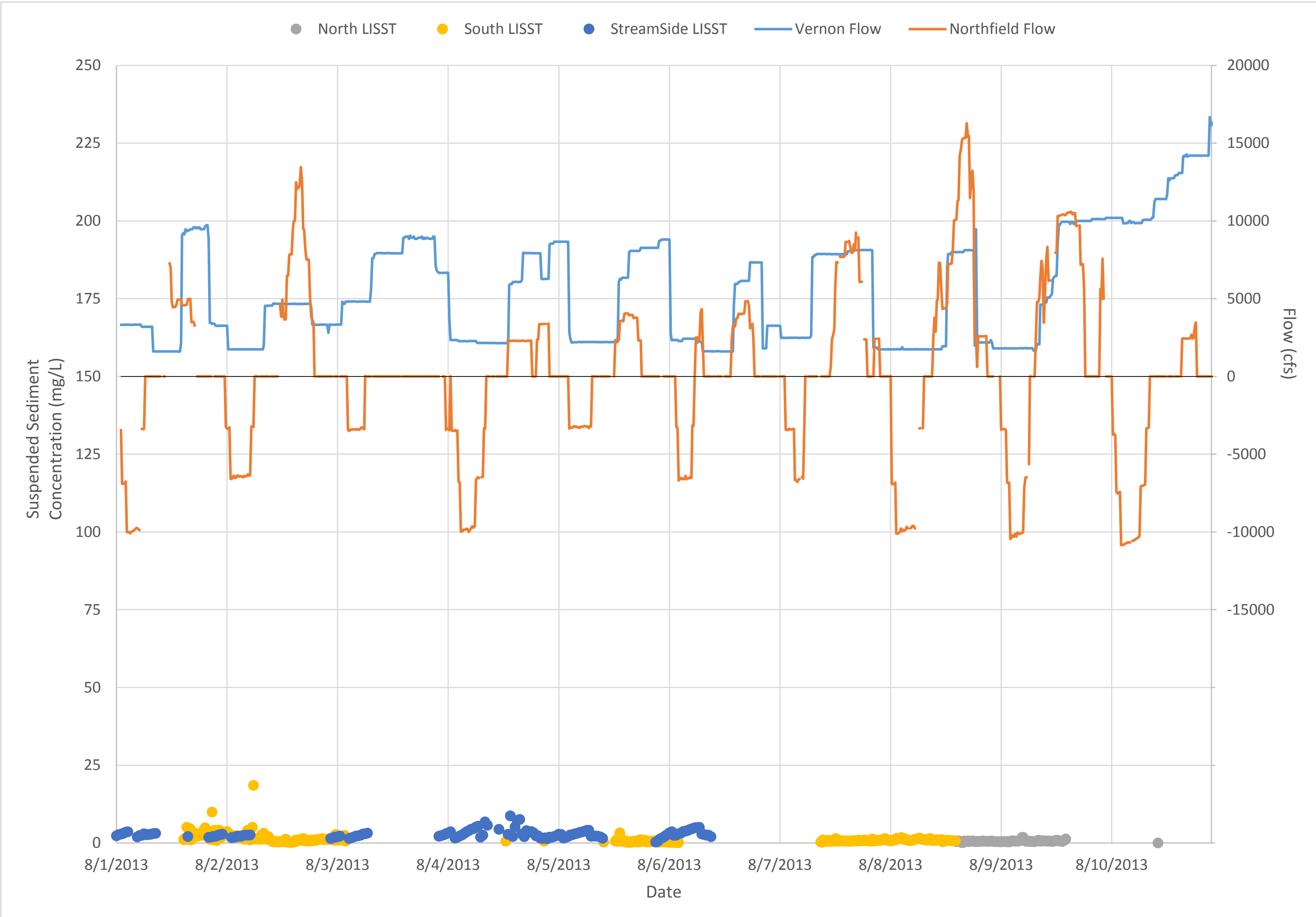
7/29/2013
7/30/2013
7/31/2013



North LISST
South LISST
StreamSide LISST
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
Flow (cfs)
Date
250
225
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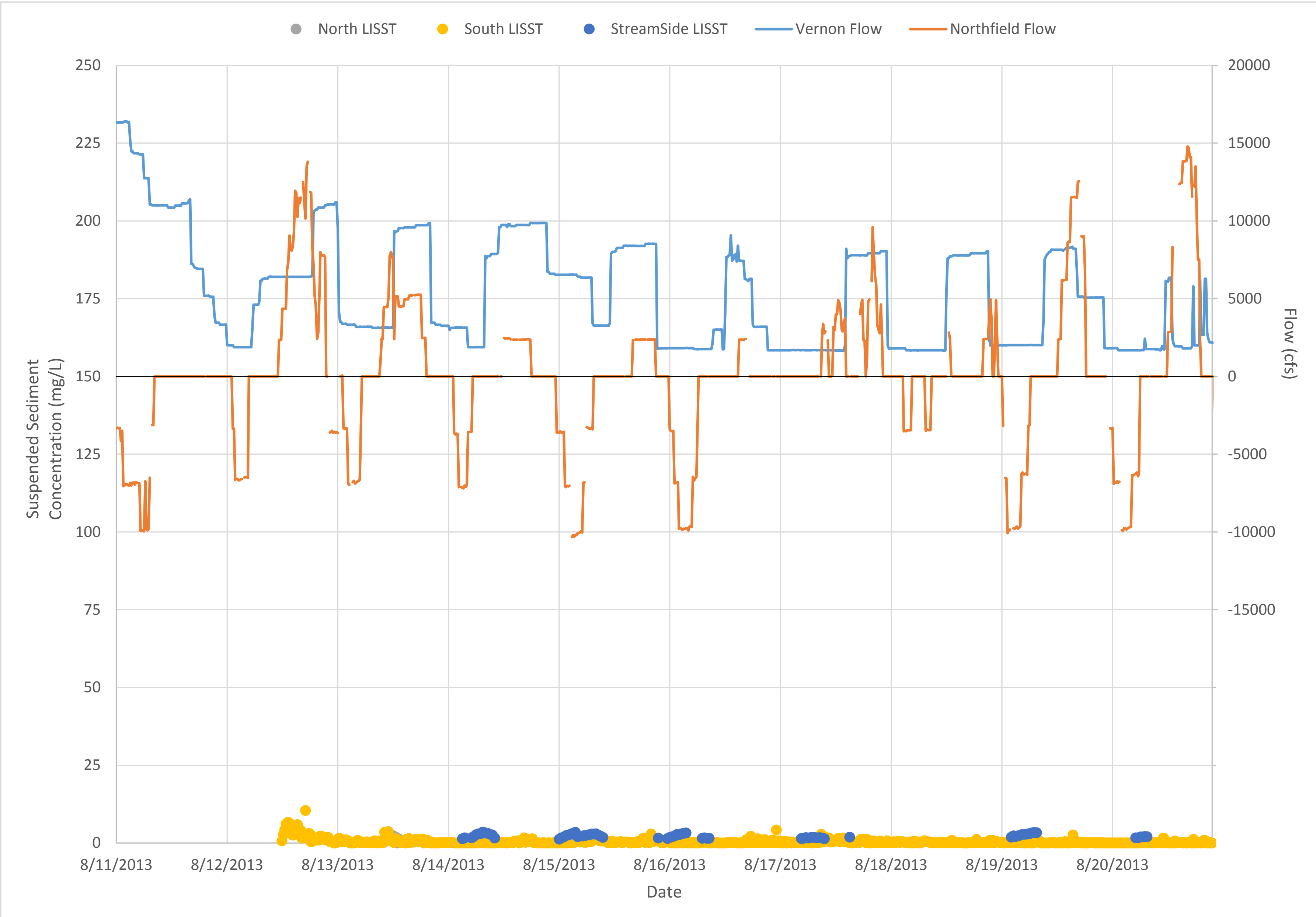
8/10/2013



North LISST
South LISST
StreamSide LISST
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
Flow (cfs)
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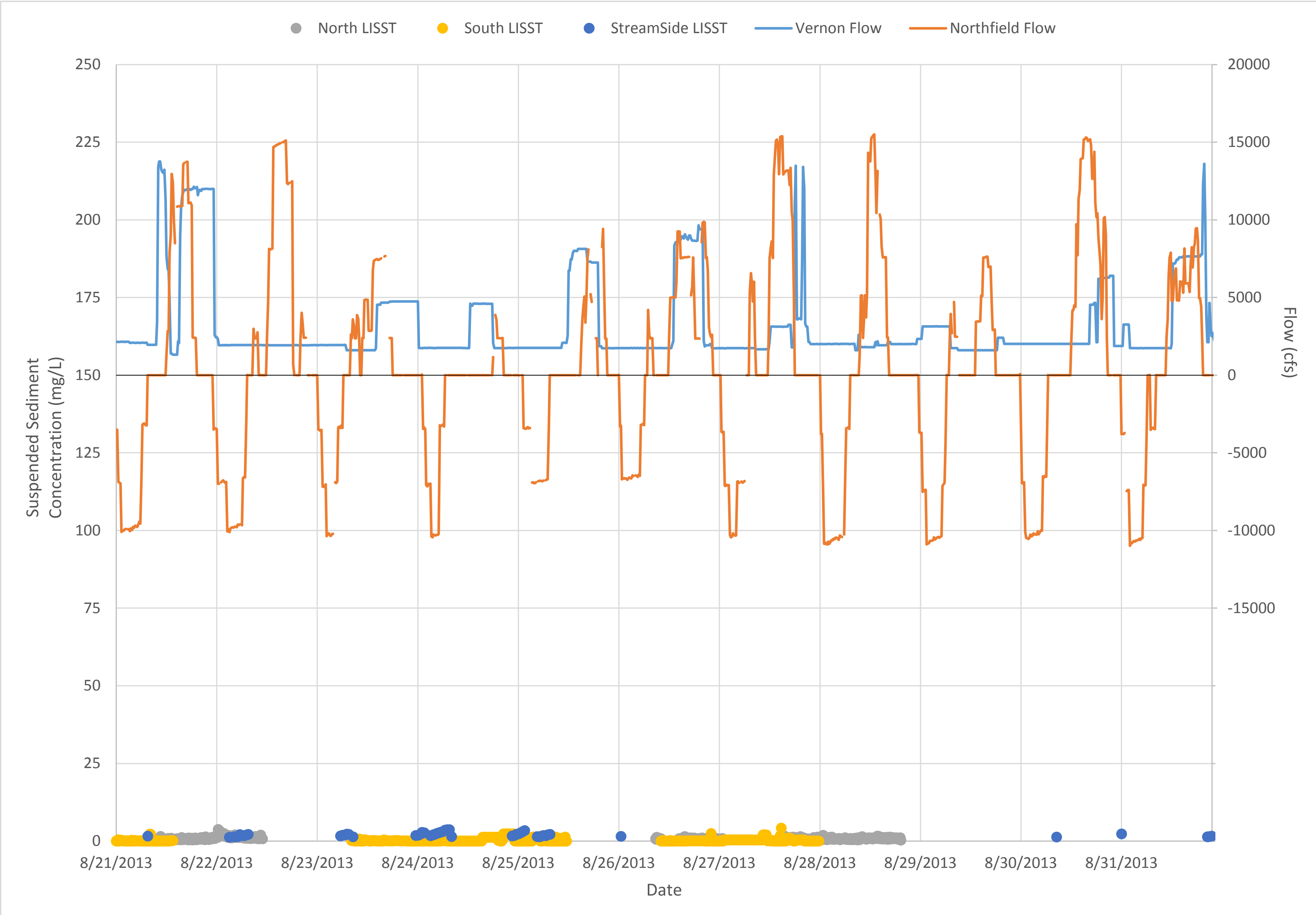
North LISST
South LISST
StreamSide LISST
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
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Flow (cfs)
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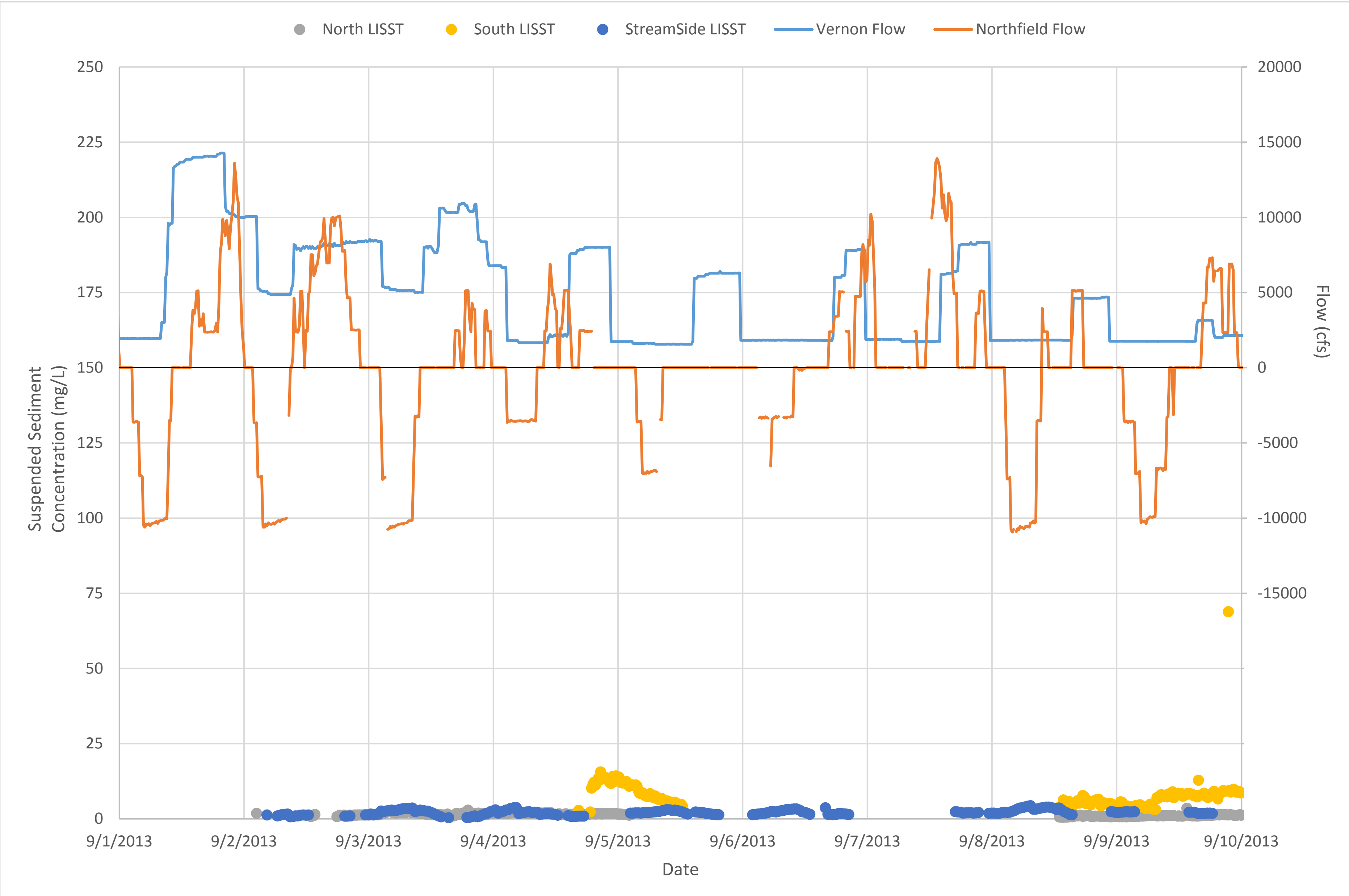
Date



North LISST
South LISST
StreamSide LISST
Vernon Flow
Northfield Flow
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Suspended Sediment Concentration (mg/L)
Flow (cfs)
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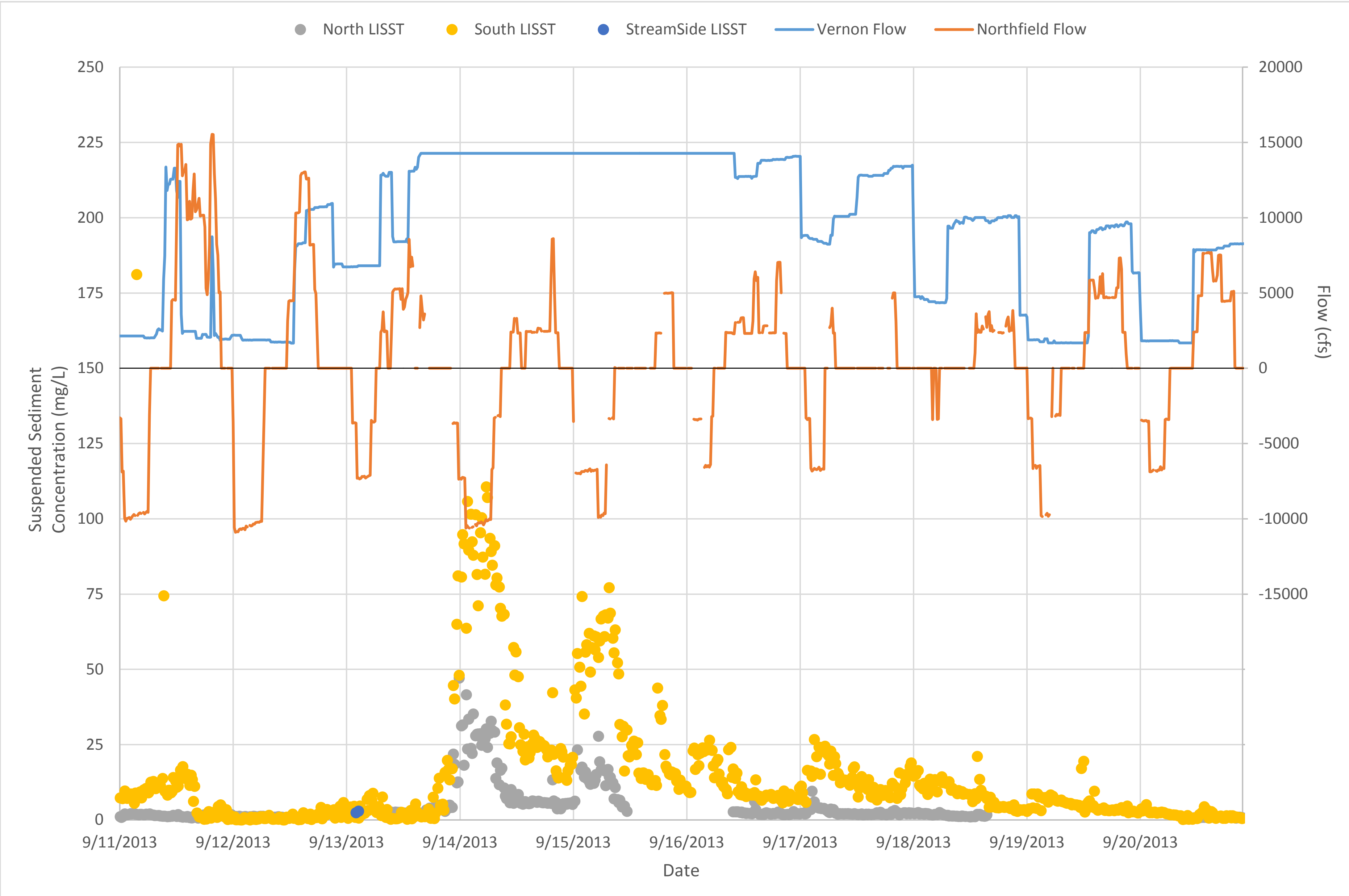
9/10/2013
Date



North LISST
South LISST
StreamSide LISST
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
Flow (cfs)
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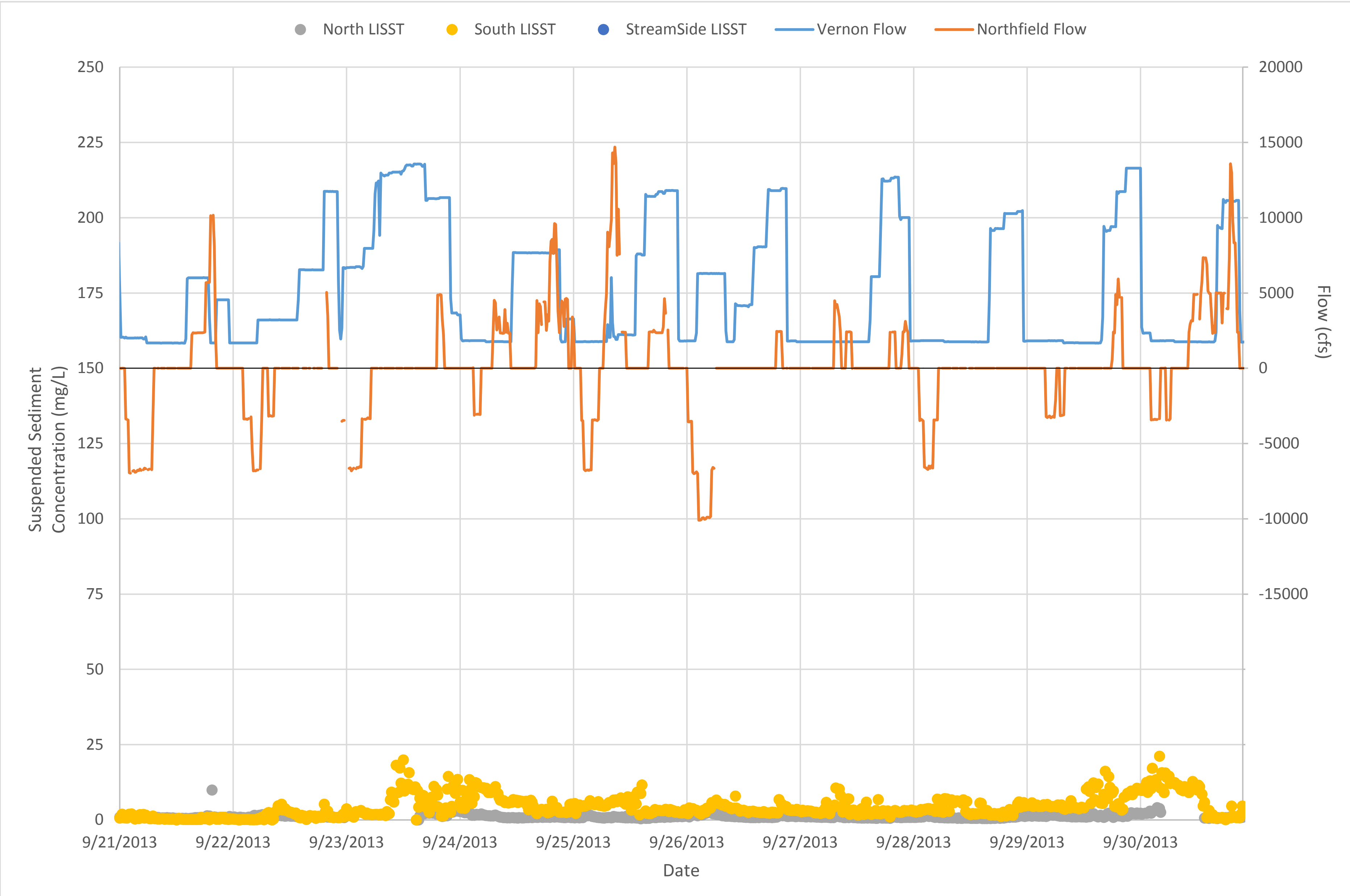
9/20/2013



North LISST
South LISST
StreamSide LISST
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
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Flow (cfs)
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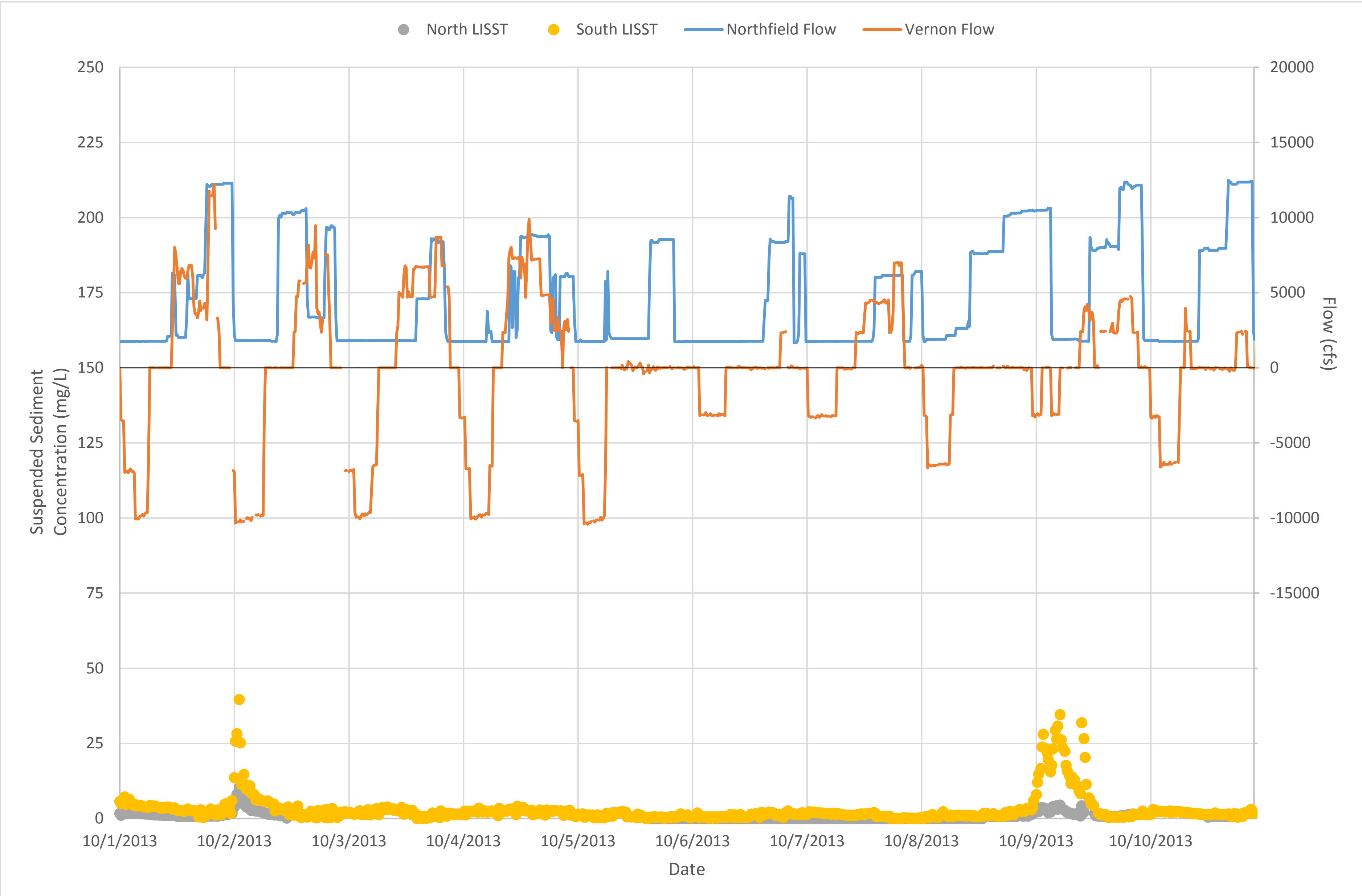
9/30/2013
Date



North LISST
South LISST
Northfield Flow
Vernon Flow
Suspended Sediment Concentration (mg/L)
Flow (cfs)
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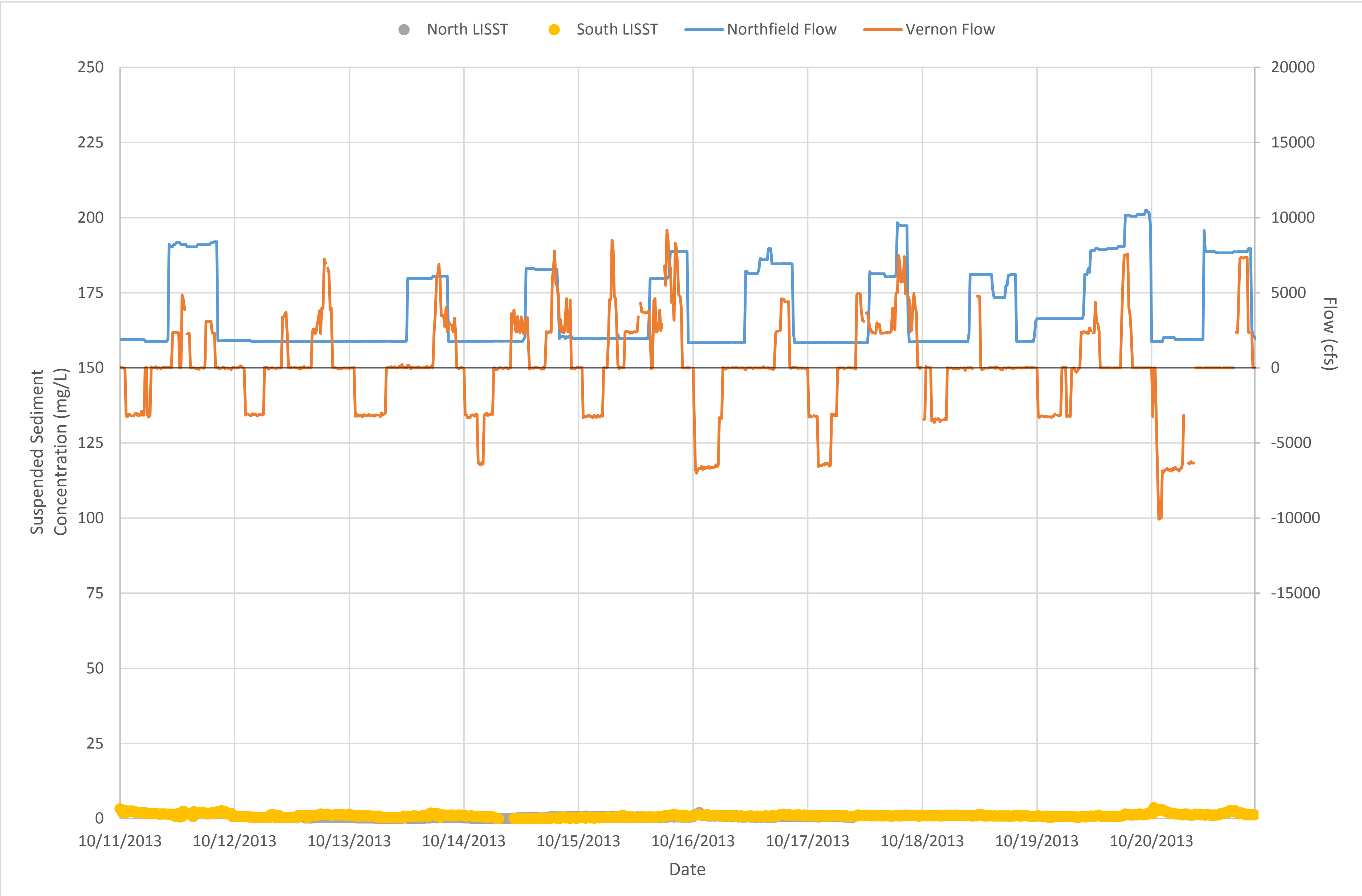
10/10/2013



North LISST
South LISST
Northfield Flow
Vernon Flow
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Suspended Sediment Concentration (mg/L)
Flow (cfs)
10/11/2013
10/12/2013
10/13/2013
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10/15/2013
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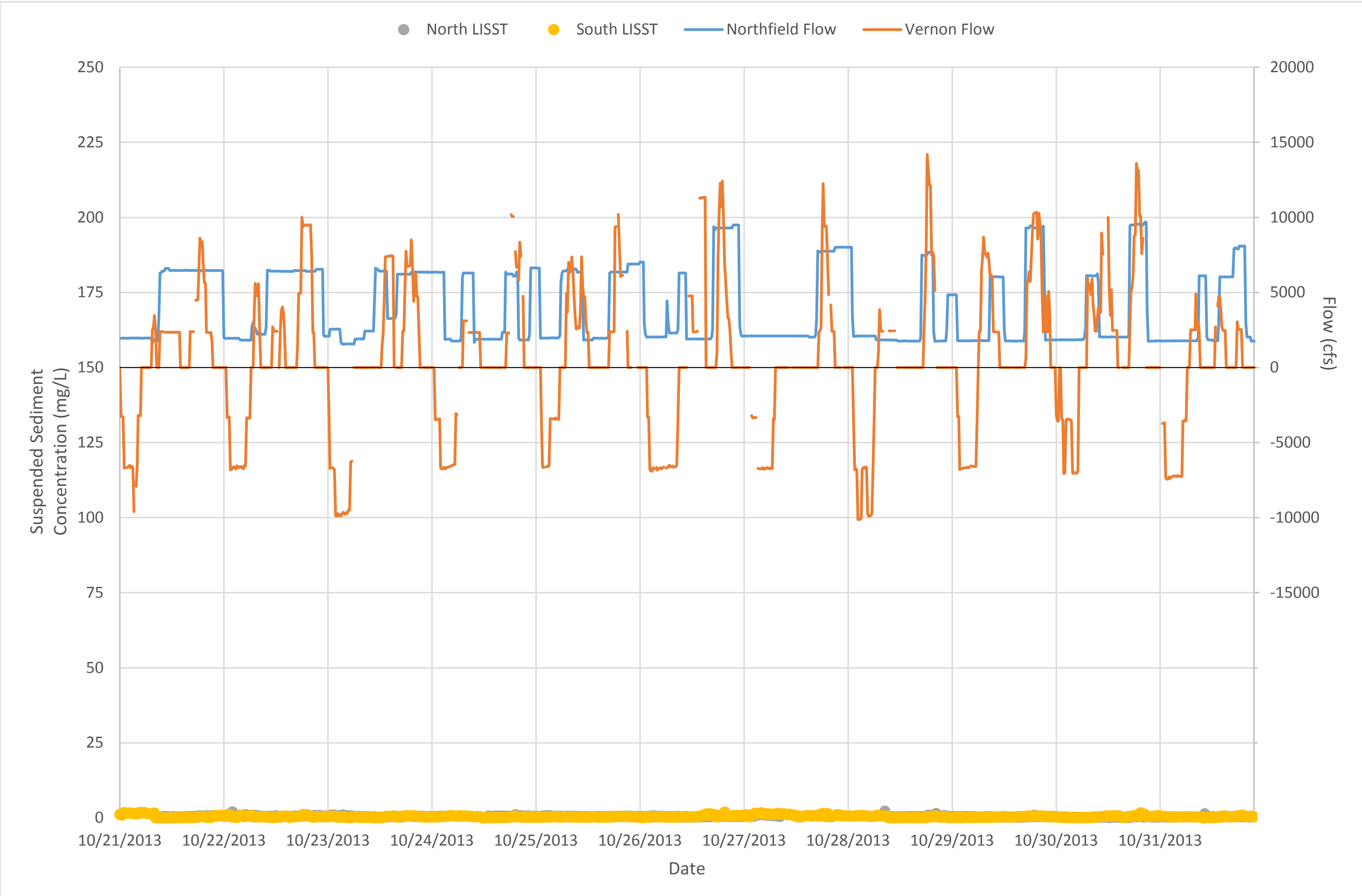
10/18/2013
10/19/2013
10/20/2013
Date



North LISST
South LISST
Northfield Flow
Vernon Flow
Suspended Sediment Concentration (mg/L)
250
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Flow (cfs)
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10/21/2013
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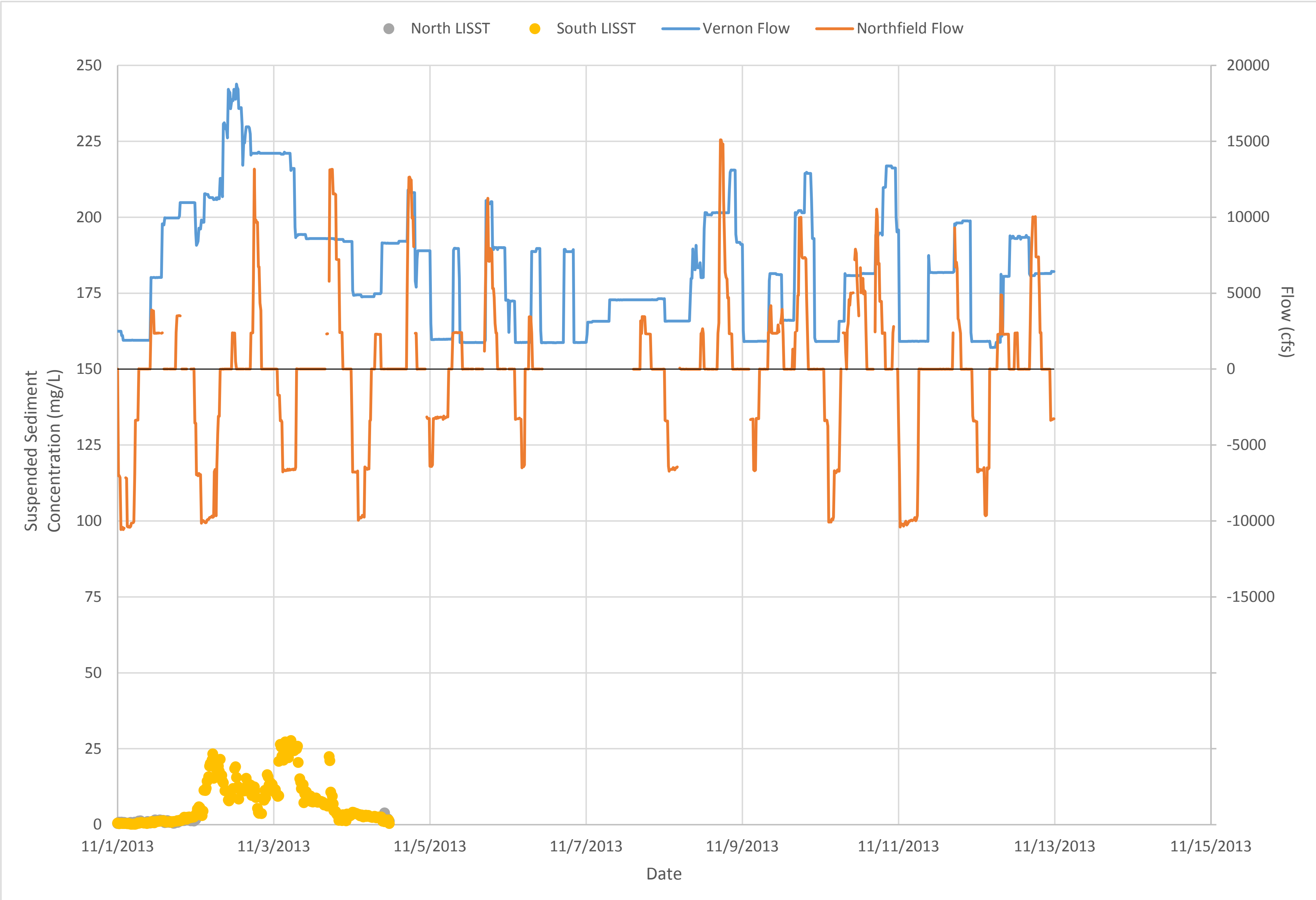
10/29/2013
10/30/2013
10/31/2013
Date



North LISST
South LISST
Vernon Flow
Northfield Flow
250
225
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175
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125
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25
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Suspended Sediment Concentration (mg/L)
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10000
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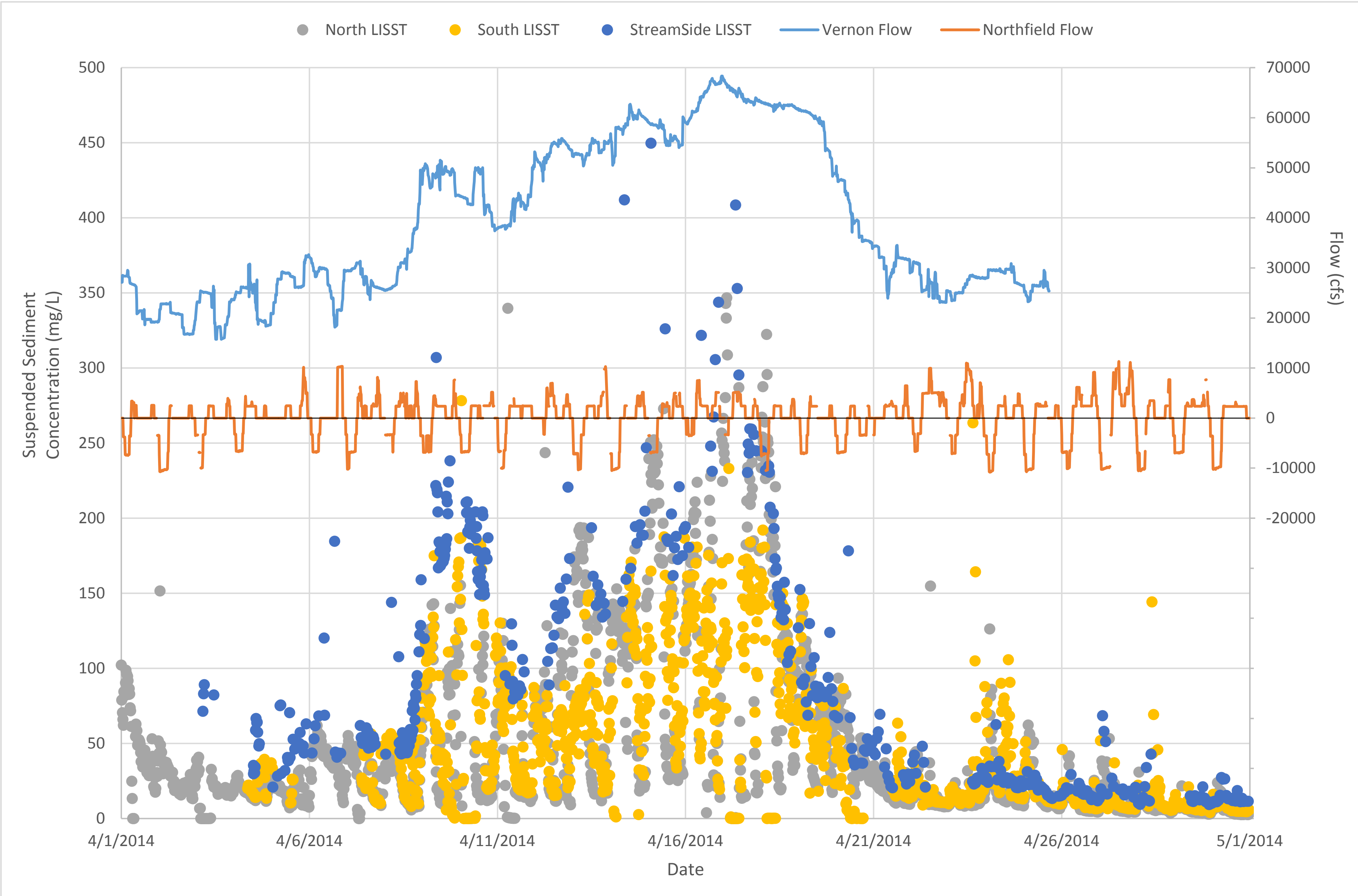
-15000
Flow (cfs)
11/1/2013
11/3/2013
11/5/2013
11/7/2013
11/9/2013
11/11/2013
11/13/2013
11/15/2013
Date

2014 CONTINUOUS LISST INSTRUMENT TIMESERIES-MONTHLY


North LISST
South LISST
StreamSide LISST
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
Flow (cfs)
500
450
400
350
300
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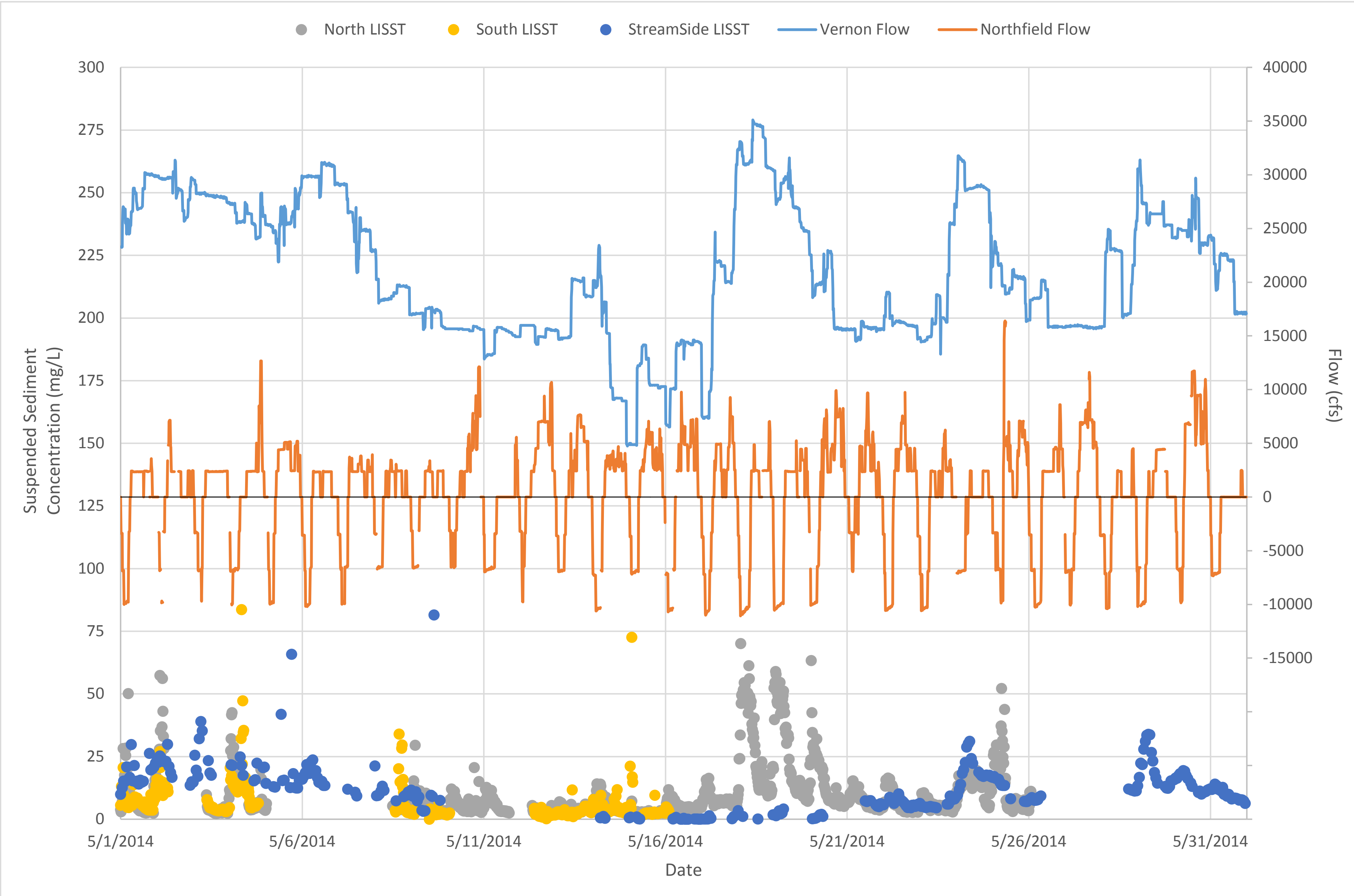
4/11/2014
4/16/2014
4/21/2014
4/26/2014
5/1/2014
Date



North LISST
South LISST
StreamSide LISST
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
300
275
250
225
200
175
150
125
100
75
50
25
0
Flow (cfs)
40000
35000
30000
25000
20000
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10000
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-5000
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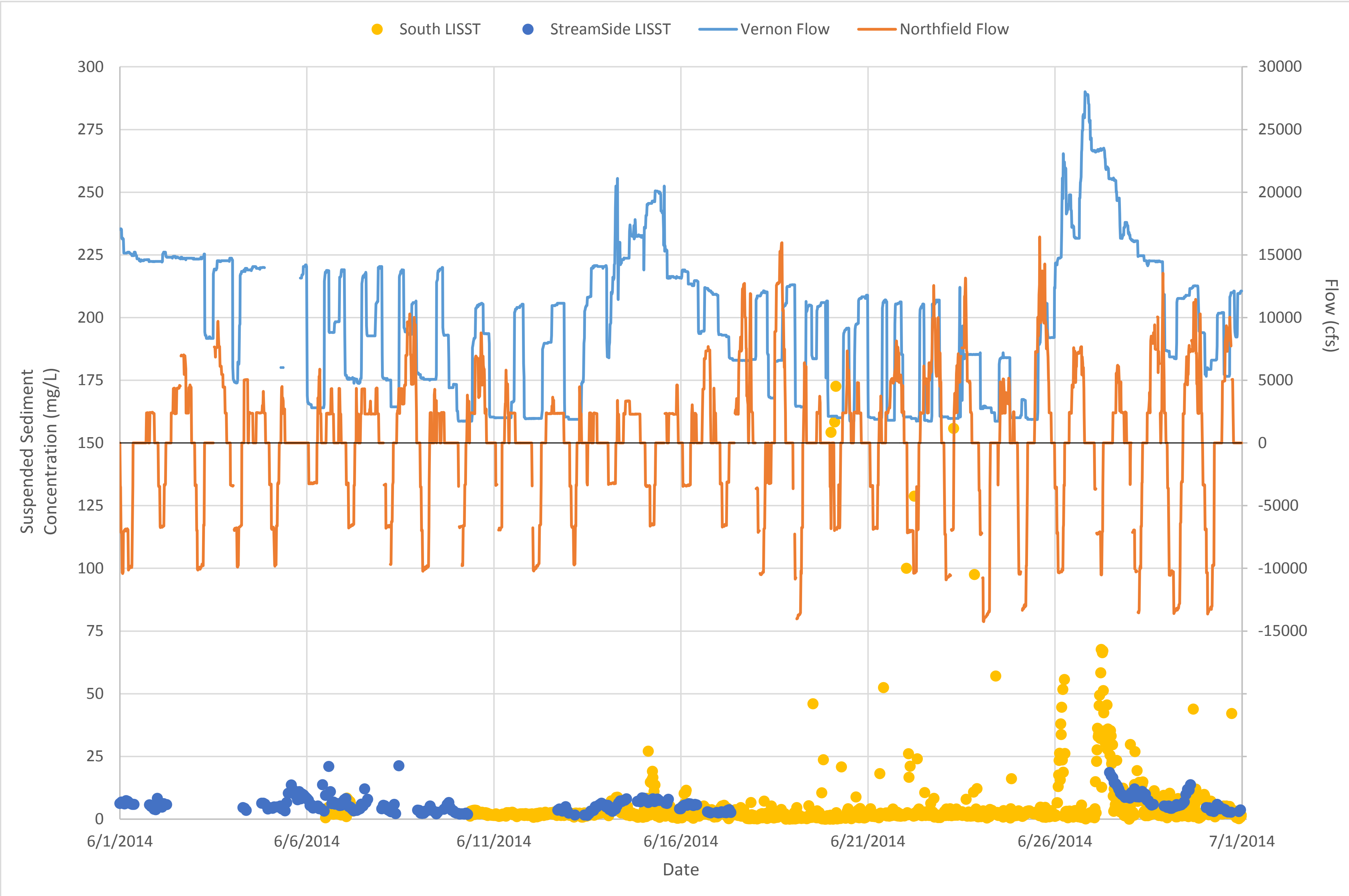
5/6/2014
5/11/2014
5/16/2014
5/21/2014
5/26/2014
5/31/2014
Date



South LISST
StreamSide LISST
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
Flow (cfs)
Date
300
275
250
225
200
175
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125
100
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0
30000
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6/1/2014
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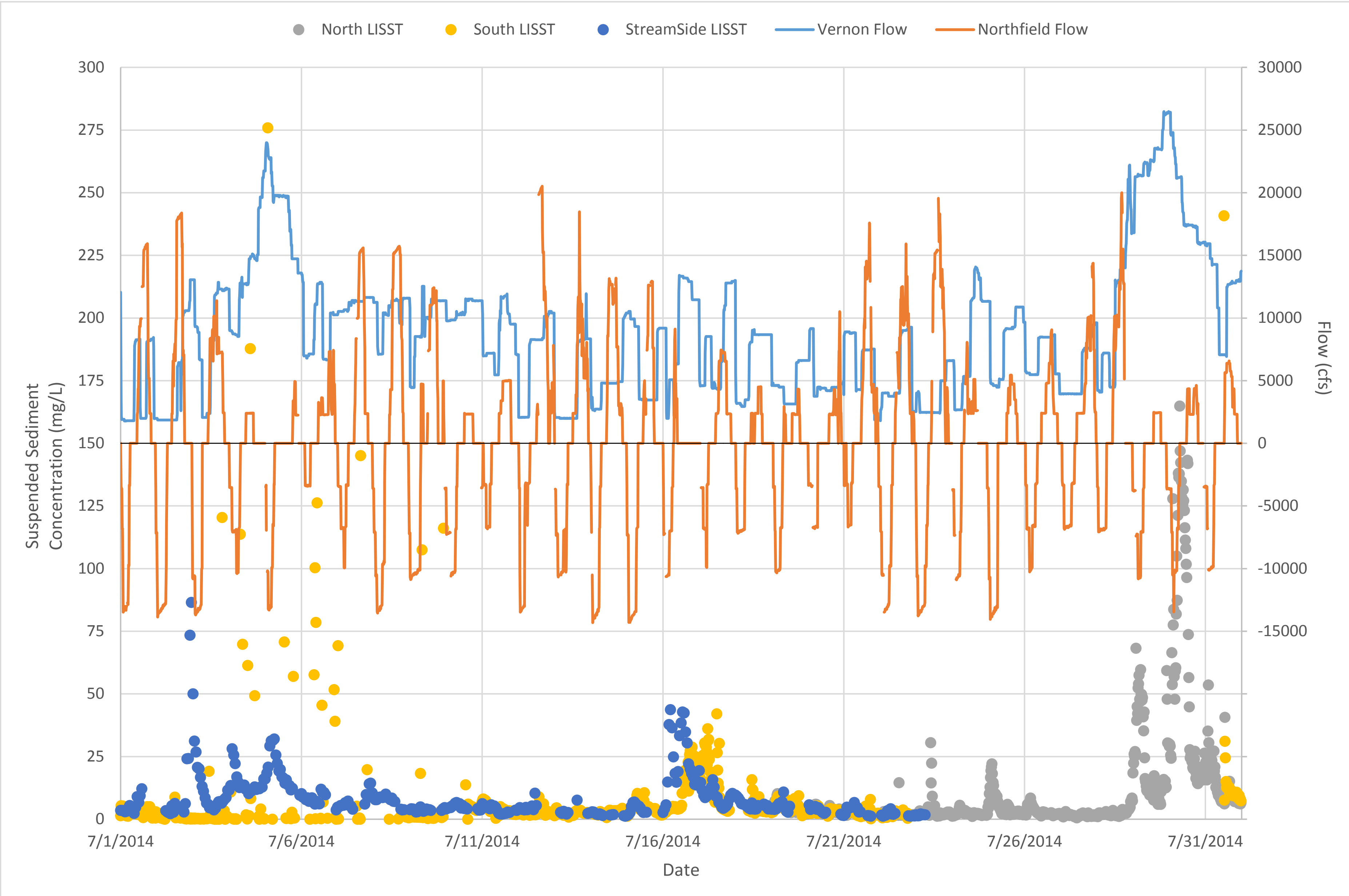
6/21/2014
6/26/2014
7/1/2014



North LISST
South LISST
StreamSide LISST
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
Flow (cfs)
300
275
250
225
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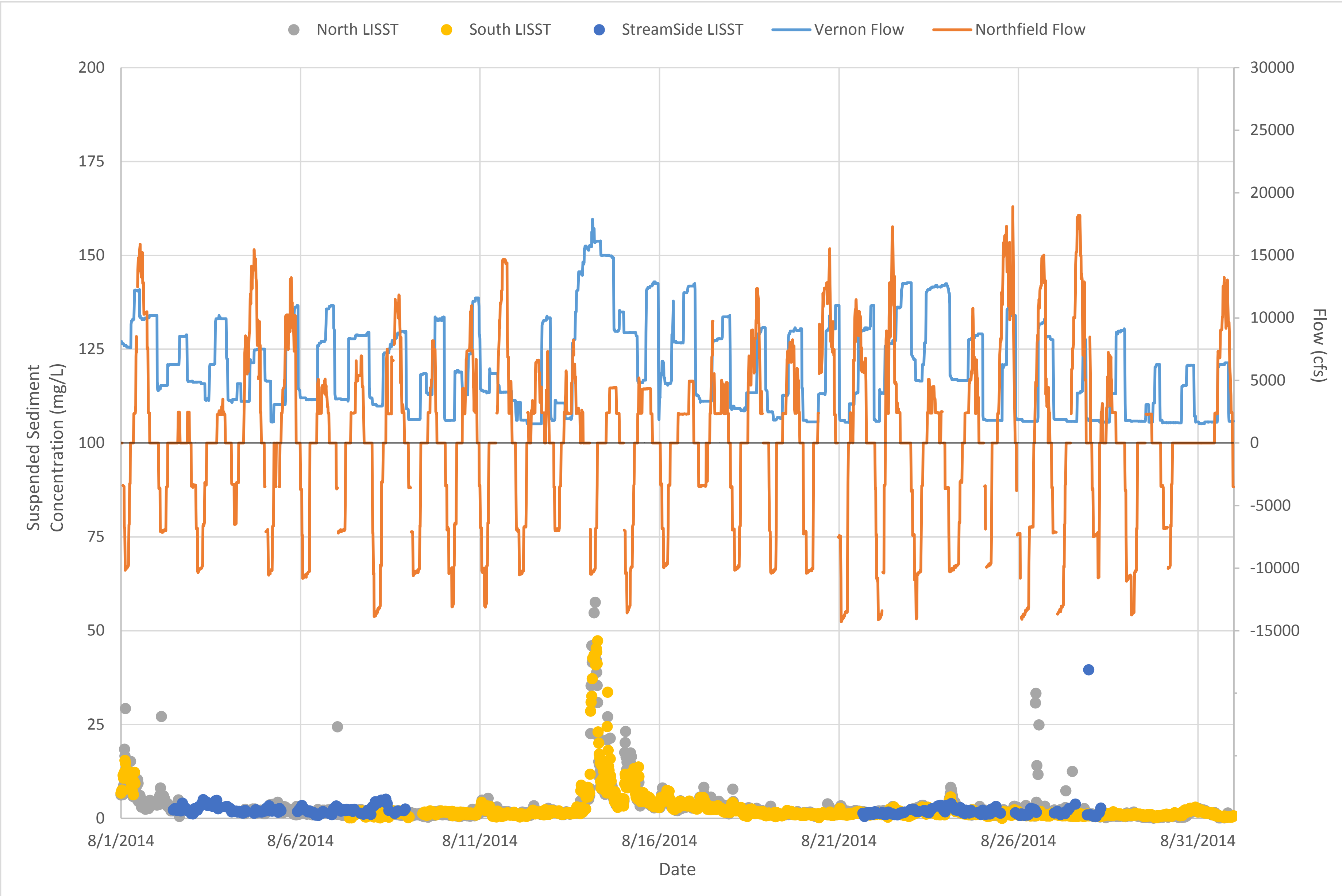
7/26/2014
7/31/2014
Date


North LISST
South LISST
StreamSide LISST
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
200
175
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Flow (cfs)
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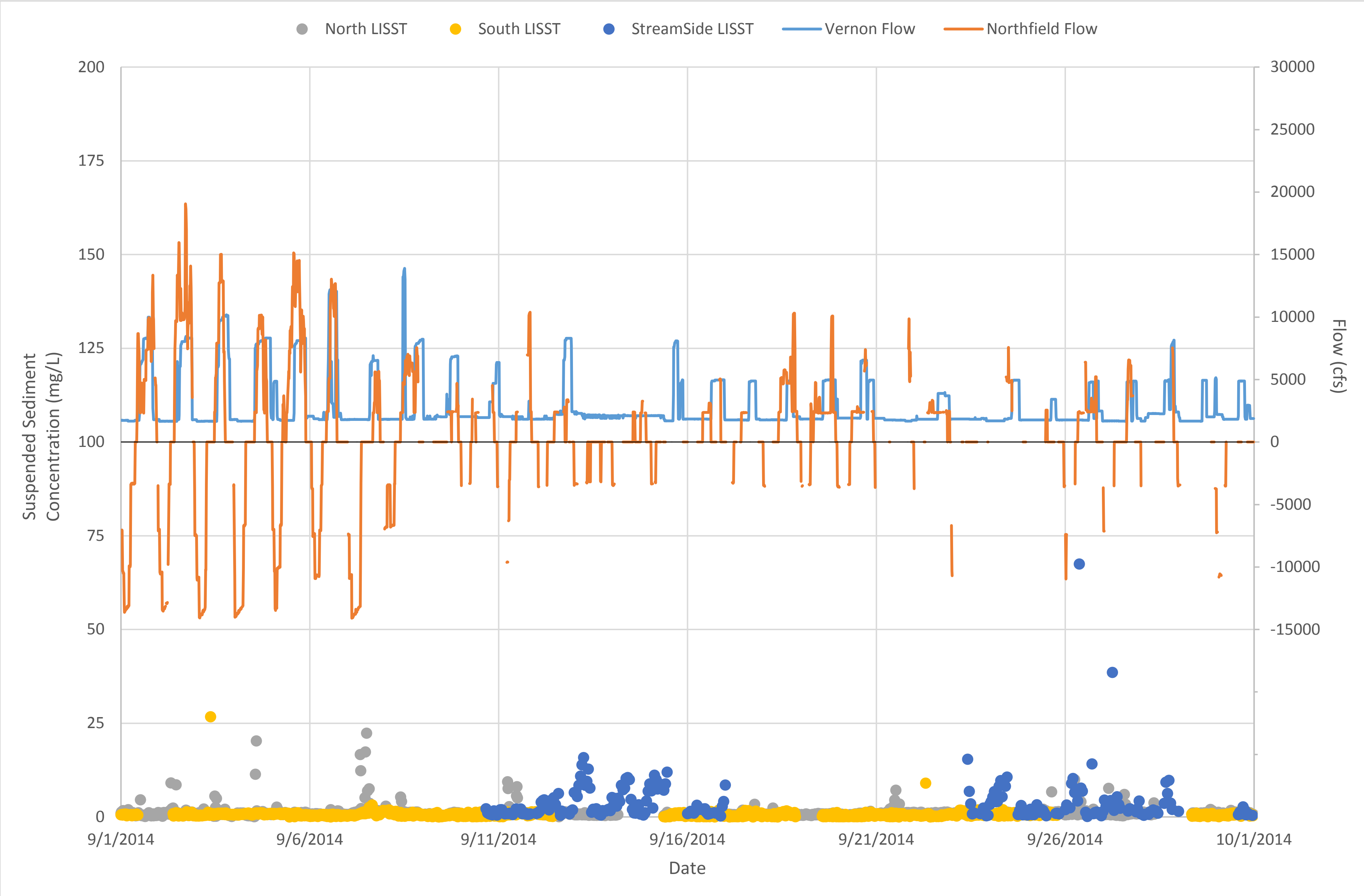
8/16/2014
8/21/2014
8/26/2014
8/31/2014
Date



North LISST
South LISST
StreamSide LISST
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
200
175
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Flow (cfs)
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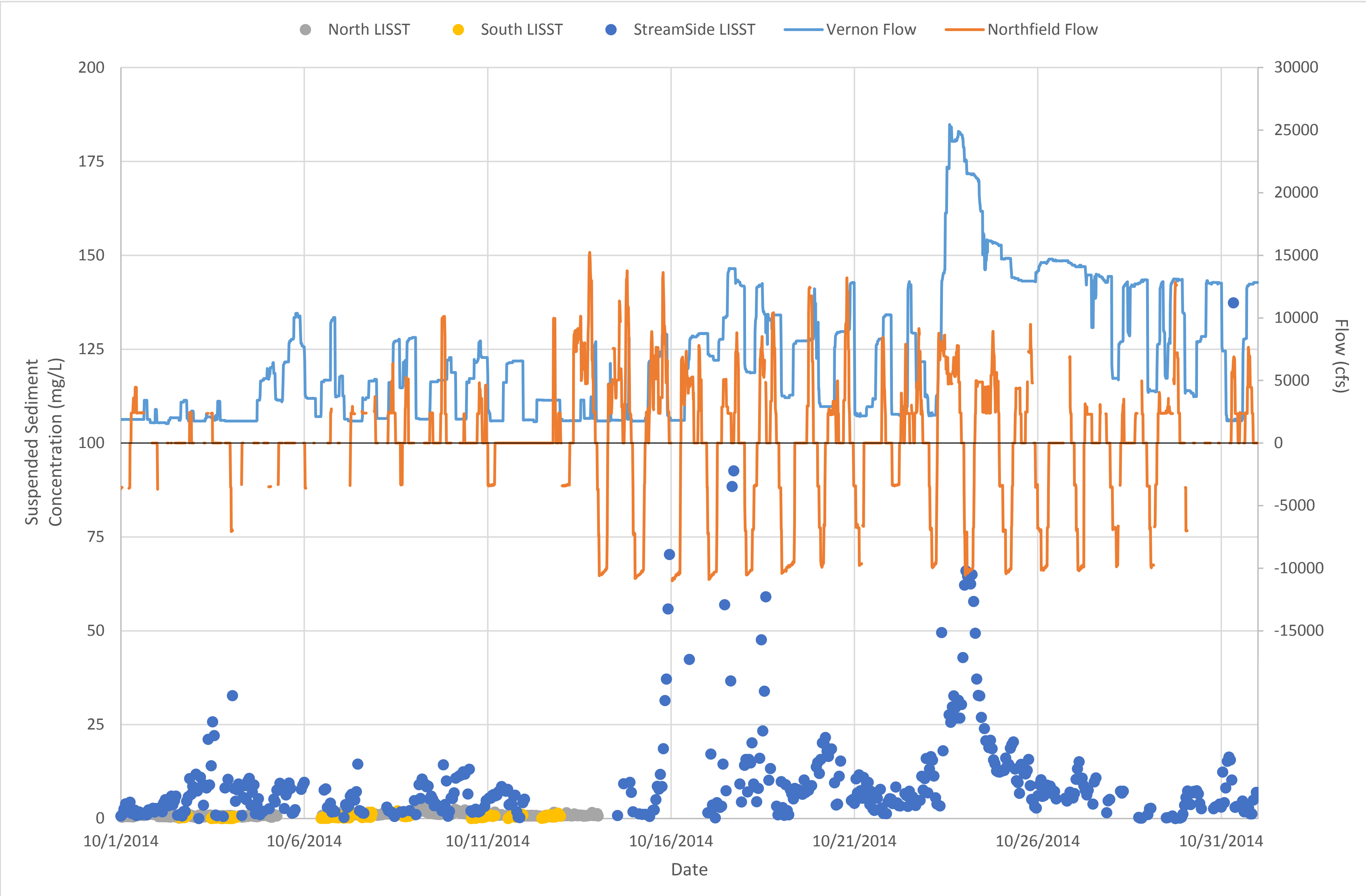
9/26/2014
10/1/2014
Date



North LISST
South LISST
StreamSide LISST
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
Flow (cfs)
Date
200
175
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10/16/2014
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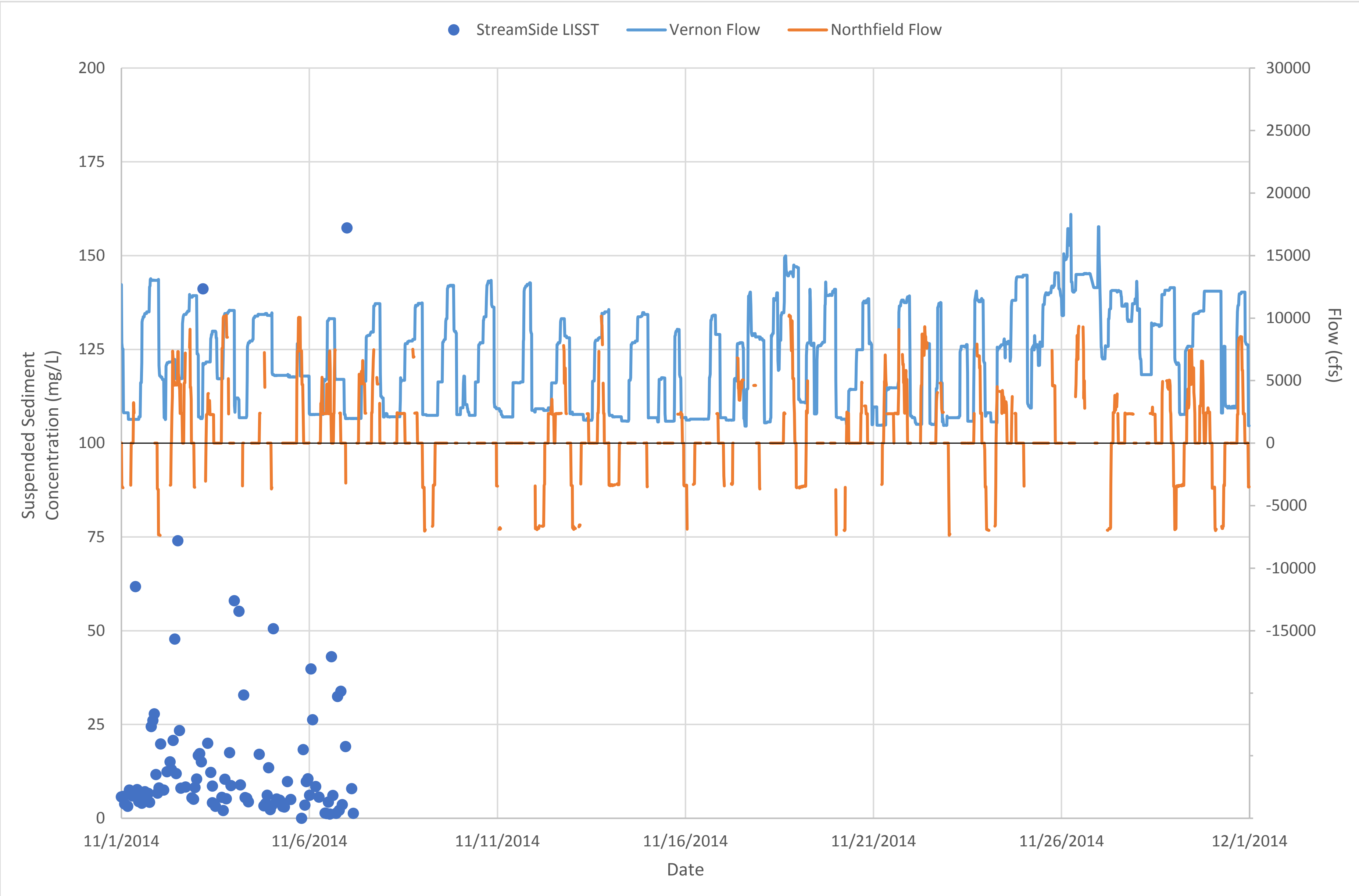
10/26/2014
10/31/2014



StreamSide LISST
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
Flow (cfs)
Date
200
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11/1/2014
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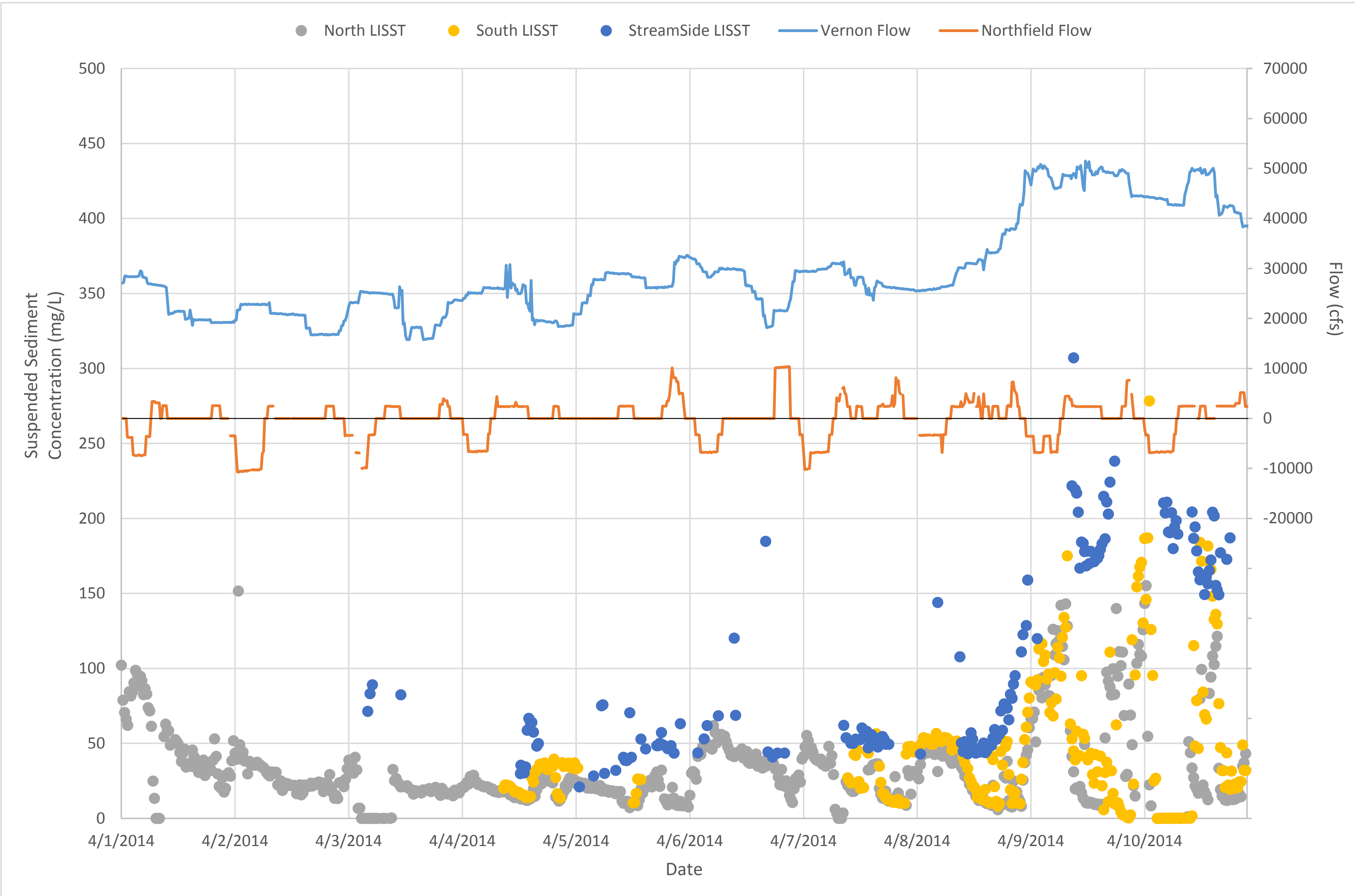
11/26/2014
12/1/2014

2014 CONTINUOUS LISST INSTRUMENT TIMESERIES-10 DAY



North LISST
South LISST
StreamSide LISST
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
Flow (cfs)
Date
500
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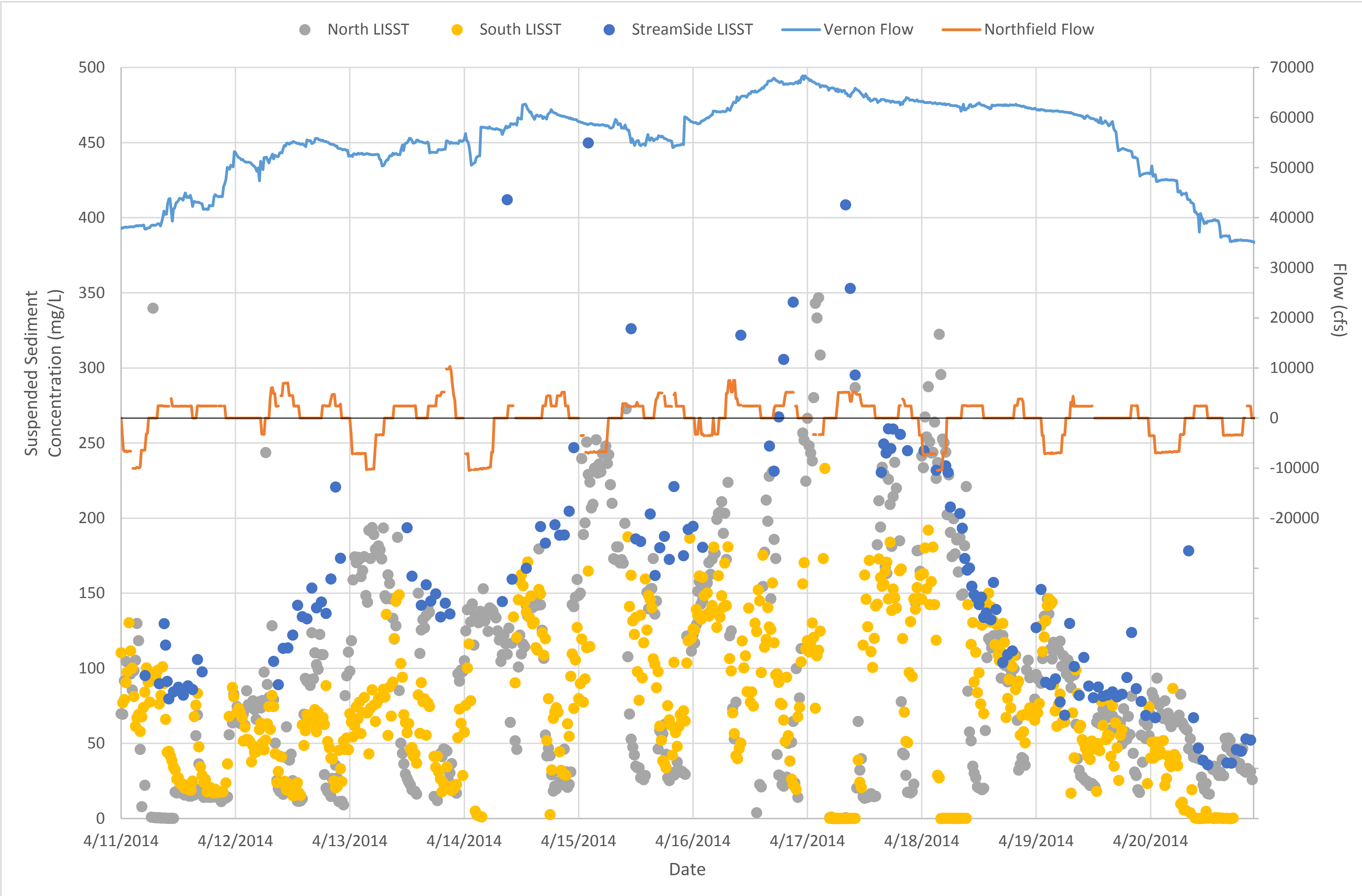

North LISST
South LISST
StreamSide LISST
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
500
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Flow (cfs)
4/11/2014
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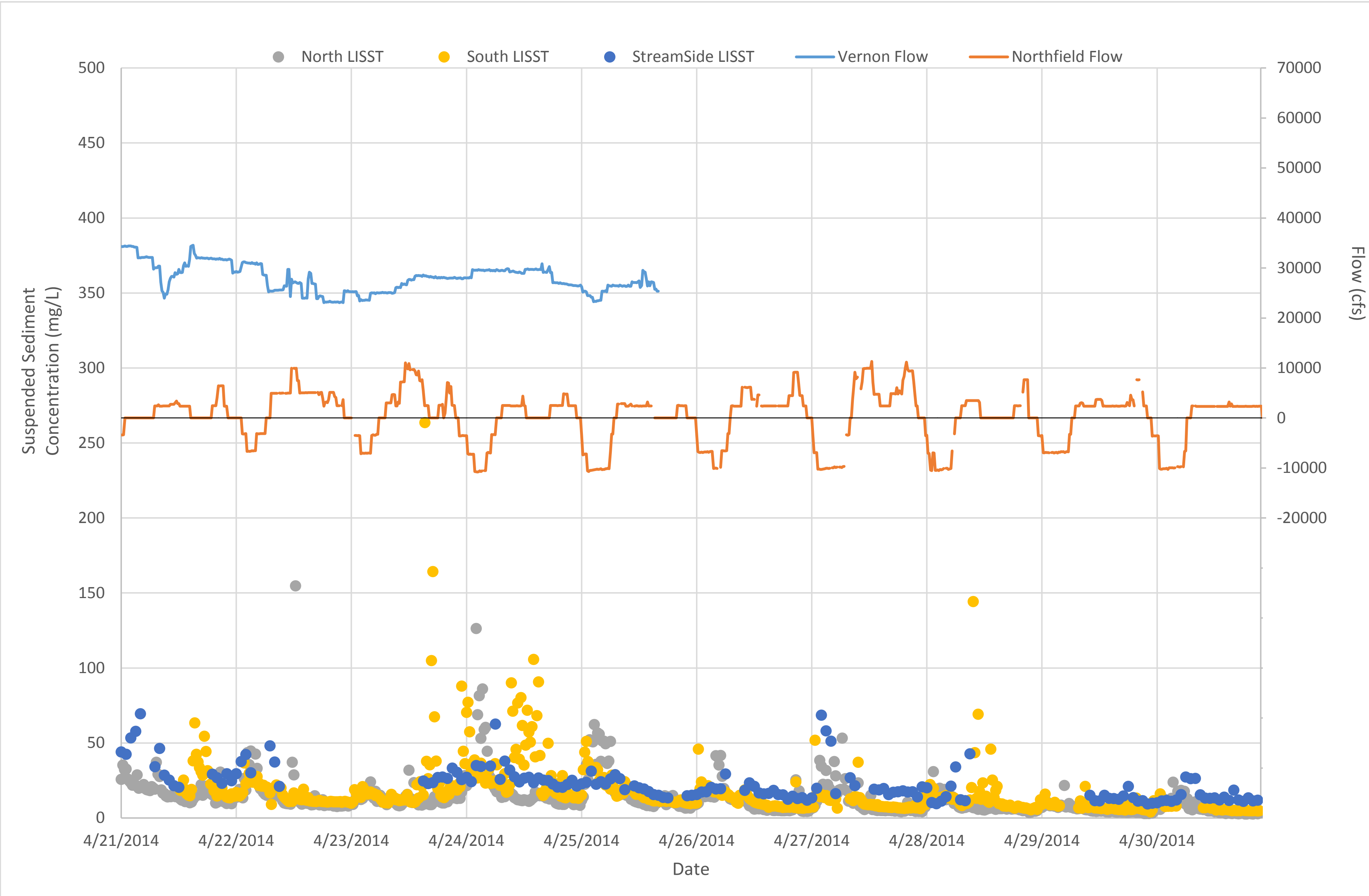
4/20/2014
Date



North LISST
South LISST
StreamSide LISST
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
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Flow (cfs)
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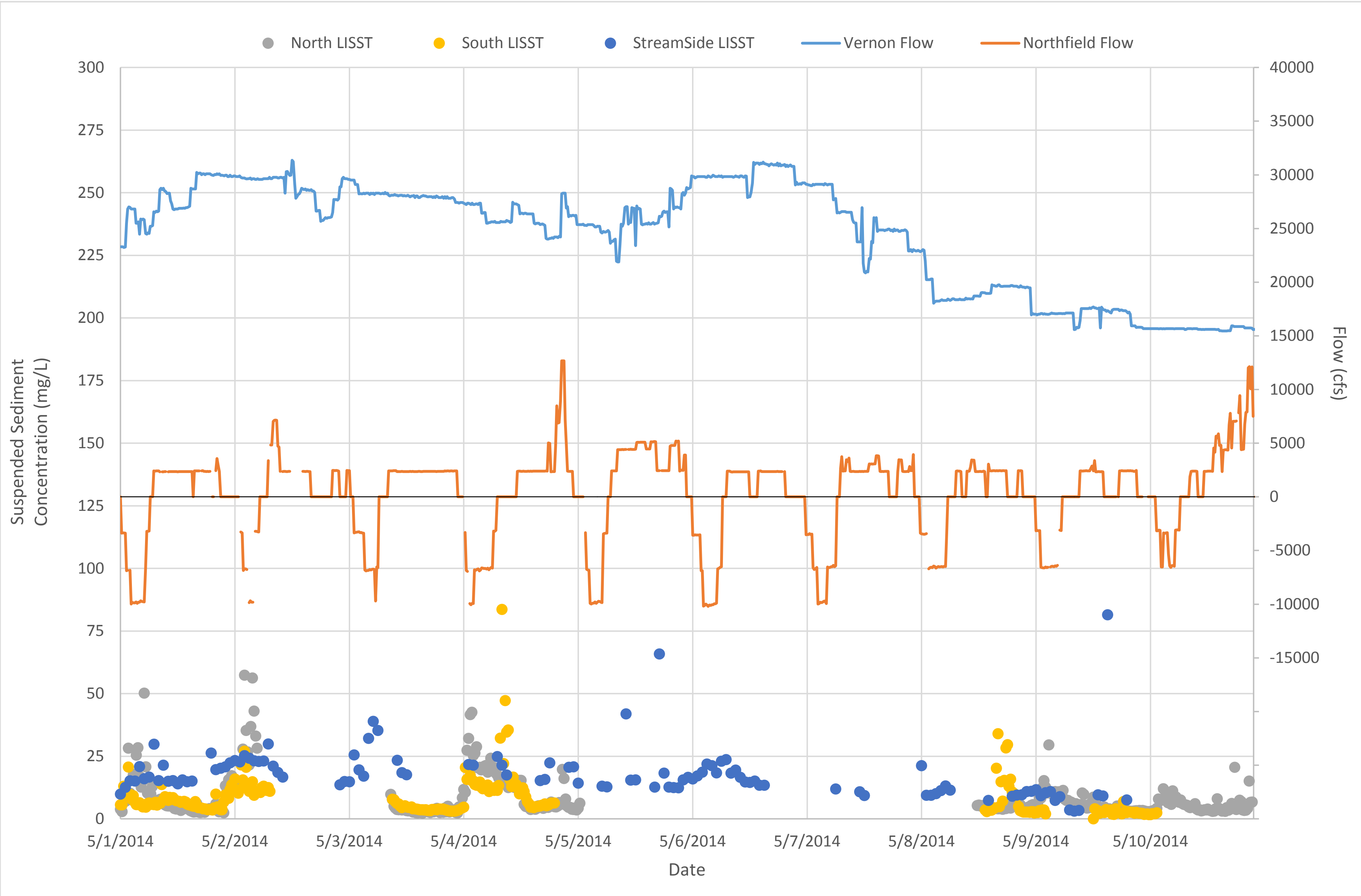
Date



North LISST
South LISST
StreamSide LISST
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
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Flow (cfs)
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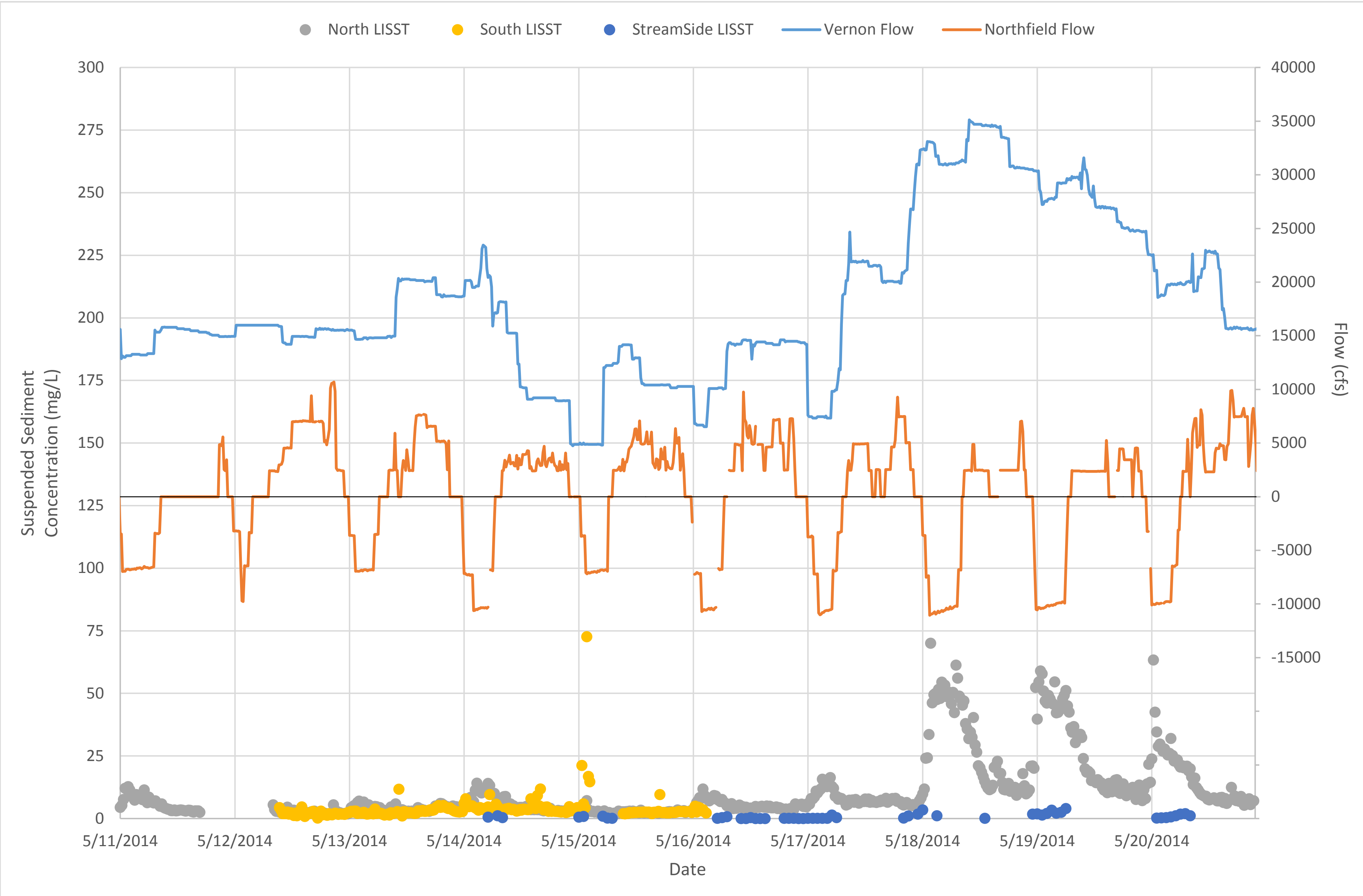
Date



North LISST
South LISST
StreamSide LISST
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
Flow (cfs)
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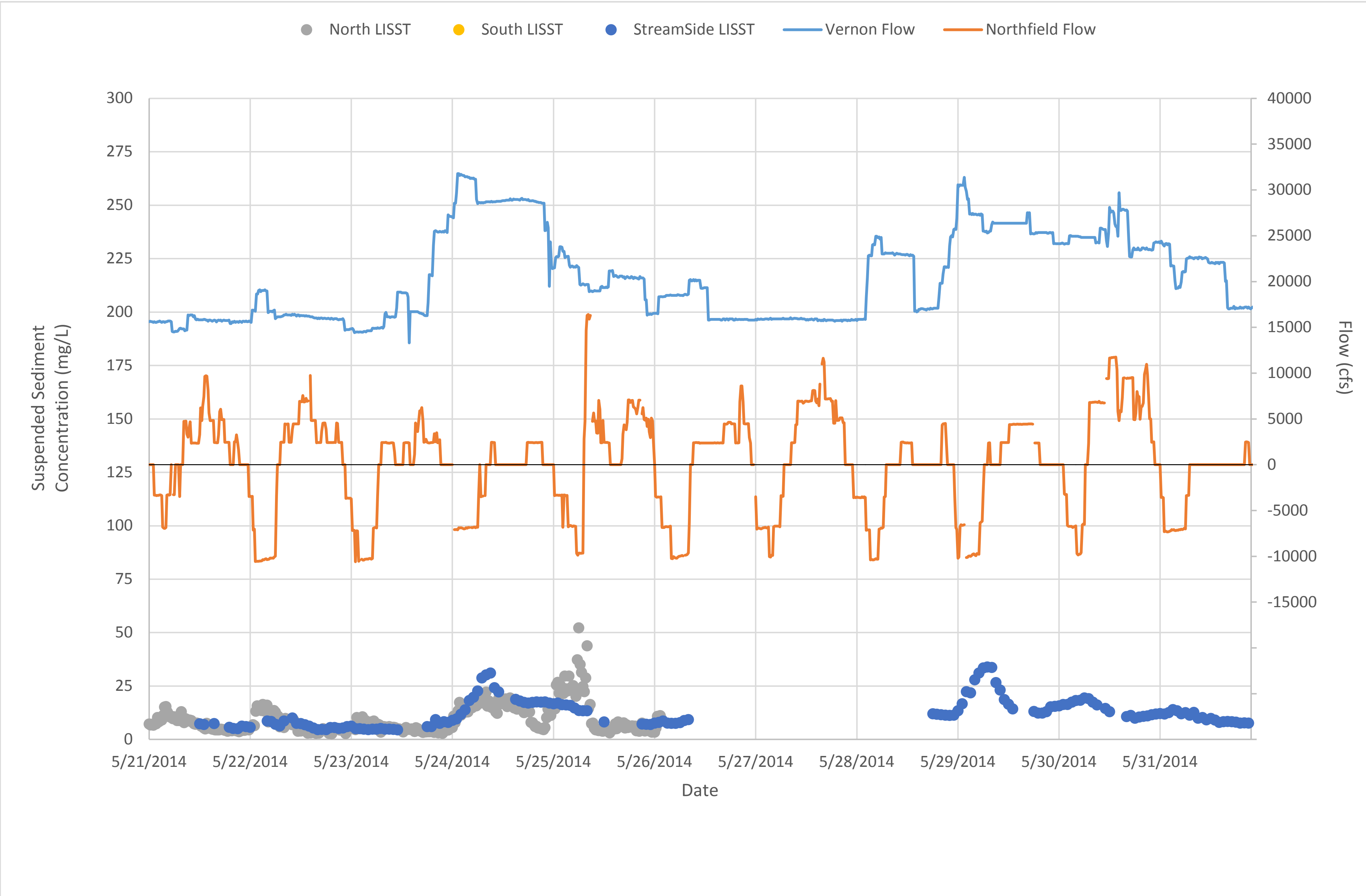

North LISST
South LISST
StreamSide LISST
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
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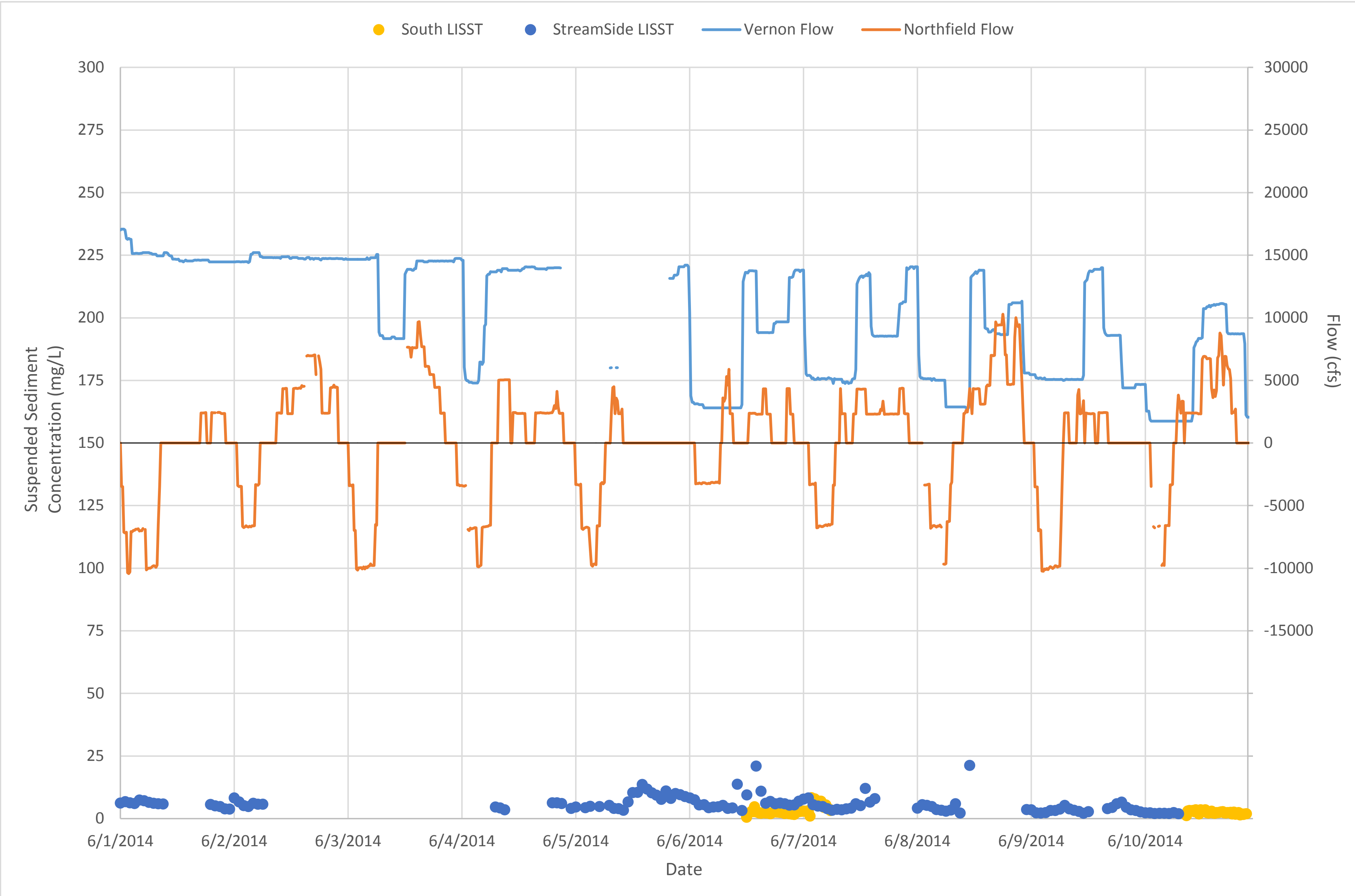
5/31/2014
Date



South LISST
StreamSide LISST
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
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Flow (cfs)
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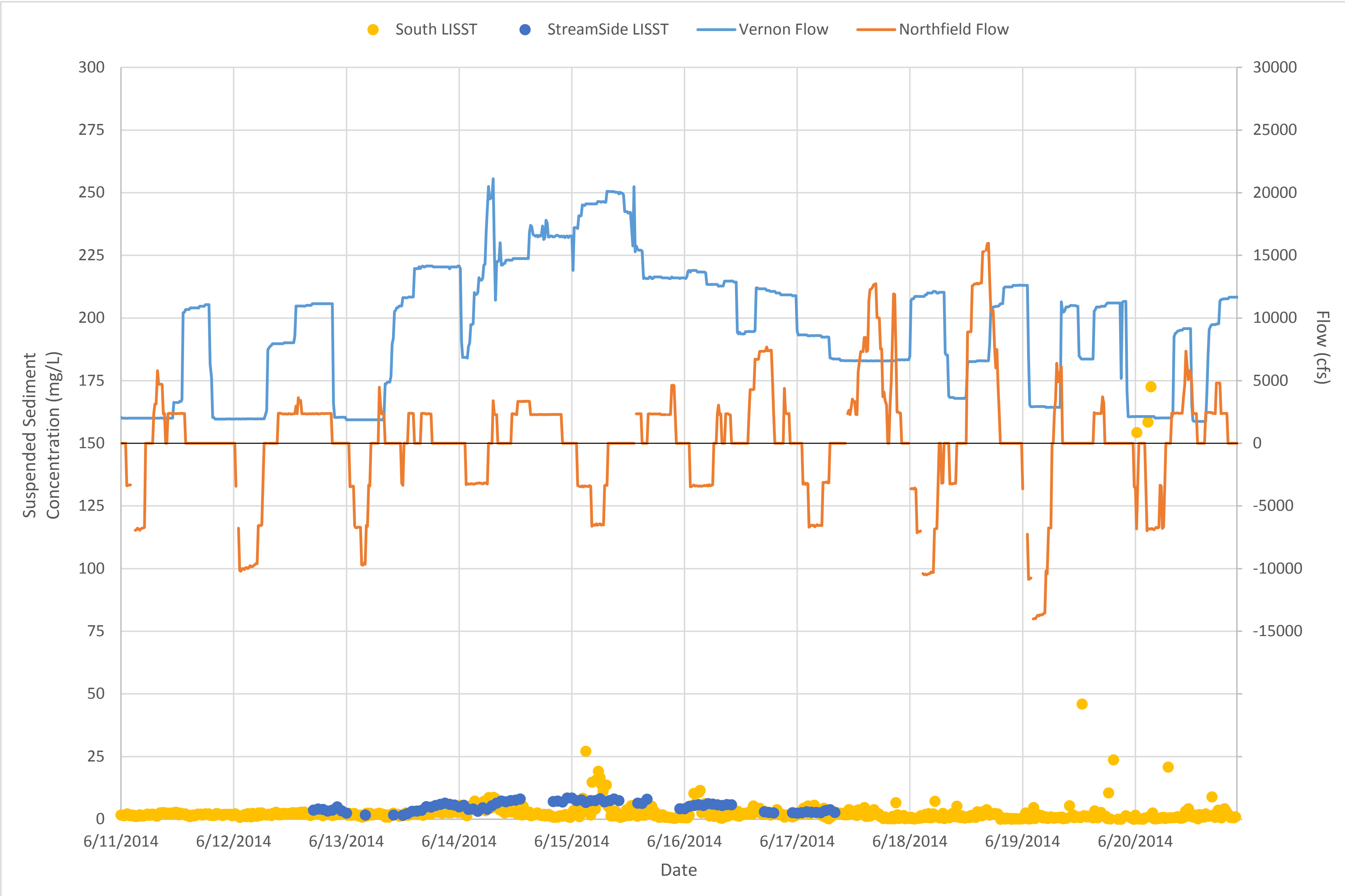
Date



South LISST
StreamSide LISST
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
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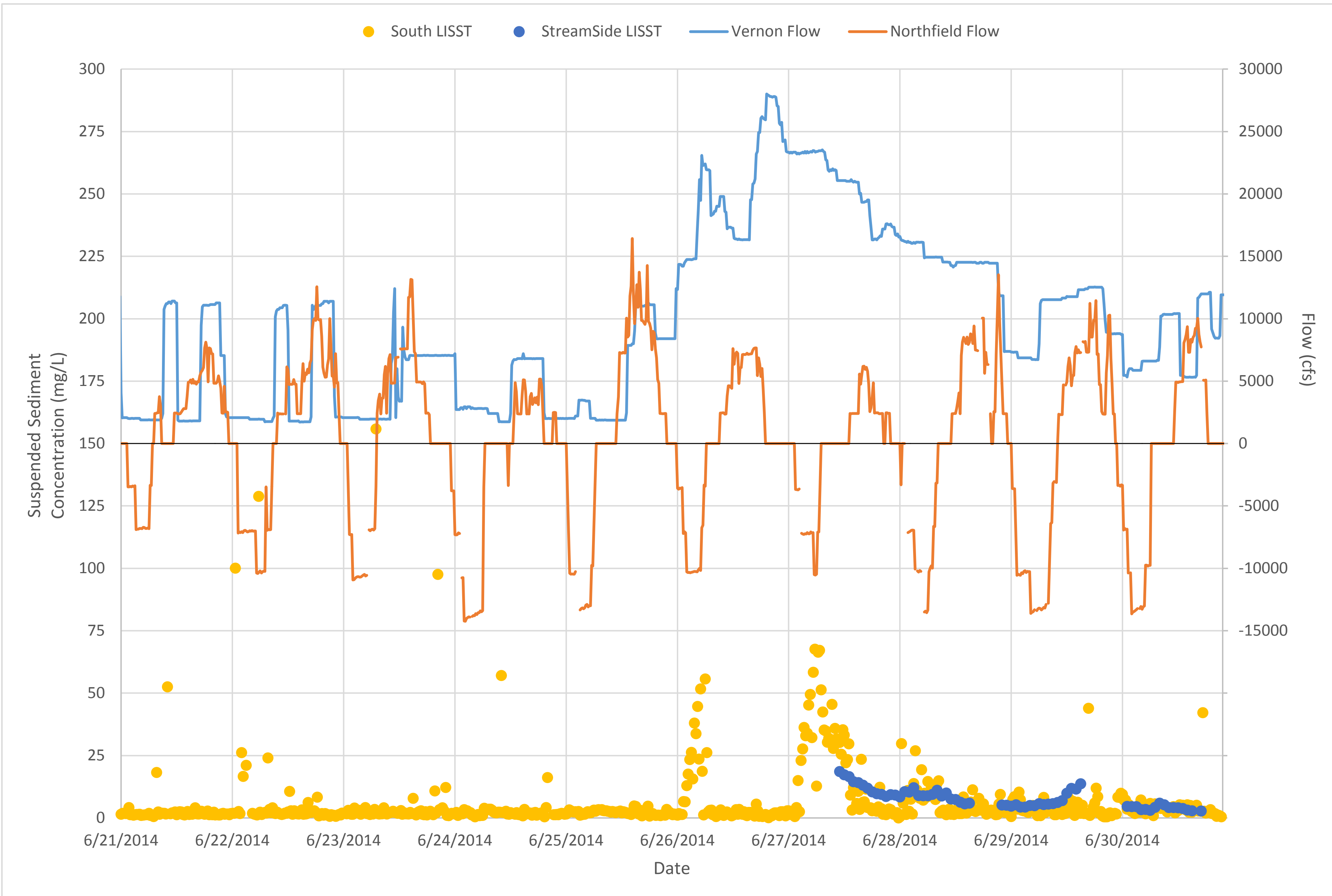
6/19/2014
6/20/2014
Date



South LISST
StreamSide LISST
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
Flow (cfs)
Date
300
275
250
225
200
175
150
125
100
75
50
25
0
30000
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6/21/2014
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6/28/2014
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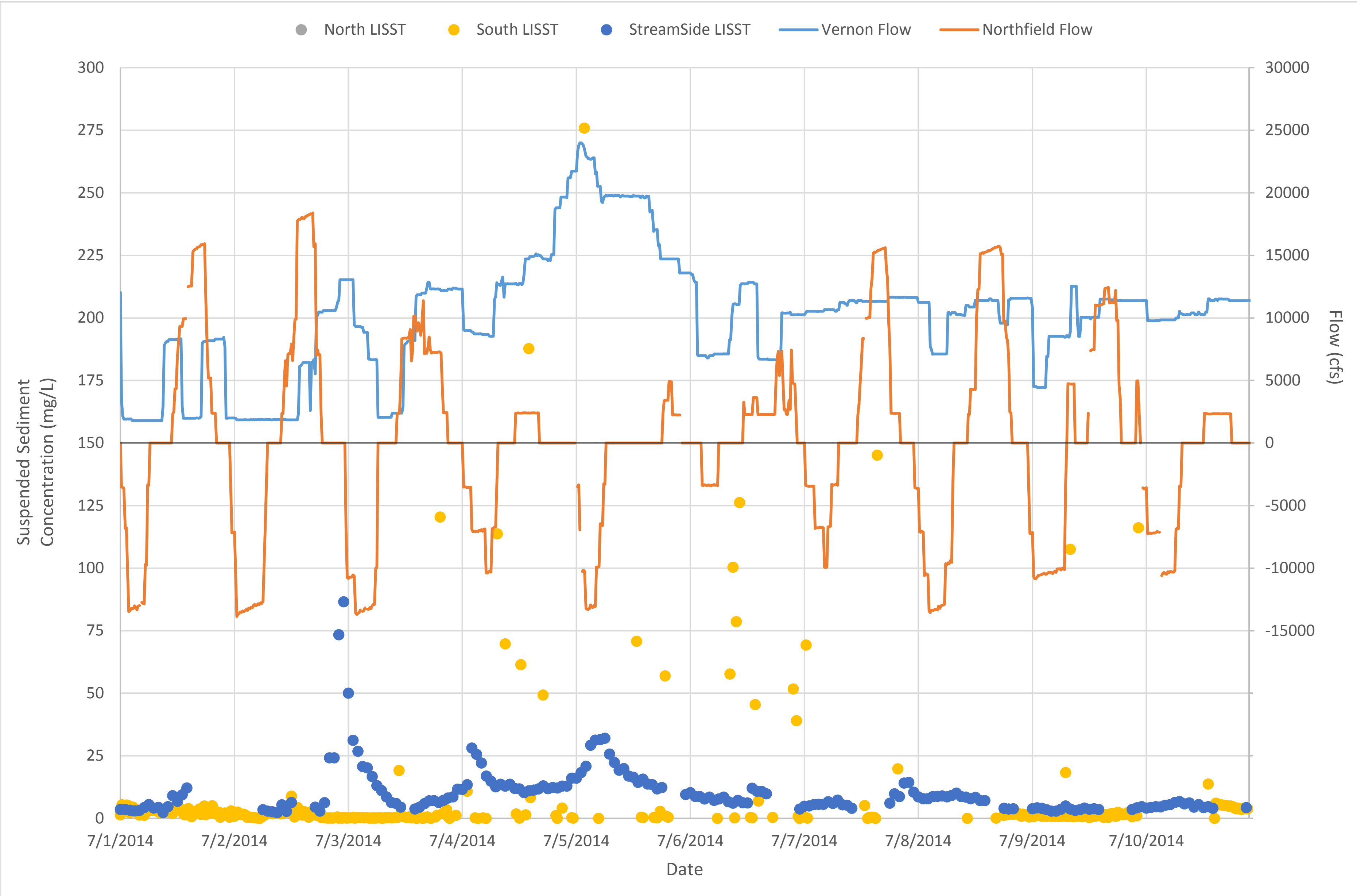
6/30/2014



North LISST
South LISST
StreamSide LISST
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
Flow (cfs)
Date
300
275
250
225
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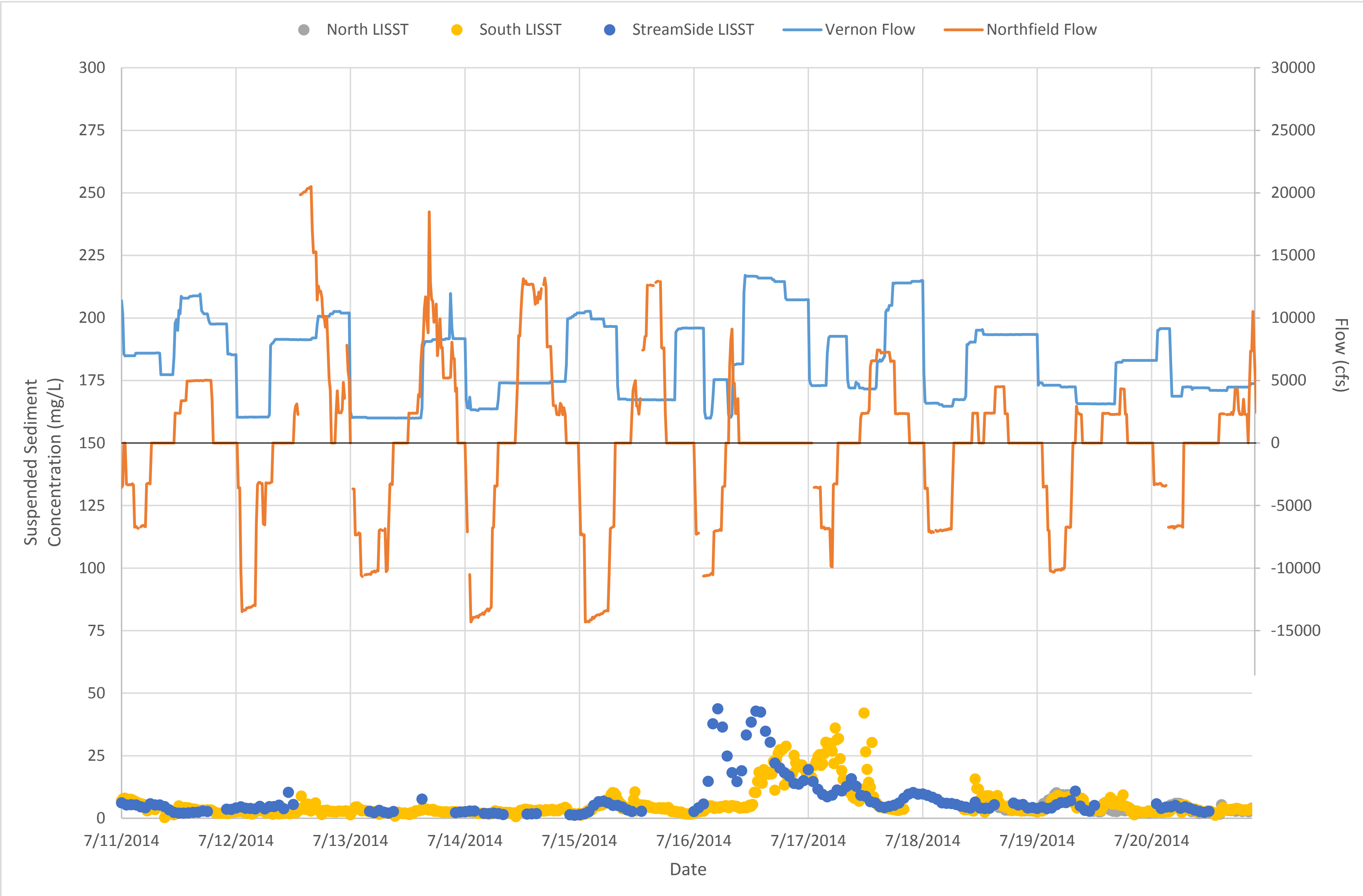

North LISST
South LISST
StreamSide LISST
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
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Flow (cfs)
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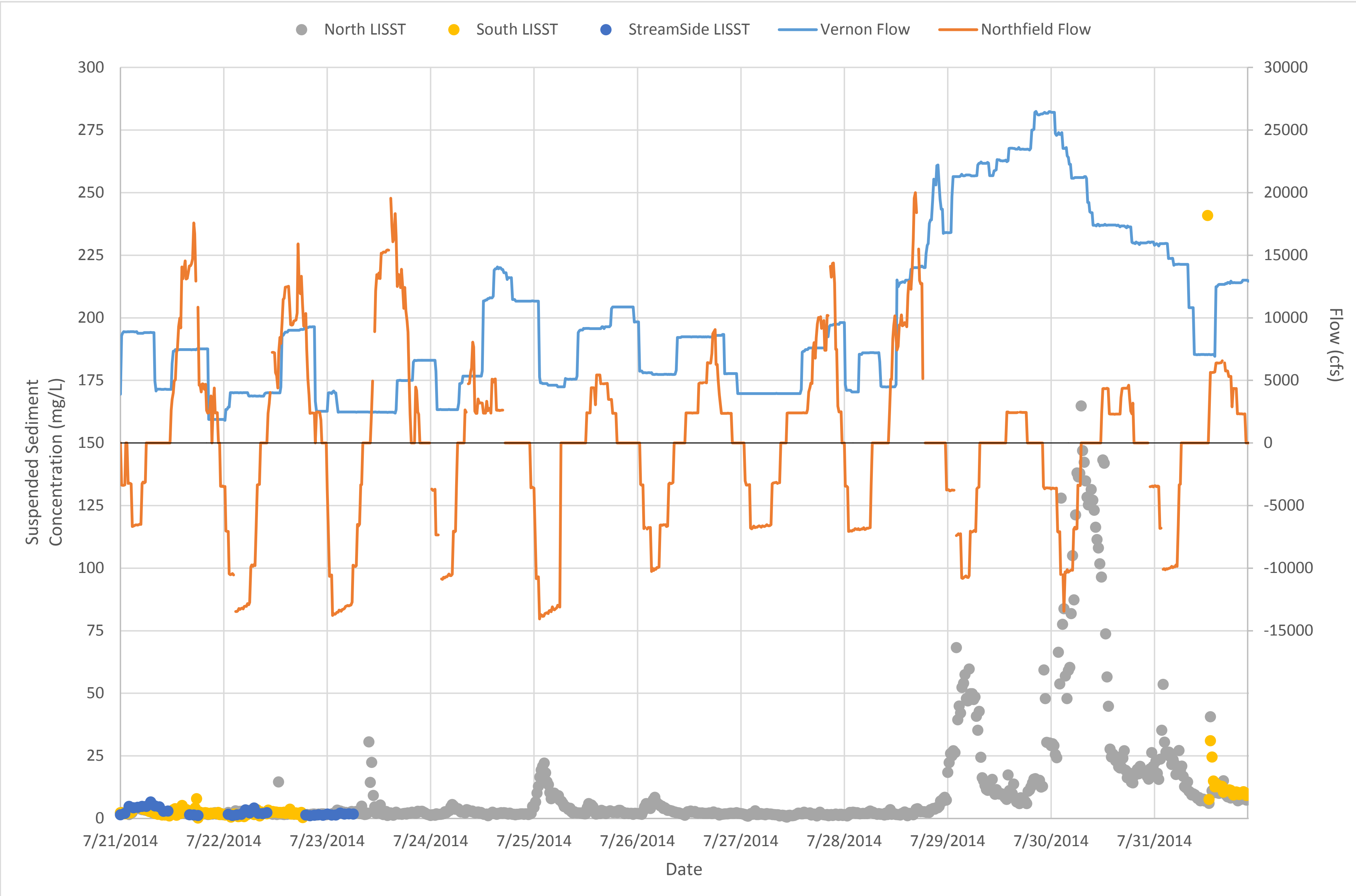
7/19/2014
7/20/2014
Date



North LISST
South LISST
StreamSide LISST
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
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Flow (cfs)
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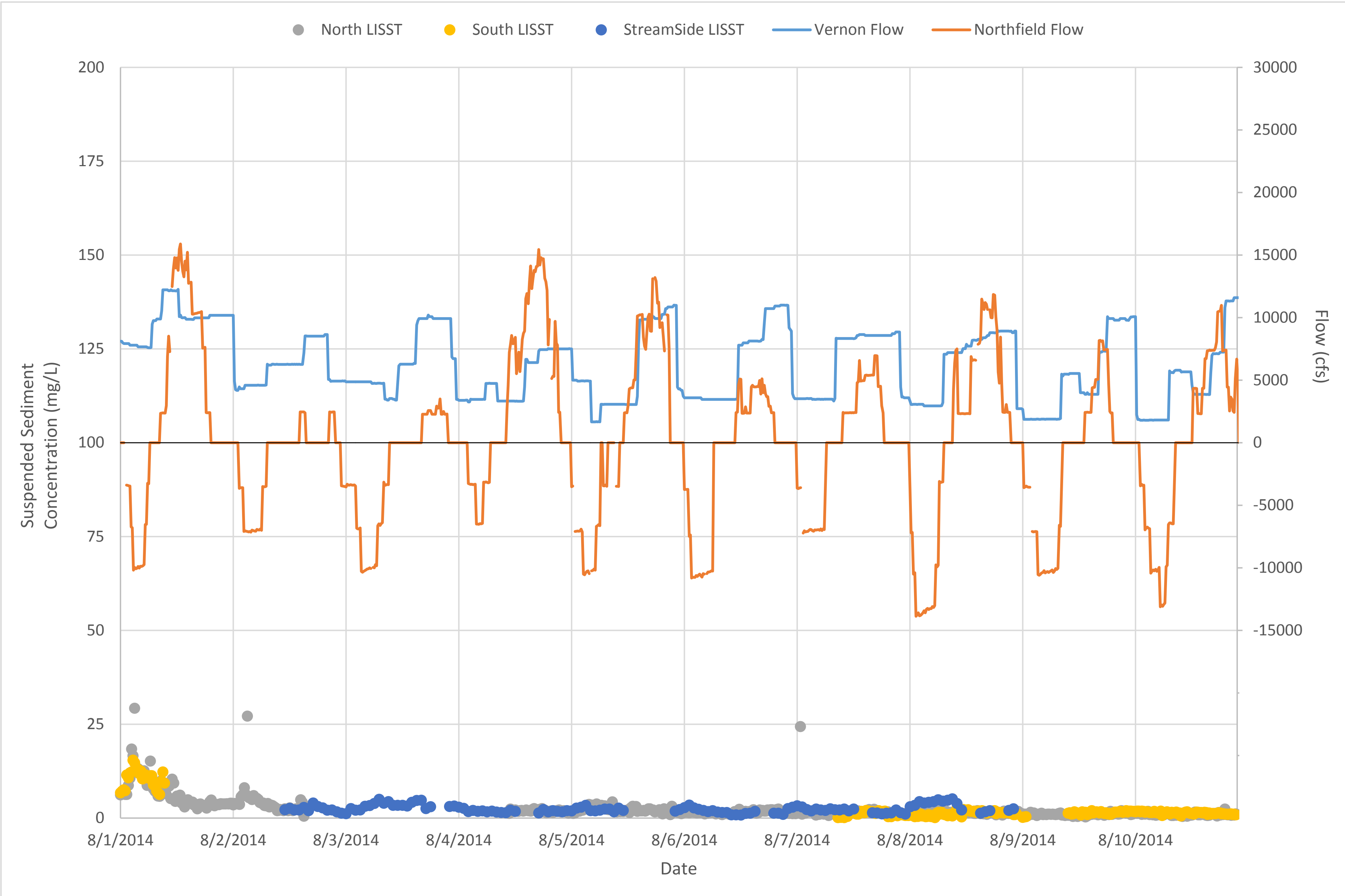
7/31/2014
Date



North LISST
South LISST
StreamSide LISST
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
Flow (cfs)
Date
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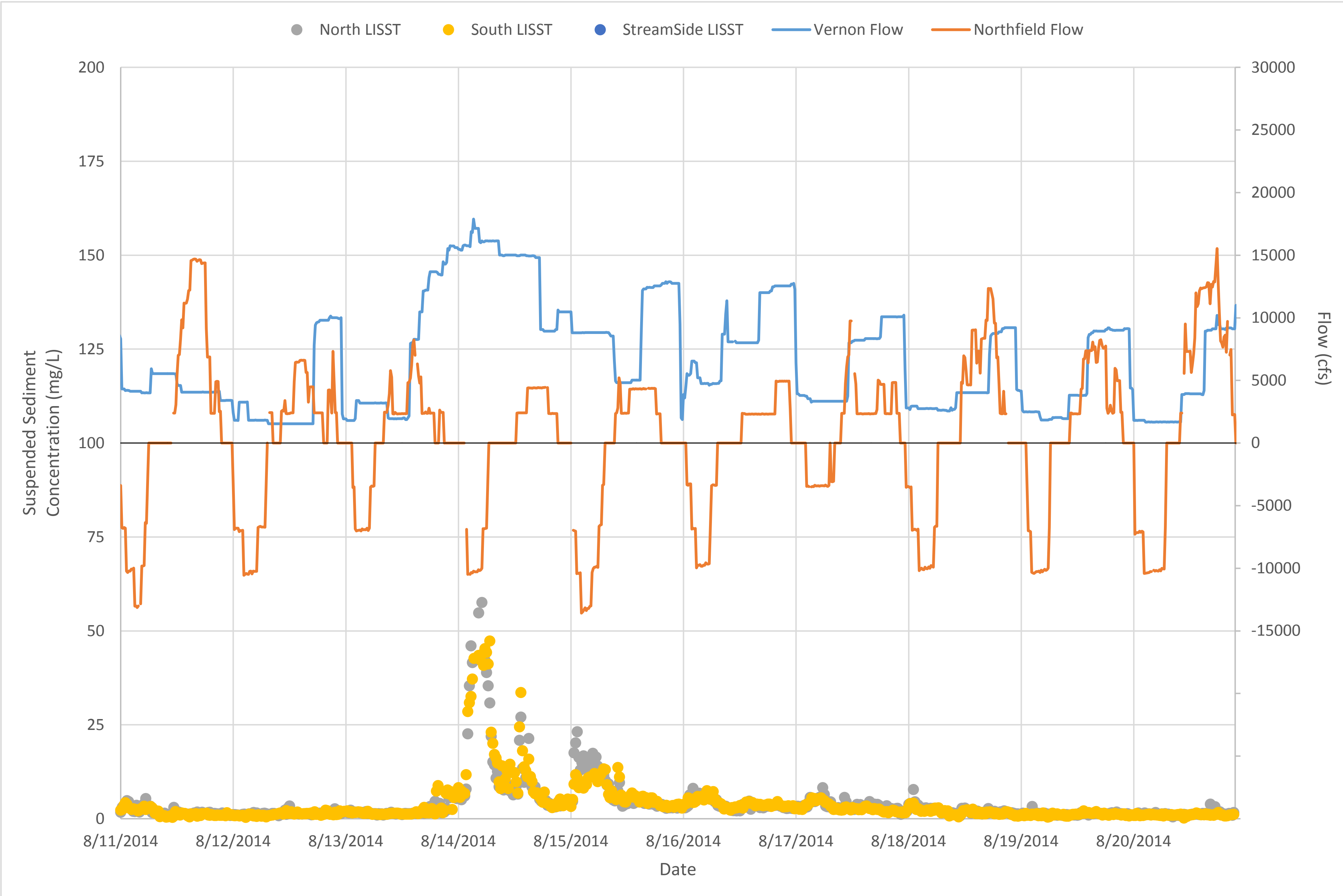
North LISST
South LISST
StreamSide LISST
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
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Flow (cfs)
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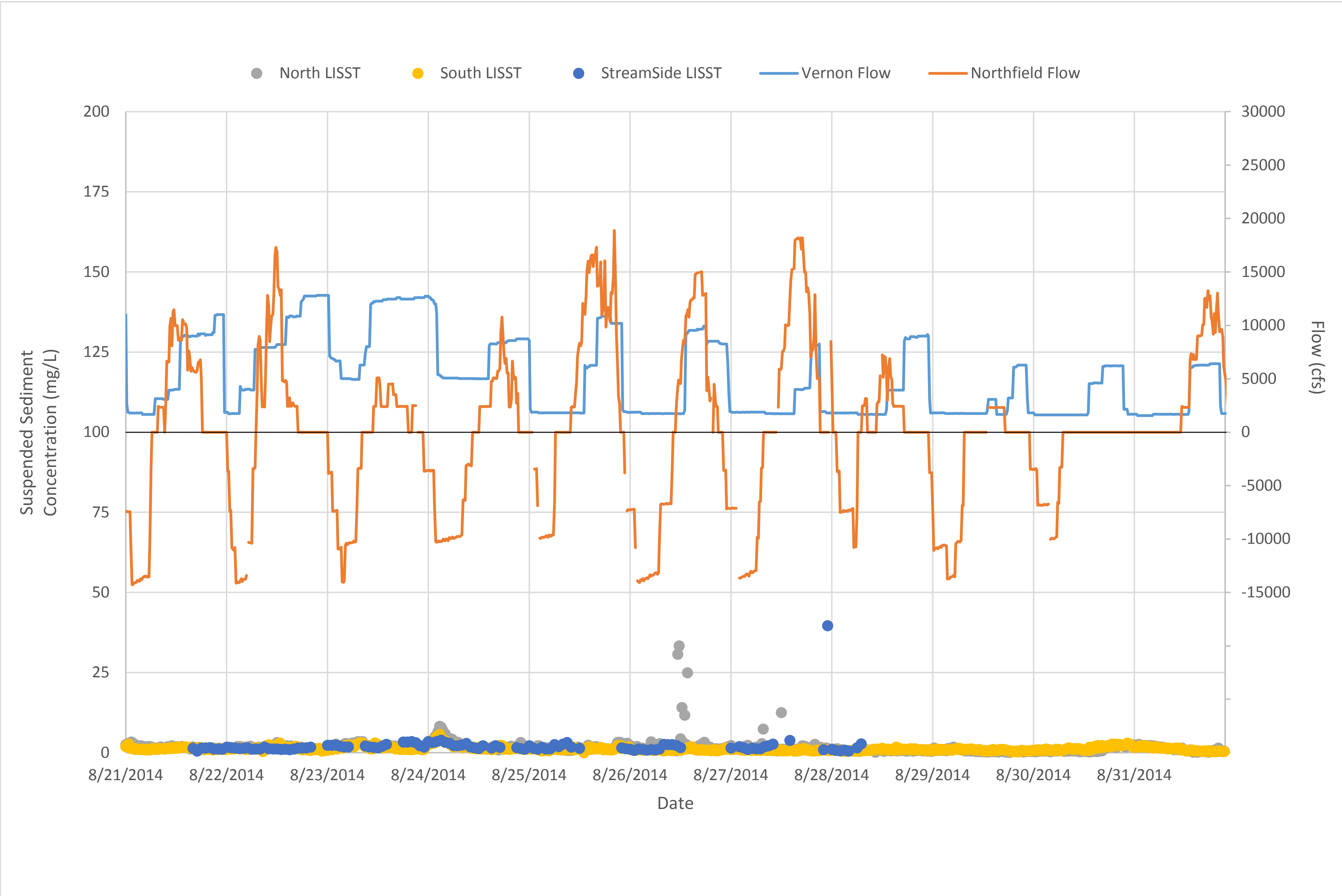
Date


North LISST
South LISST
StreamSide LISST
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
Flow (cfs)
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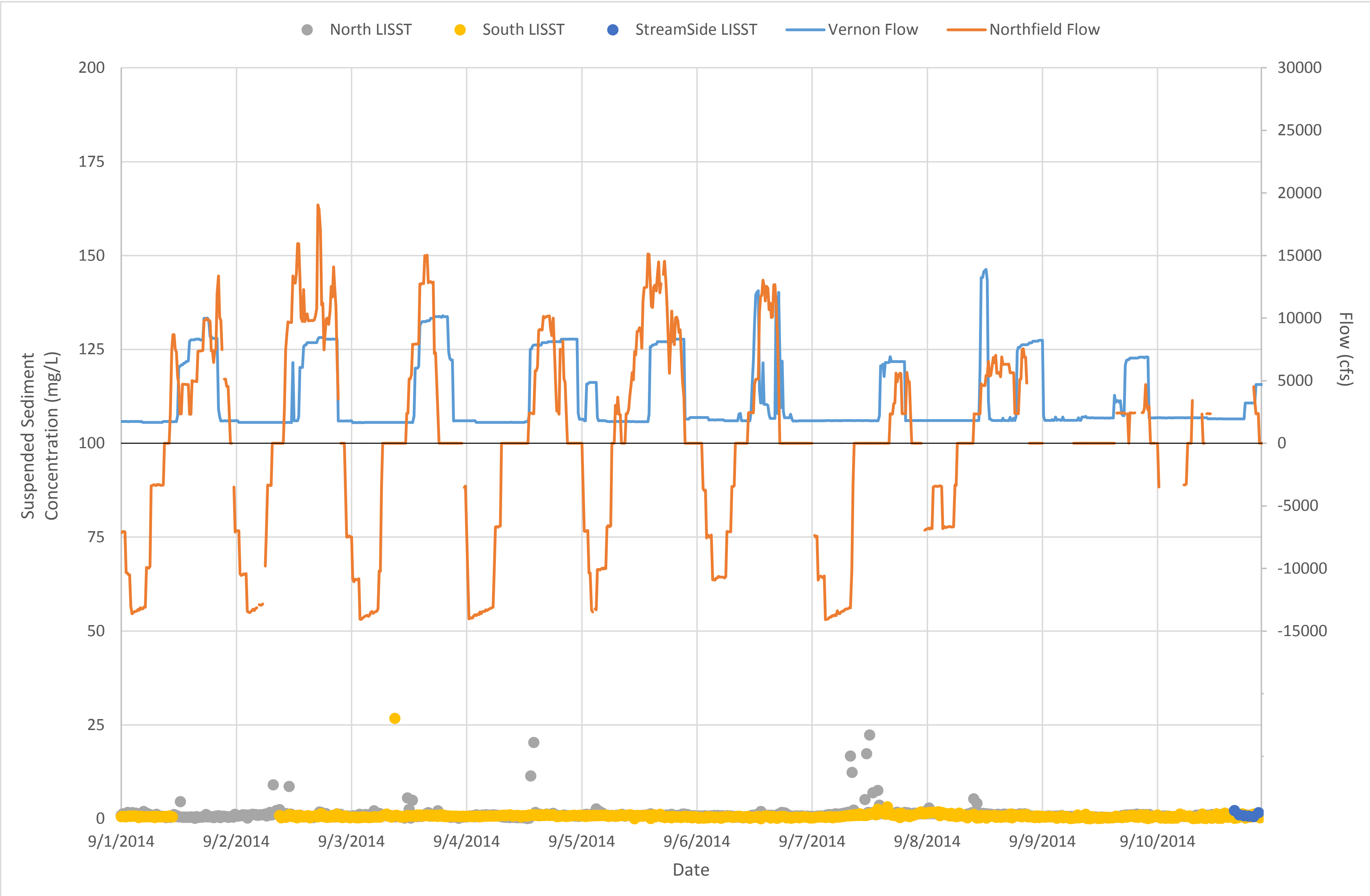
8/31/2014
Date



North LISST
South LISST
StreamSide LISST
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
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Flow (cfs)
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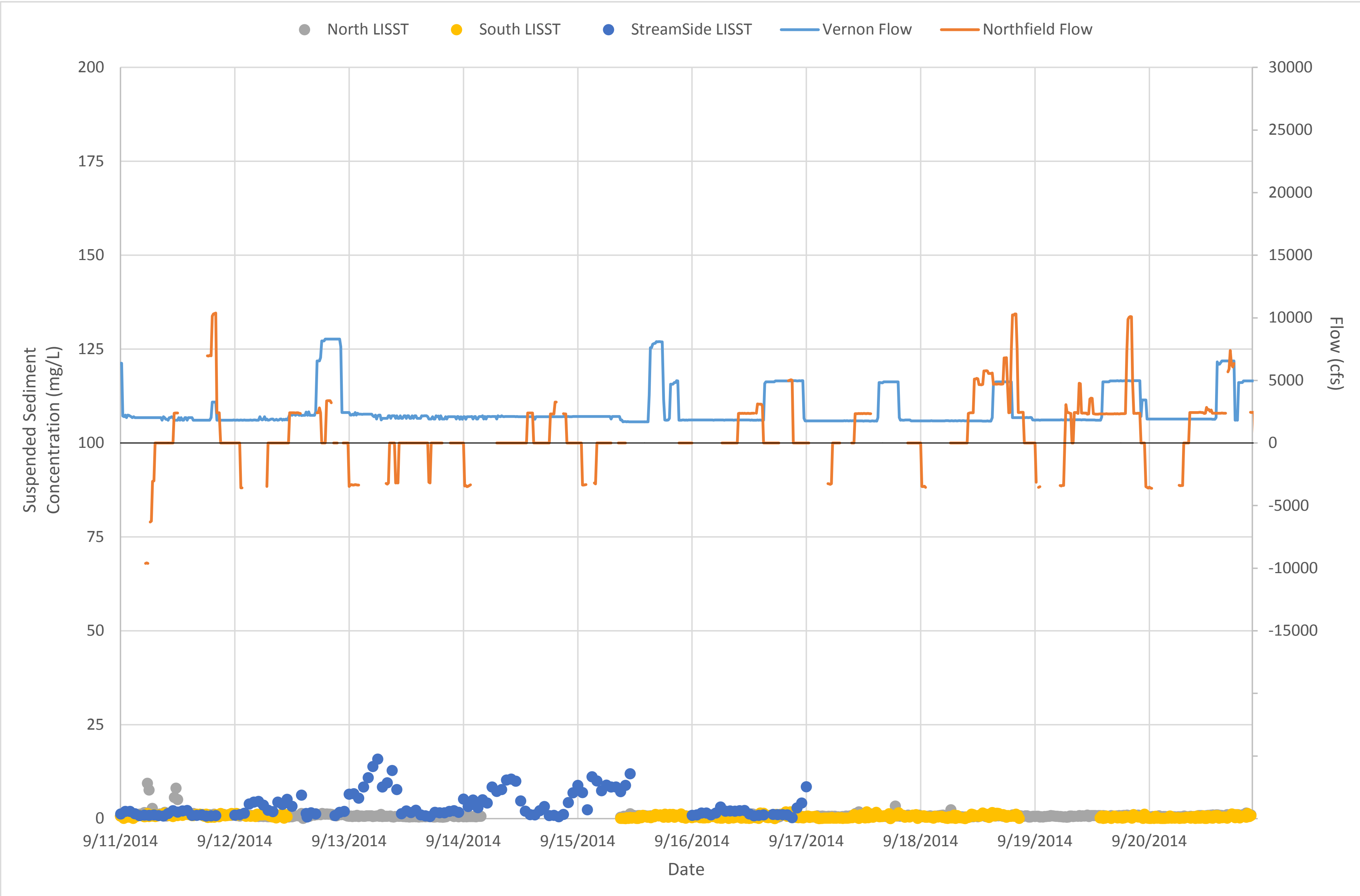
9/10/2014
Date


North LISST
South LISST
StreamSide LISST
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
Flow (cfs)
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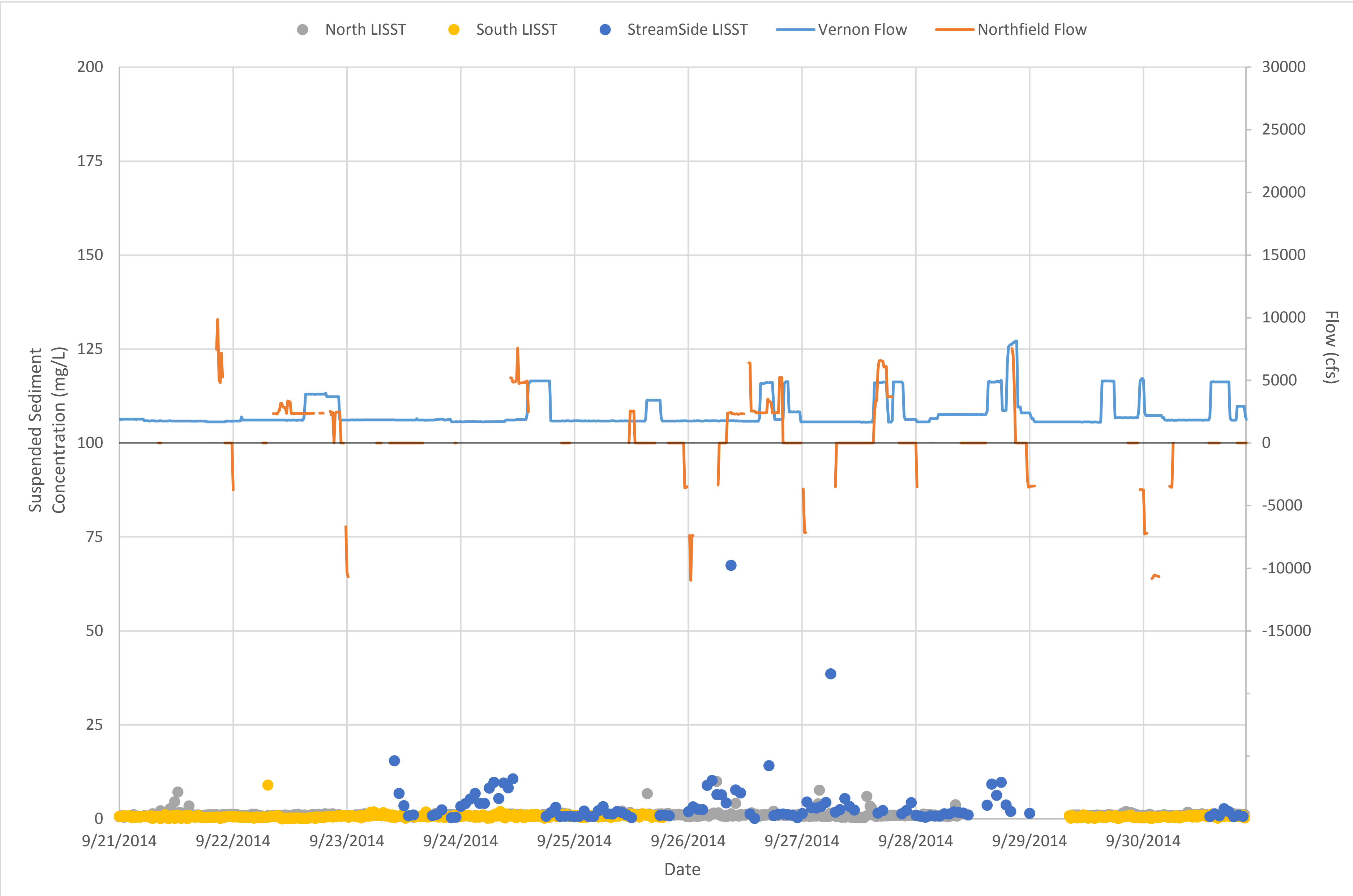
North LISST
South LISST
StreamSide LISST
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
Flow (cfs)
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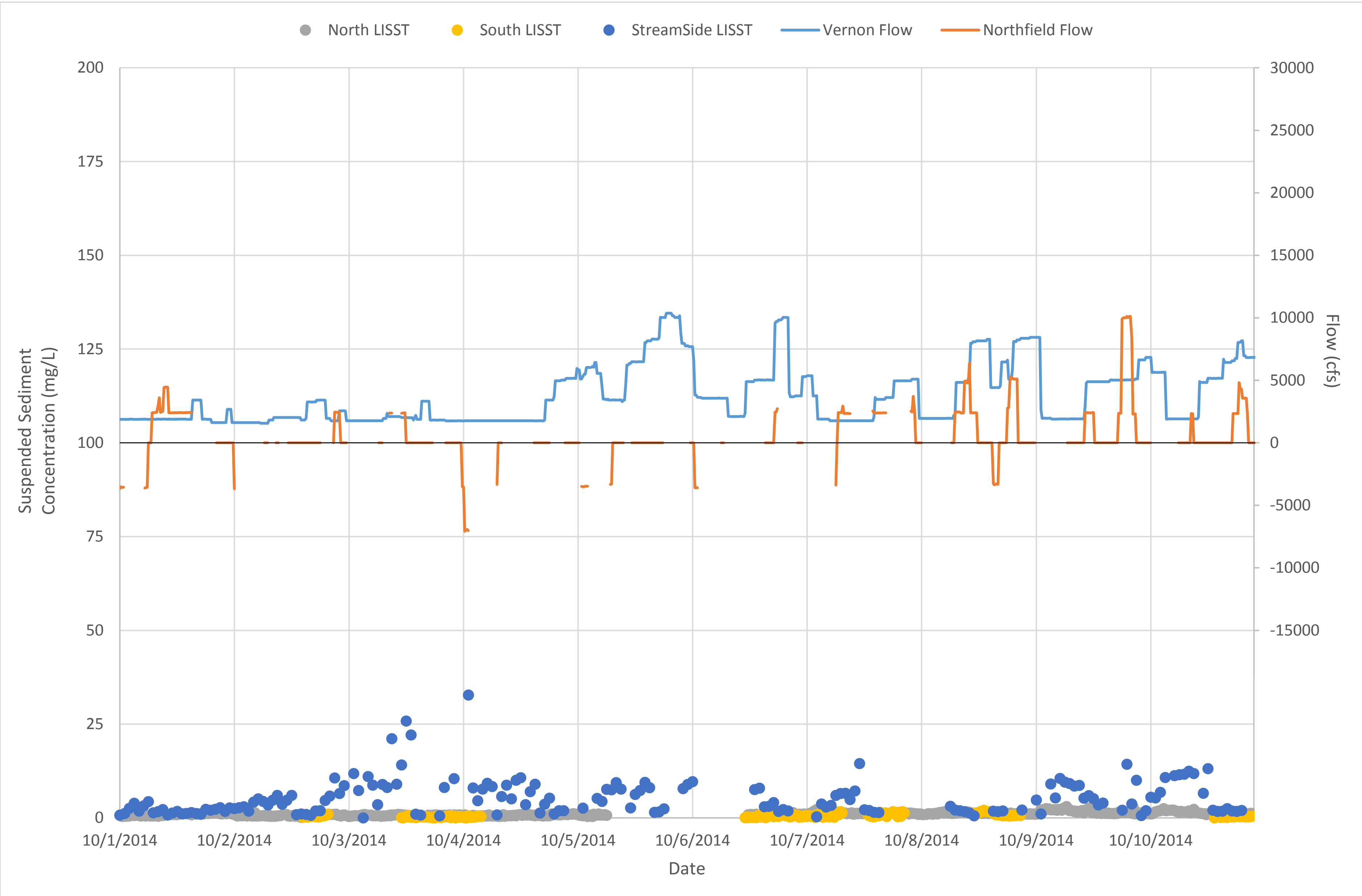
9/30/2014



North LISST
South LISST
StreamSide LISST
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
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Flow (cfs)
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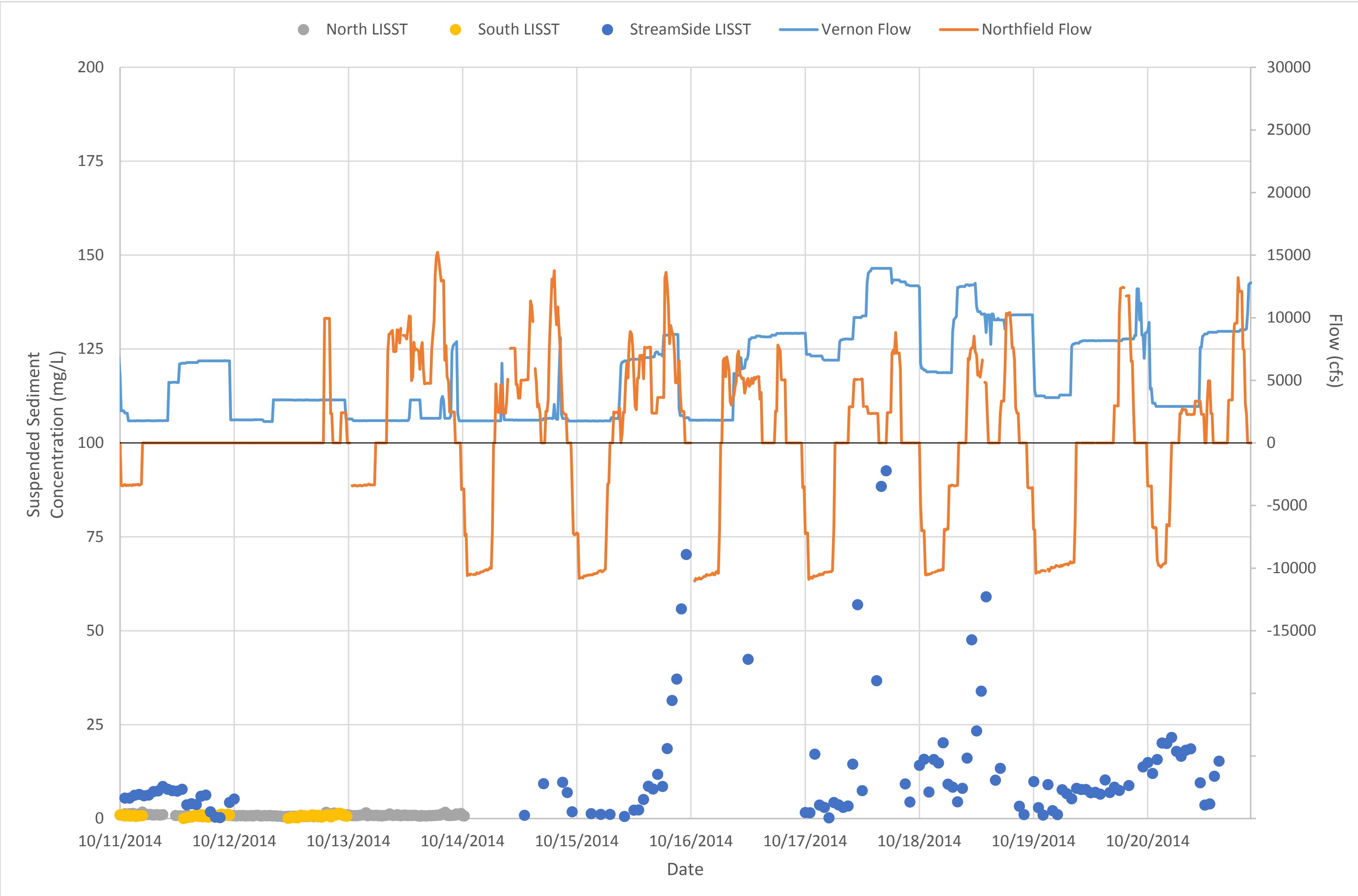
10/9/2014
10/10/2014
Date


North LISST
South LISST
StreamSide LISST
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
Flow (cfs)
Date
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10/11/2014
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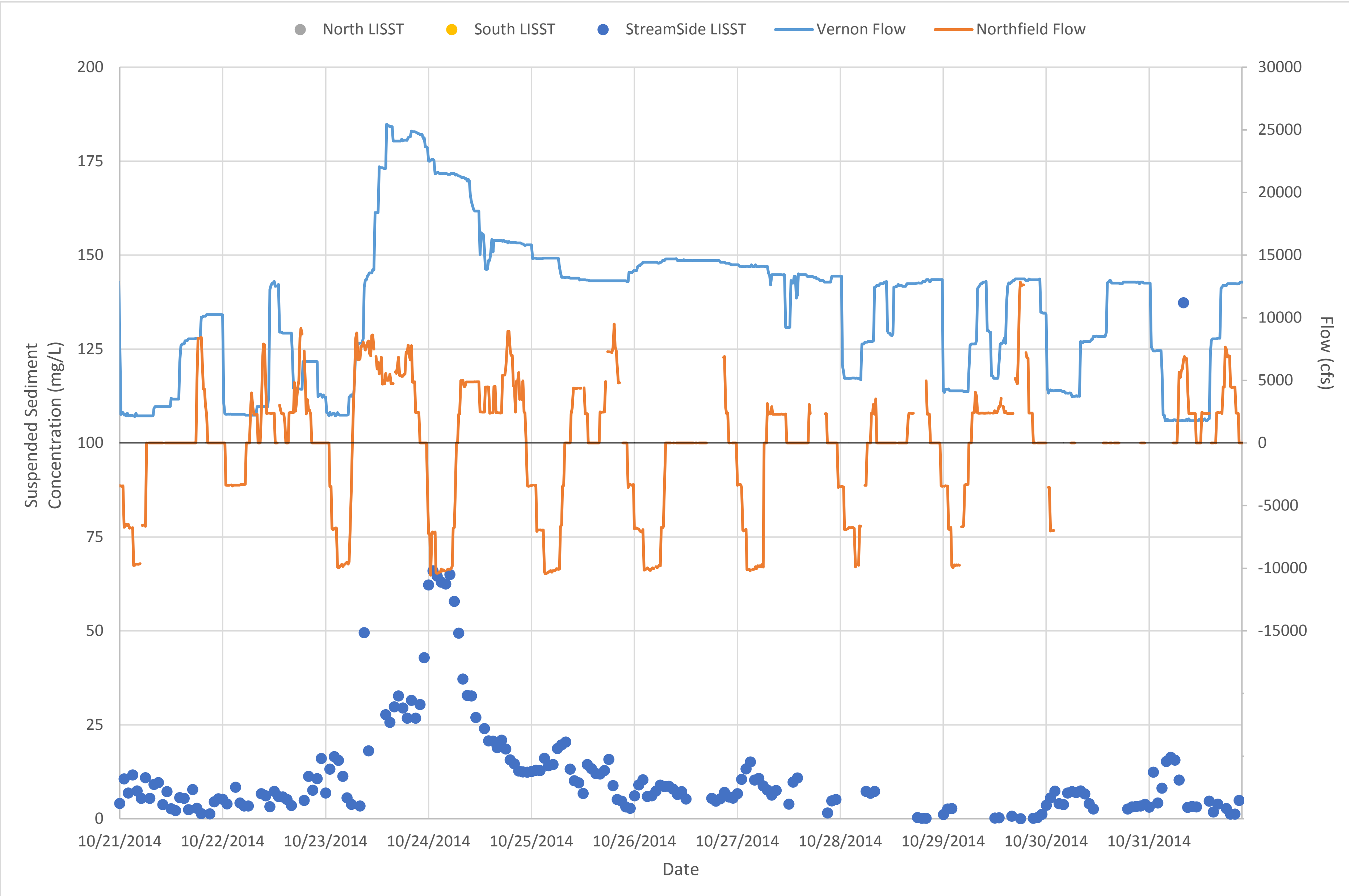
10/20/2014


North LISST
South LISST
StreamSide LISST
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
200
175
150
125
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Flow (cfs)
10/21/2014
10/22/2014
10/23/2014
10/24/2014
10/25/2014
10/26/2014
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10/28/2014
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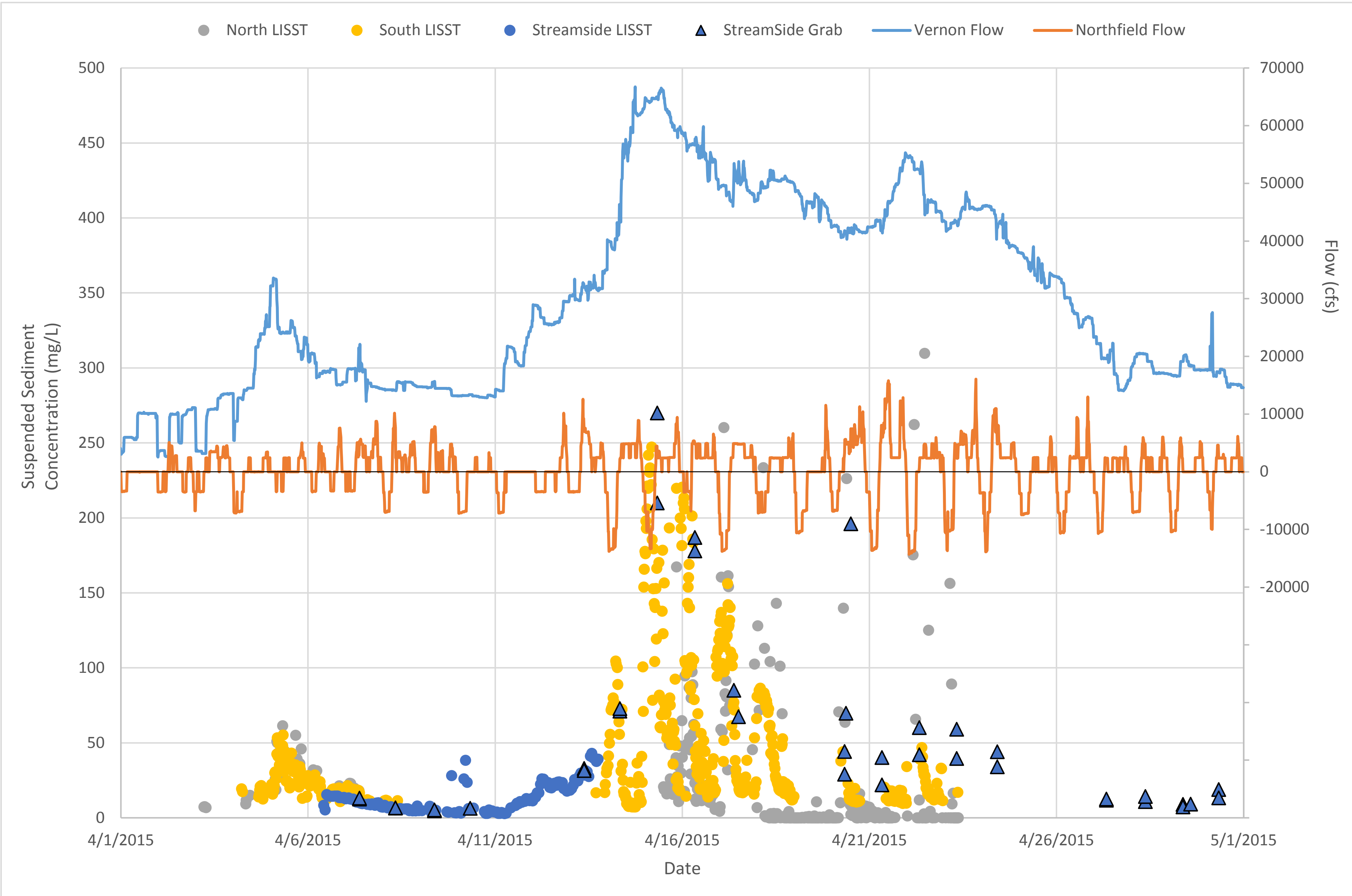
10/30/2014
10/31/2014
Date

2015 CONTINUOUS LISST INSTRUMENT TIMESERIES-MONTHLY


North LISST
South LISST
Streamside LISST
StreamSide Grab
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
Flow (cfs)
Date
500
450
400
350
300
250
200
150
100
50
0
70000
60000
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40000
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10000
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-20000
4/1/2015
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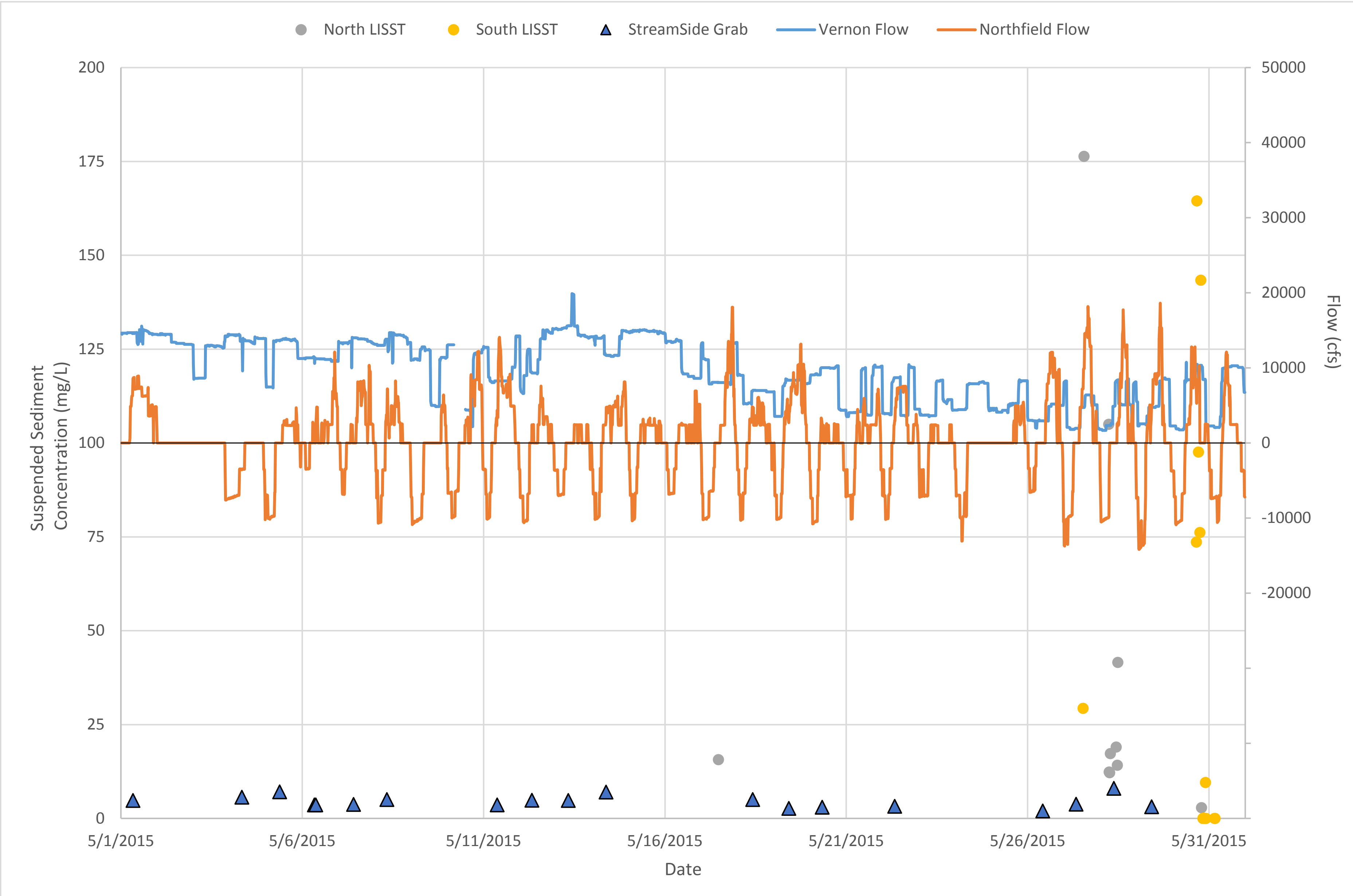
4/21/2015
4/26/2015
5/1/2015


North LISST
South LISST
StreamSide Grab
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
200
175
150
125
100
75
50
25
0
Flow (cfs)
50000
40000
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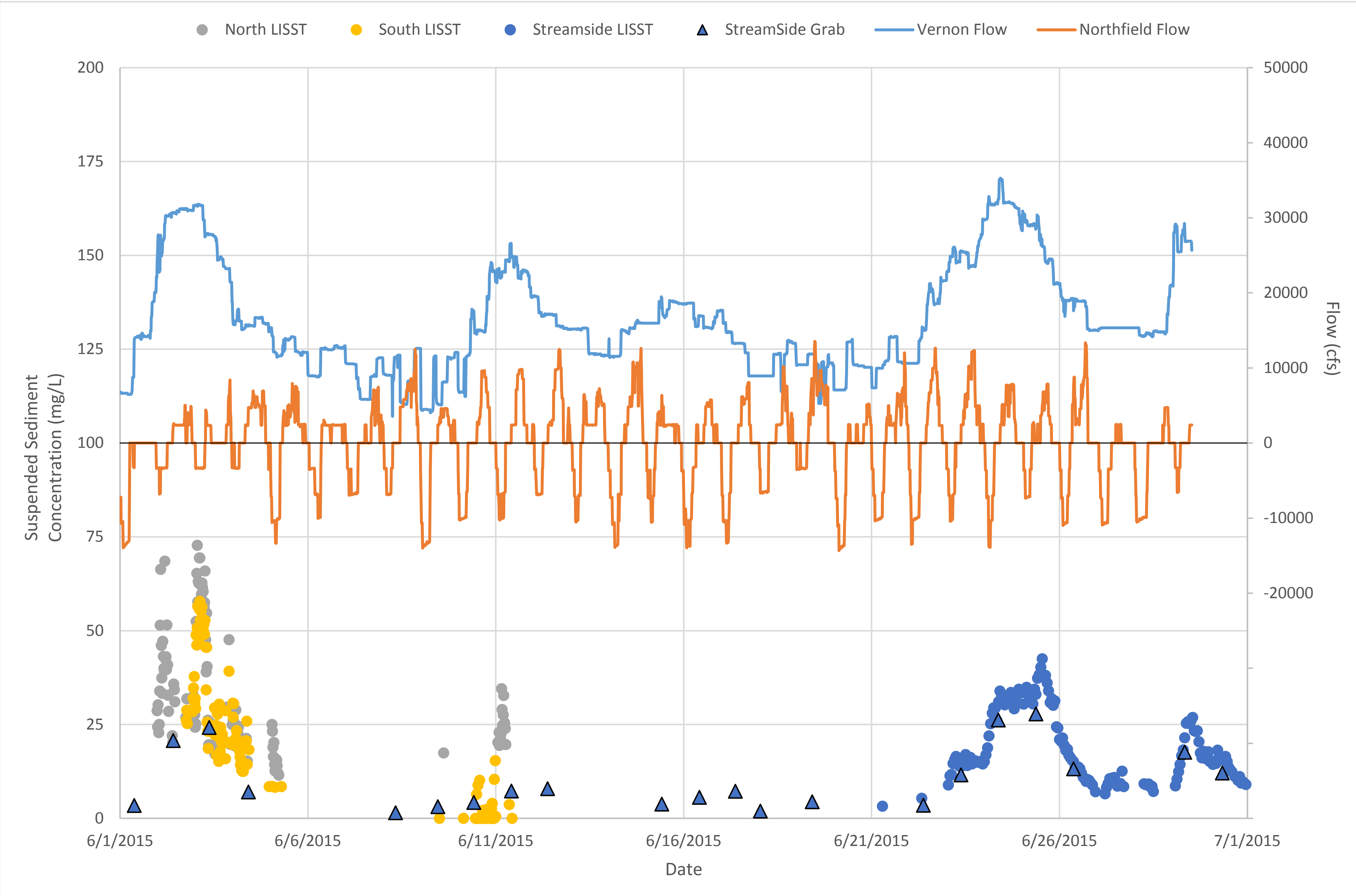
5/31/2015
Date


North LISST
South LISST
Streamside LISST
StreamSide Grab
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
Flow (cfs)
Date
200
175
150
125
100
75
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6/1/2015
6/6/2015
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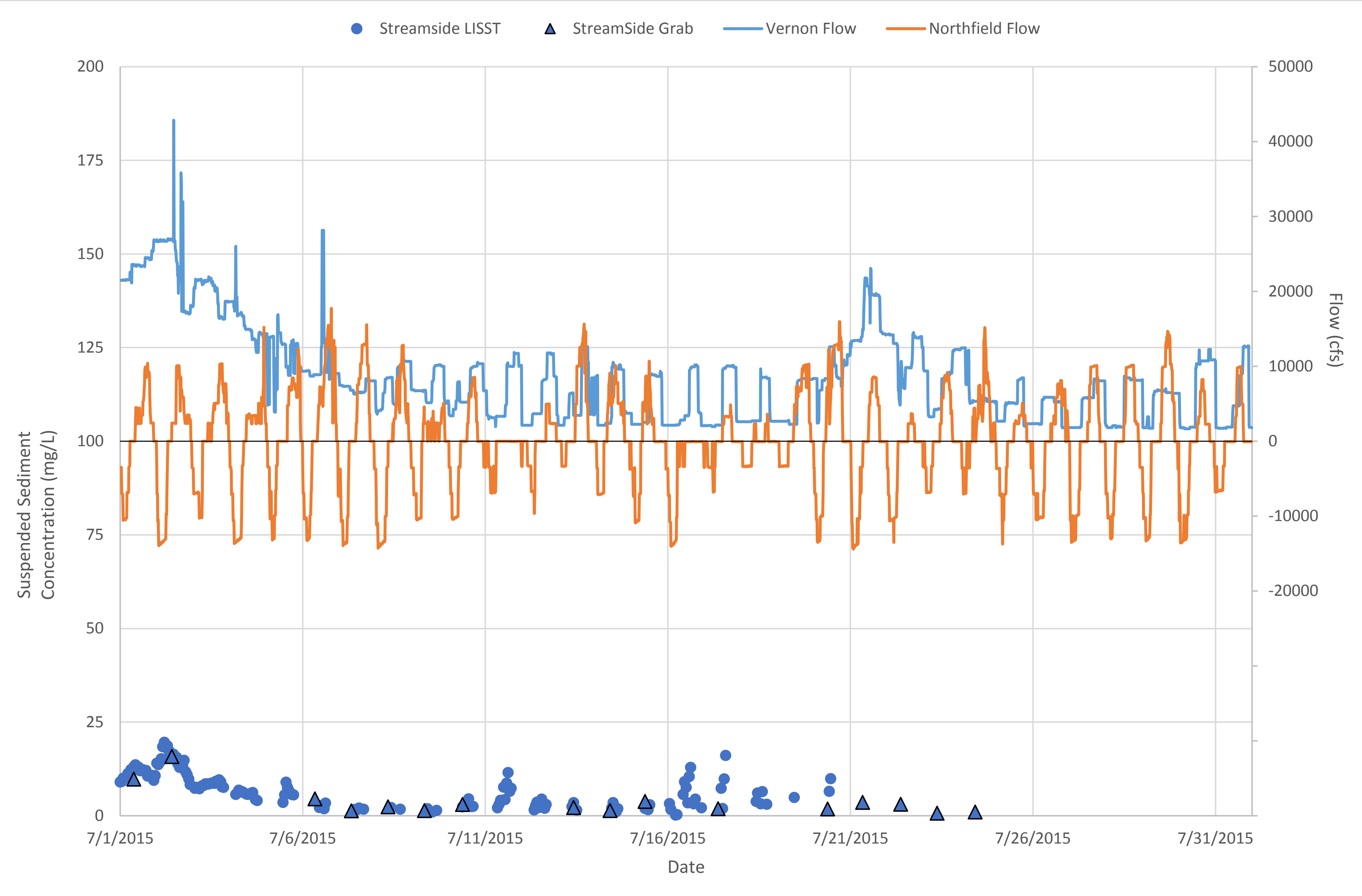
6/21/2015
6/26/2015
7/1/2015



Streamside LISST
StreamSide Grab
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
200
175
150
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Flow (cfs)
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7/1/2015
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7/11/2015
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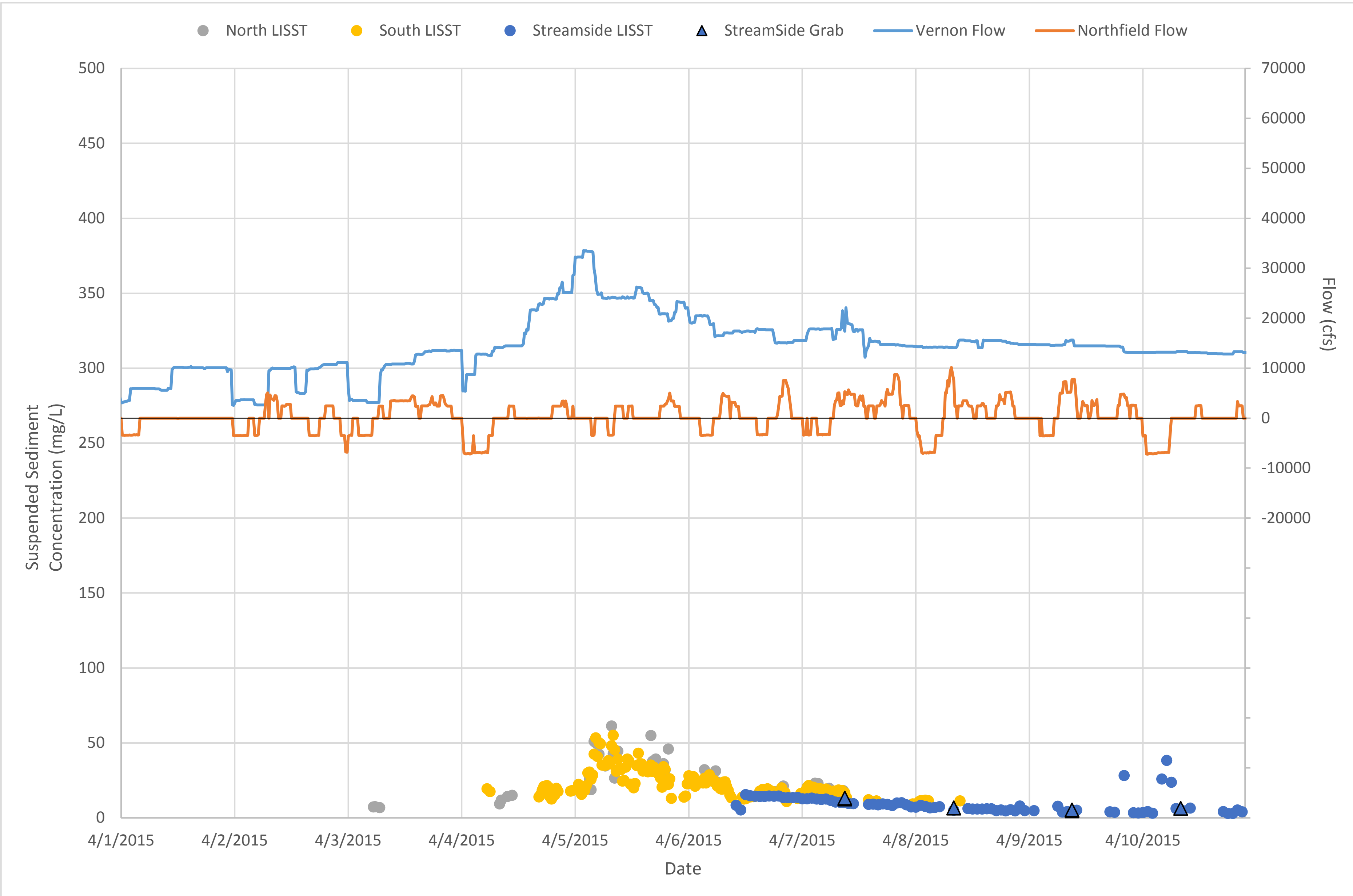
7/21/2015
7/26/2015
7/31/2015
Date

2015 CONTINUOUS LISST INSTRUMENT TIMESERIES-10 DAY


North LISST
South LISST
Streamside LISST
StreamSide Grab
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
500
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Flow (cfs)
4/1/2015
4/2/2015
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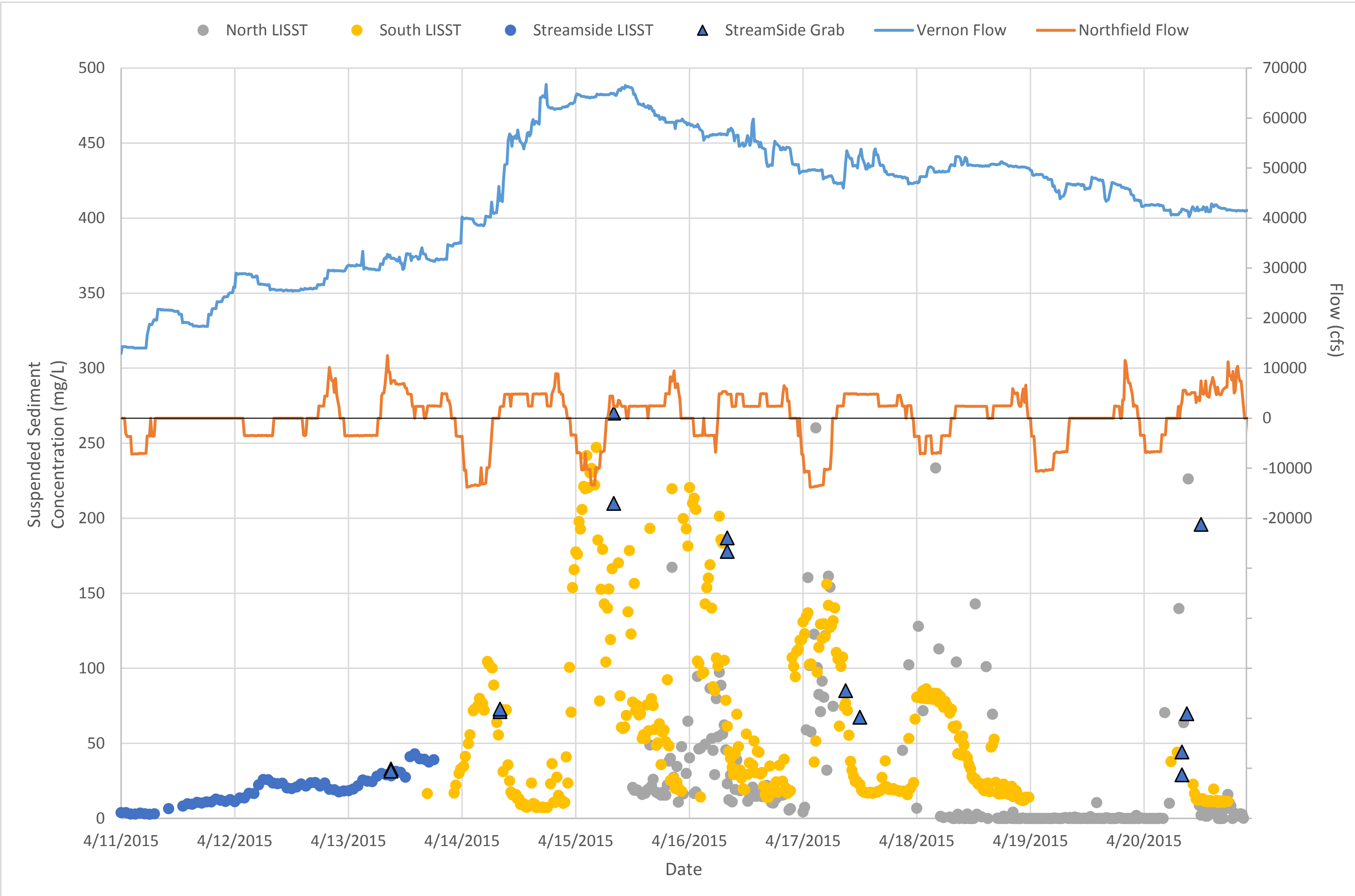
4/10/2015
Date



North LISST
South LISST
Streamside LISST
StreamSide Grab
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
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Flow (cfs)
4/11/2015
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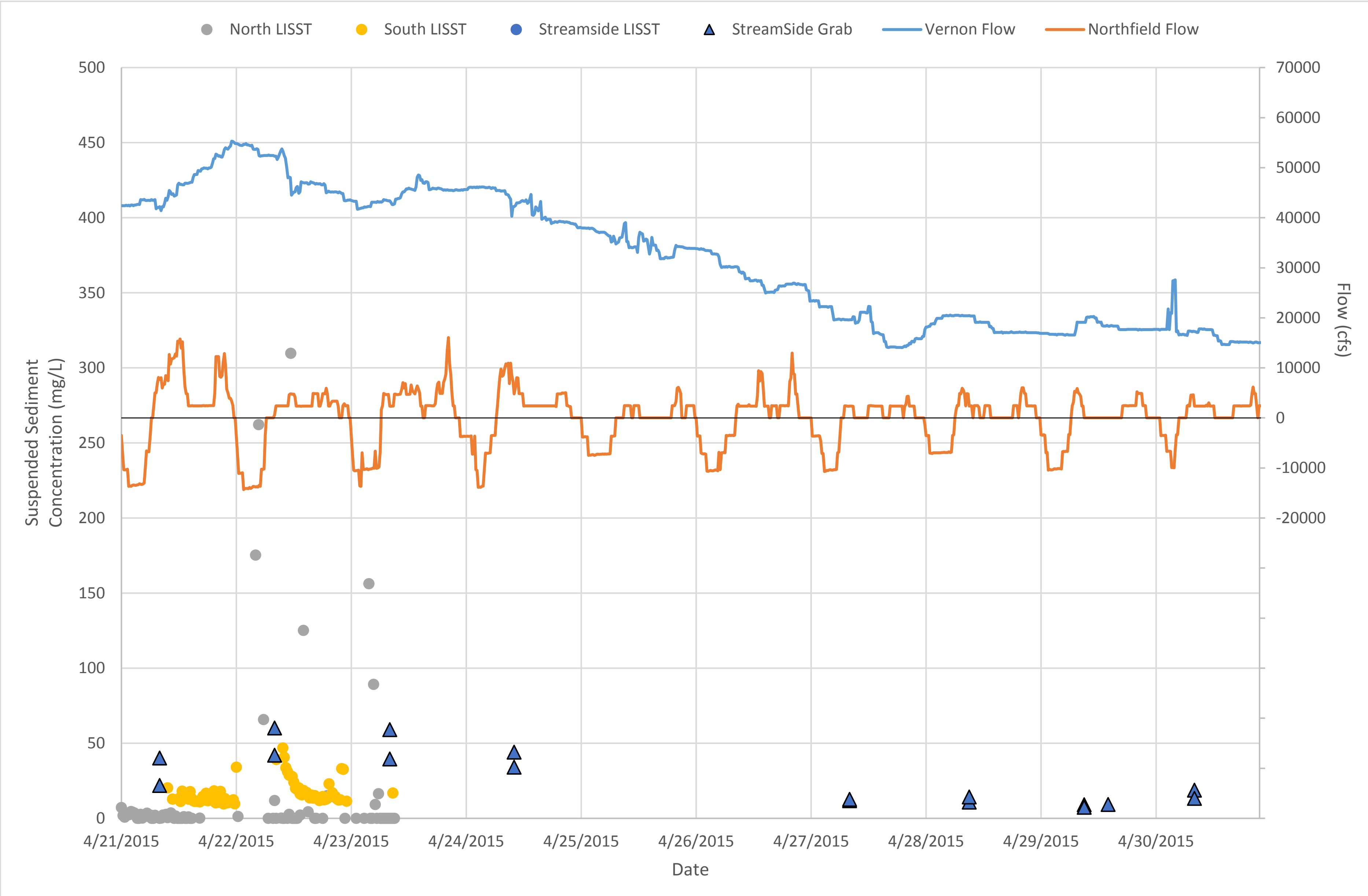
4/20/2015
Date



North LISST
South LISST
Streamside LISST
StreamSide Grab
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
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Flow (cfs)
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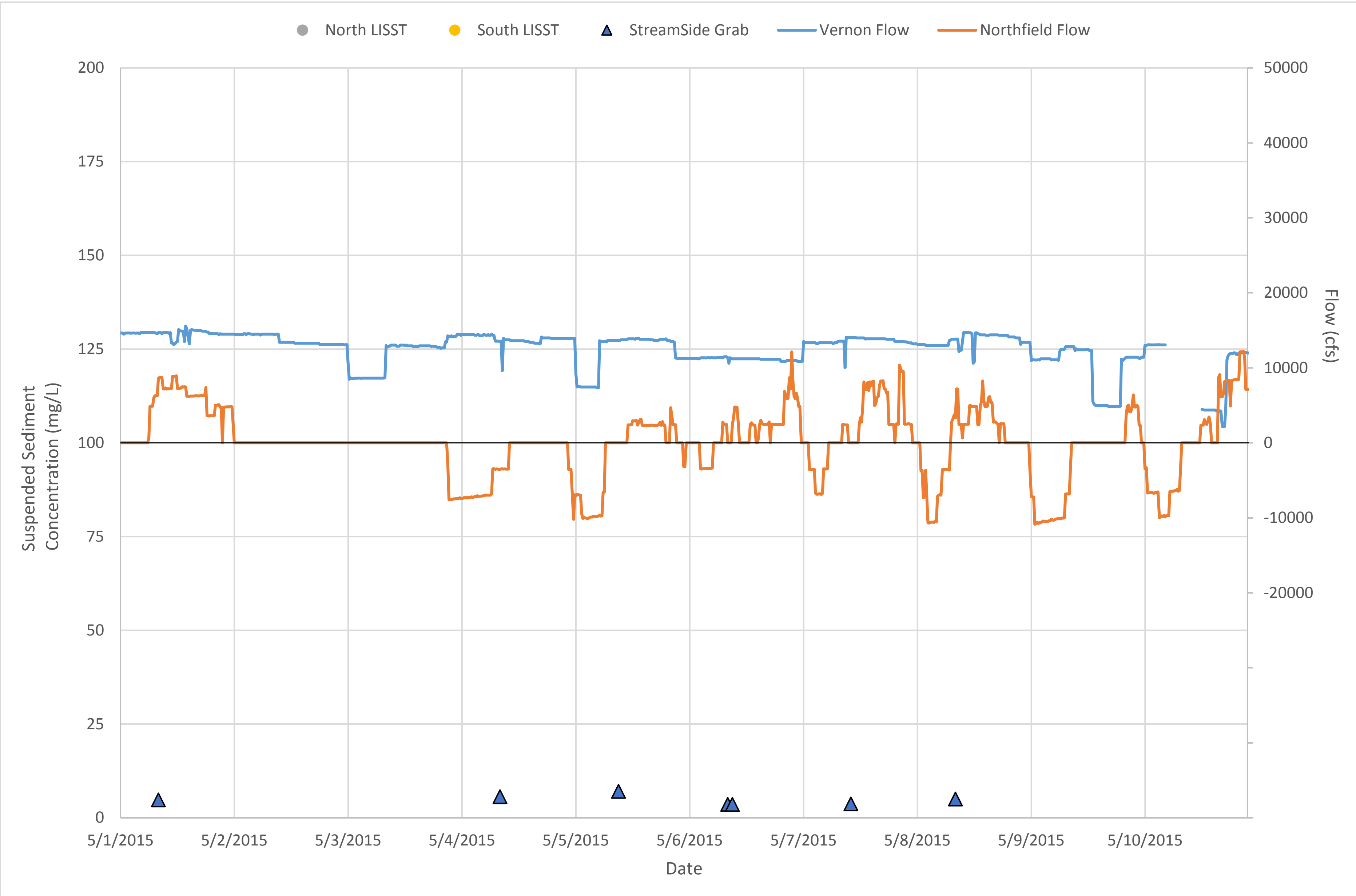
Date



North LISST
South LISST
StreamSide Grab
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
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Flow (cfs)
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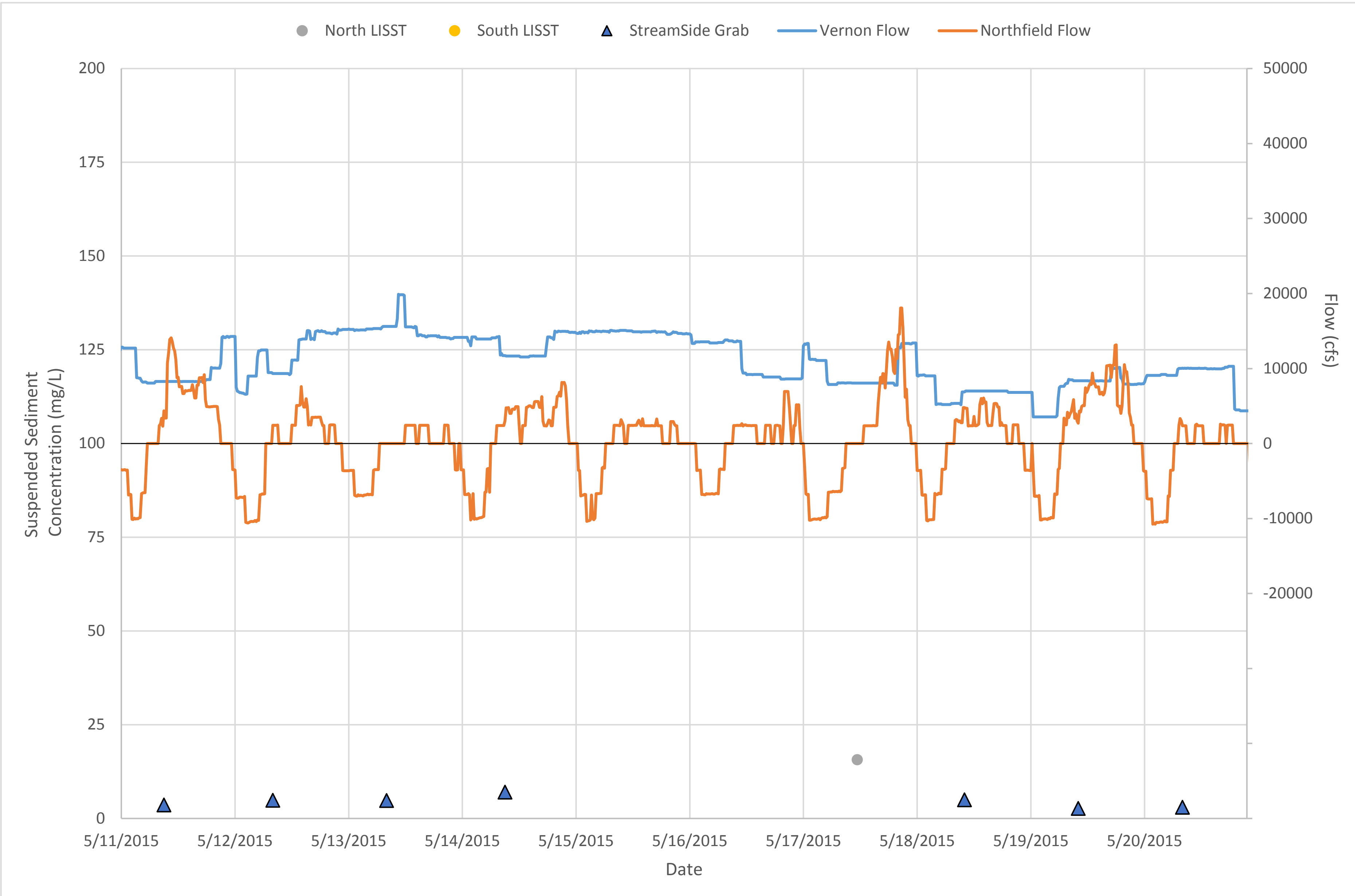
Date



North LISST
South LISST
StreamSide Grab
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
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Flow (cfs)
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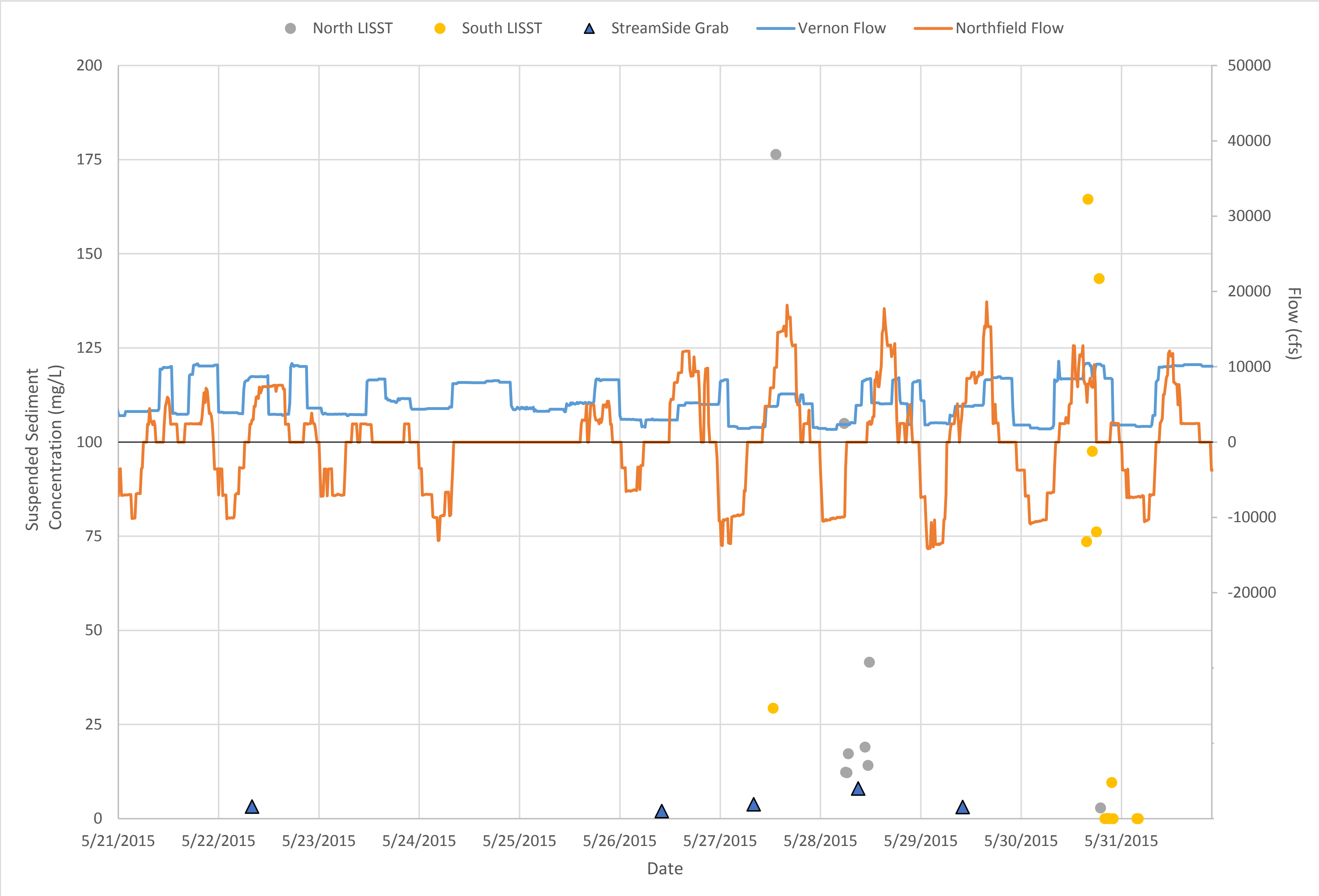
Date



North LISST
South LISST
StreamSide Grab
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
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Flow (cfs)
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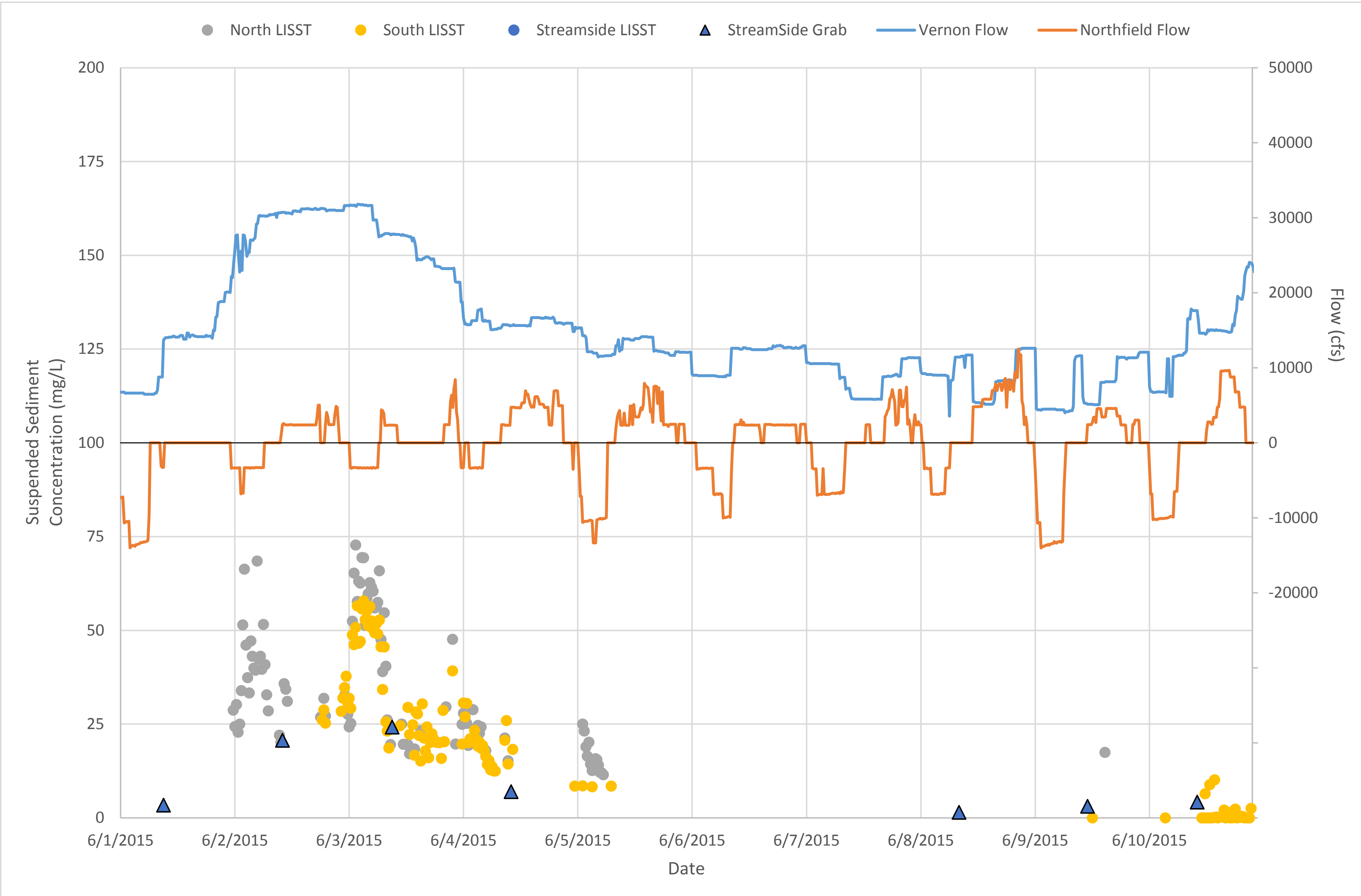
Date



North LISST
South LISST
Streamside LISST
StreamSide Grab
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
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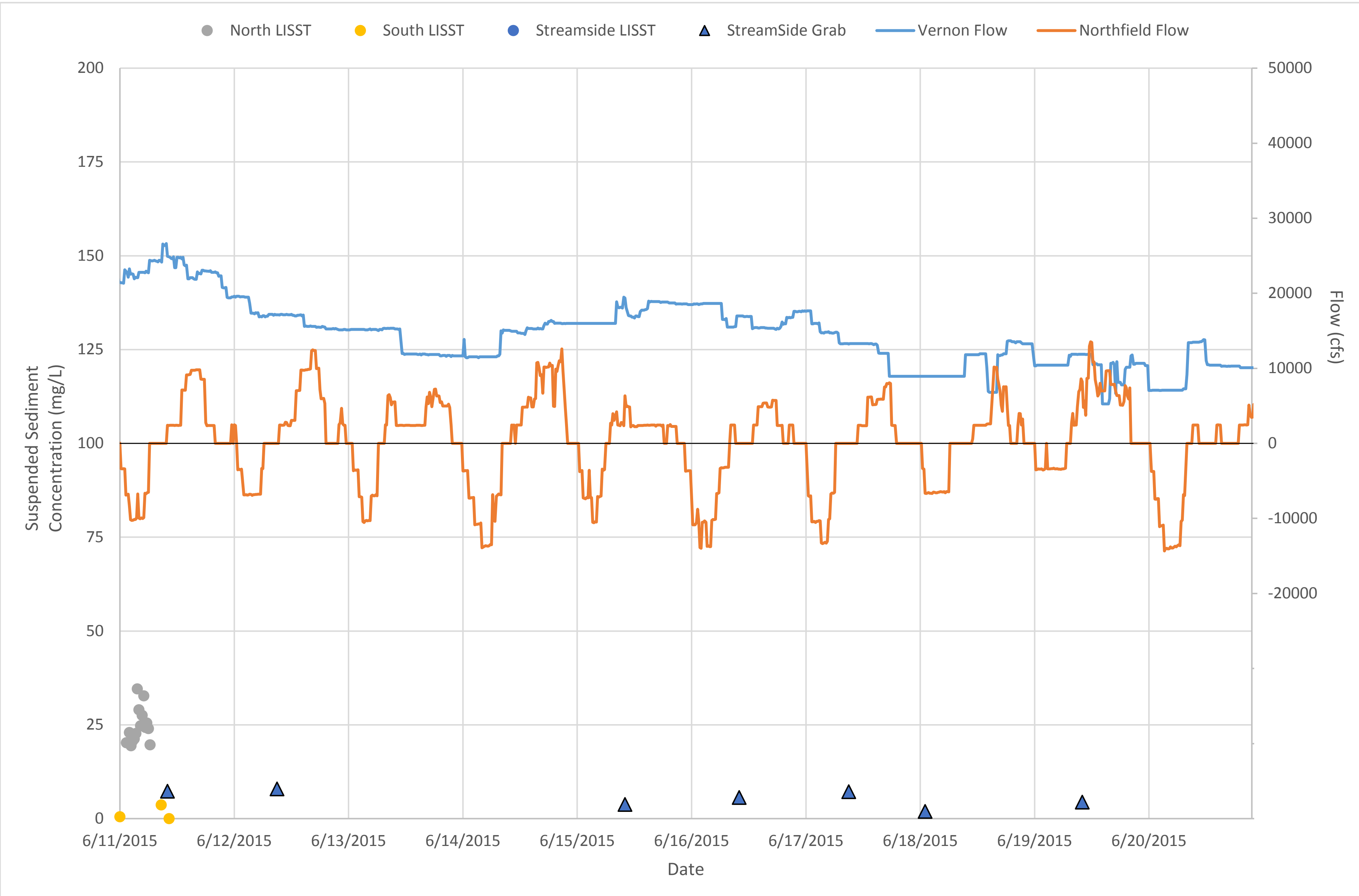

North LISST
South LISST
Streamside LISST
StreamSide Grab
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
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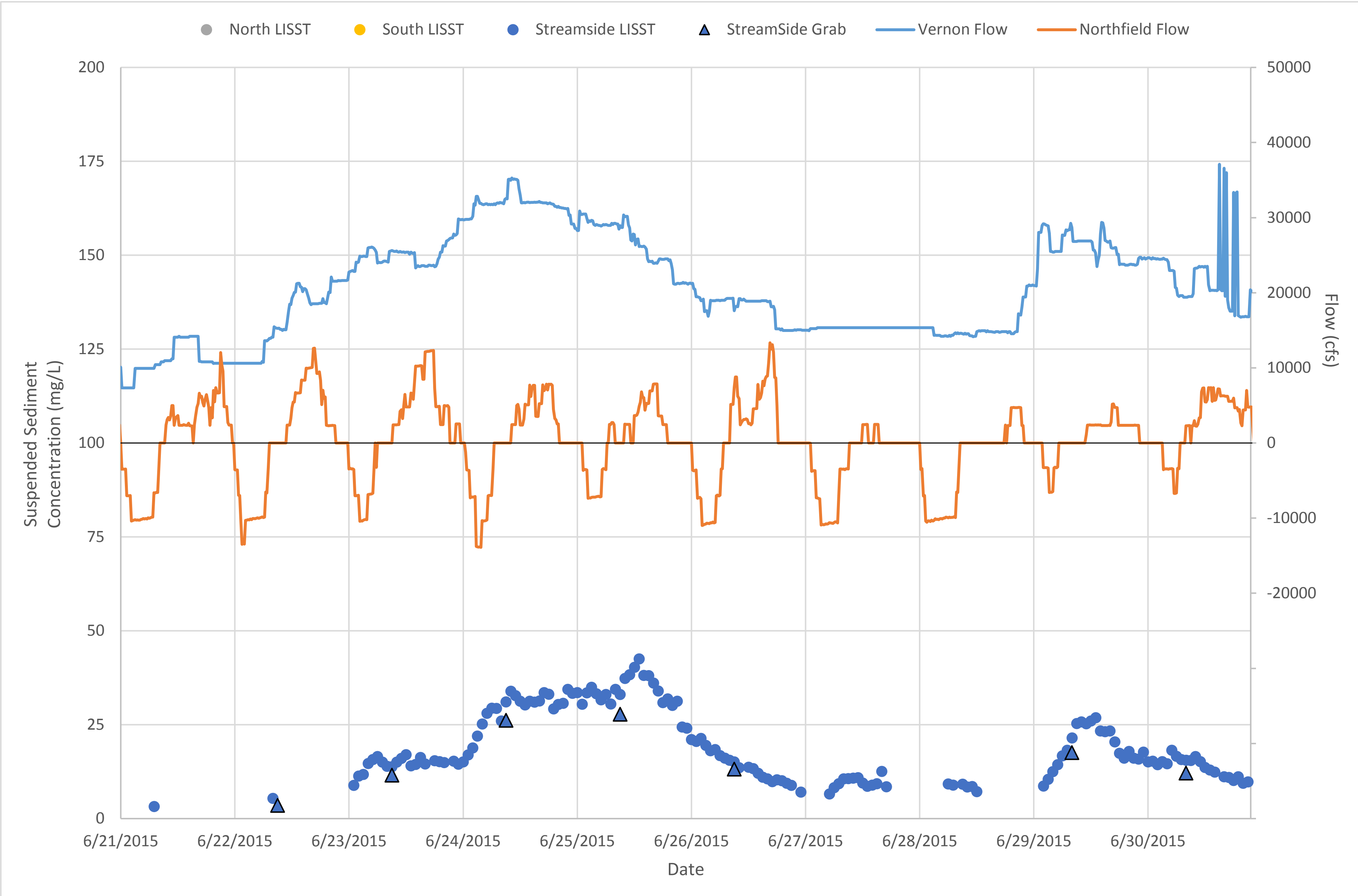

North LISST
South LISST
Streamside LISST
StreamSide Grab
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
Flow (cfs)
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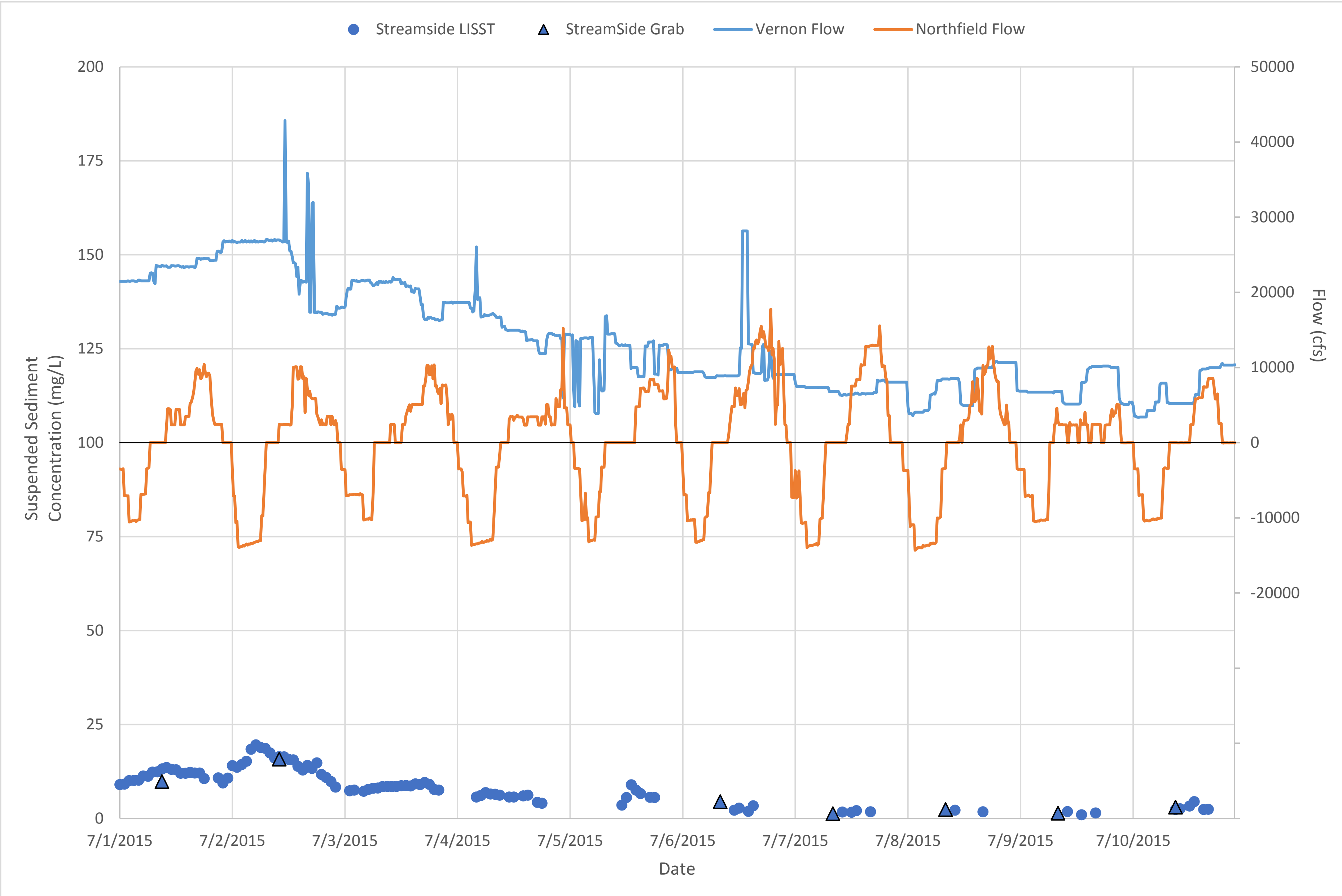

Streamside LISST
StreamSide Grab
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
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Flow (cfs)
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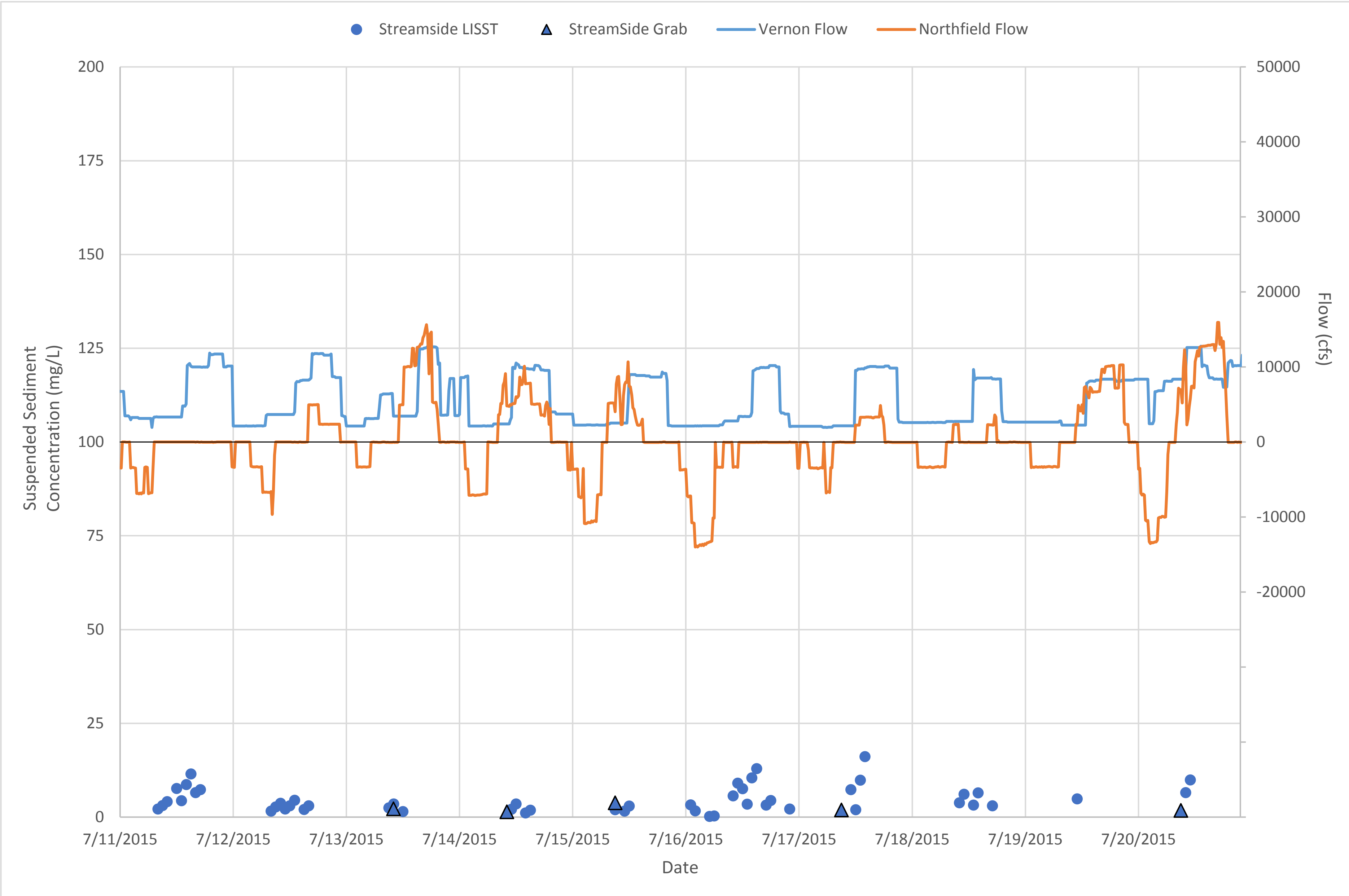
Date



Streamside LISST
StreamSide Grab
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
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Flow (cfs)
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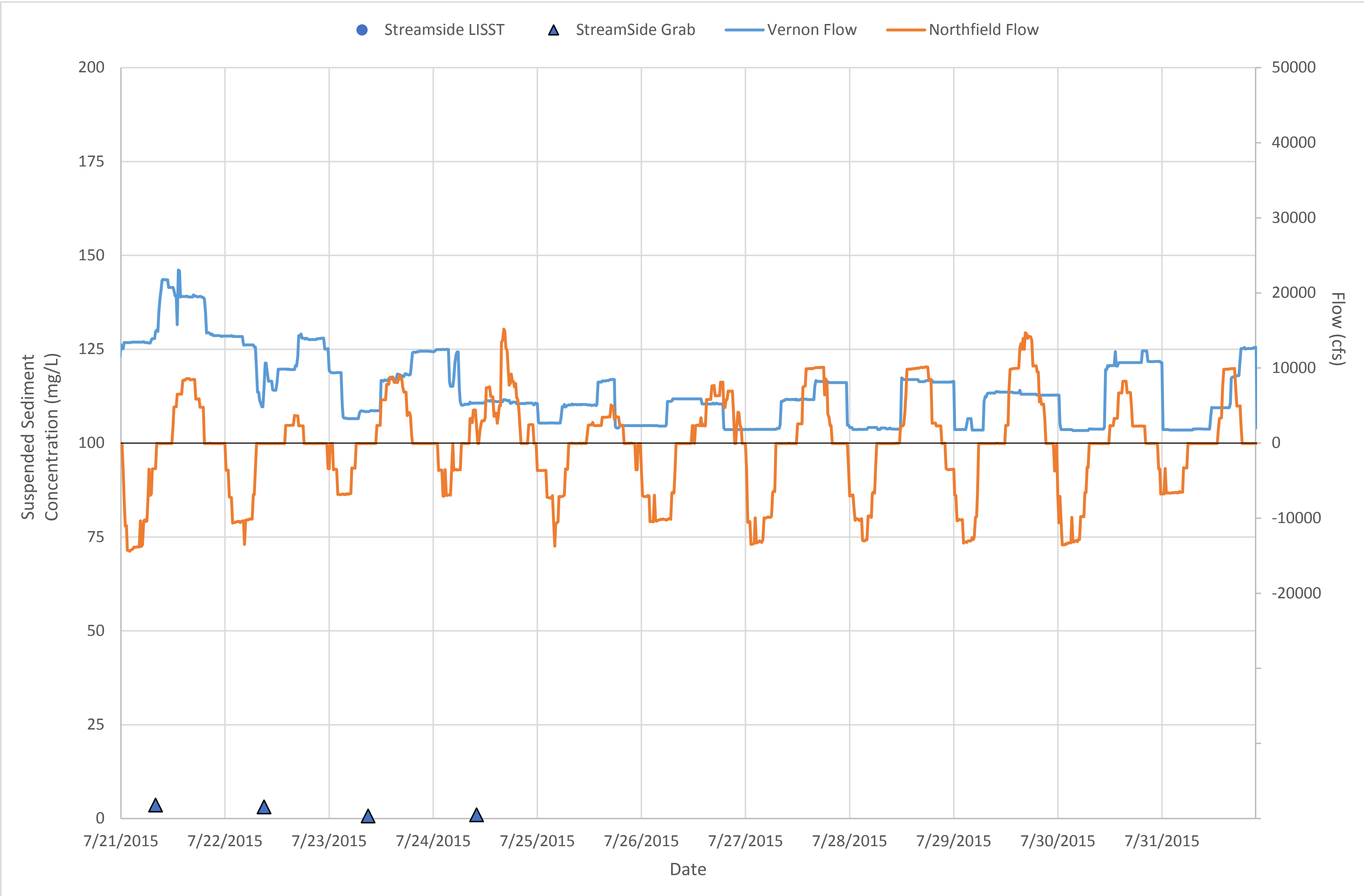
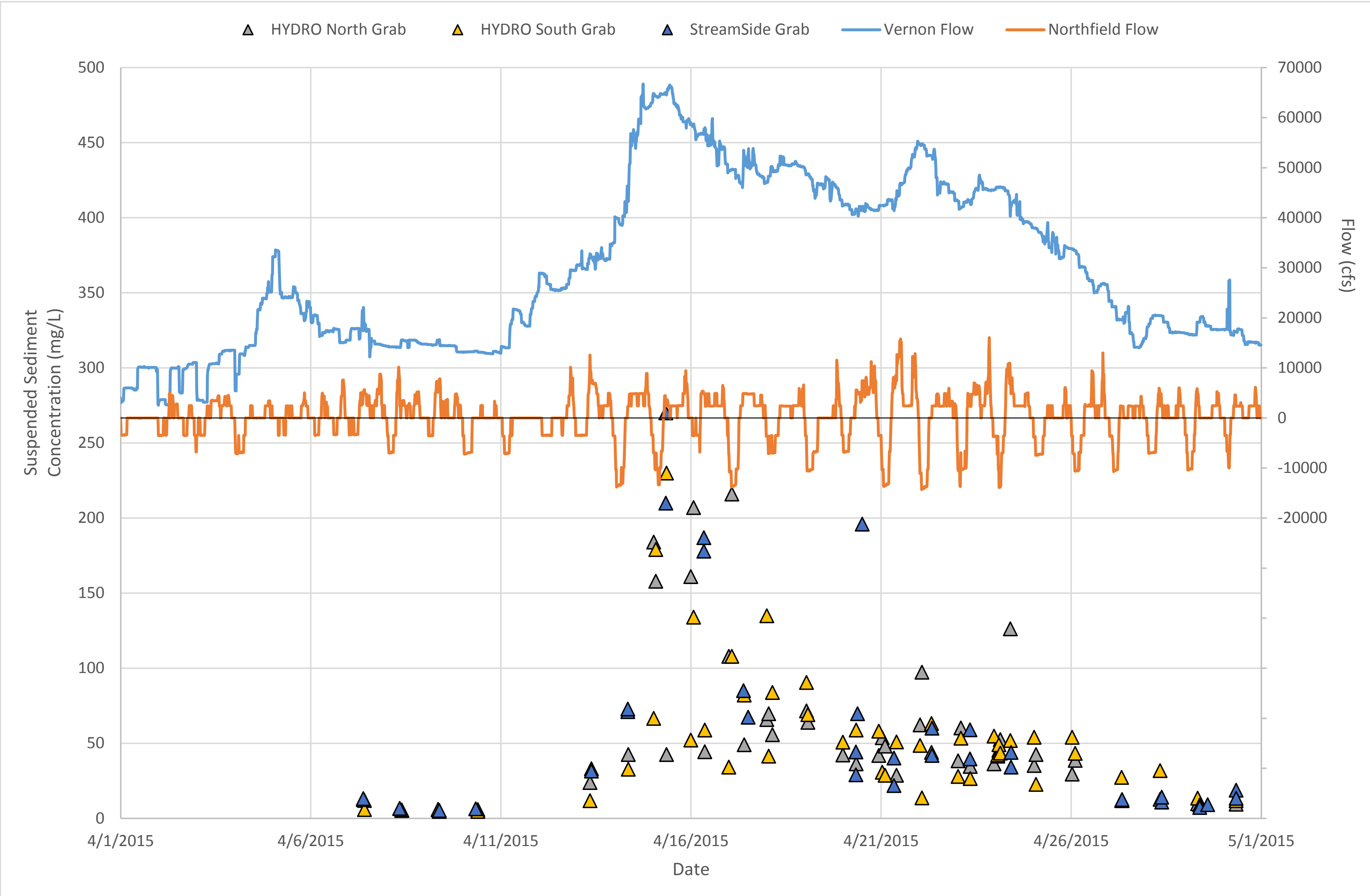
7/20/2015
Date



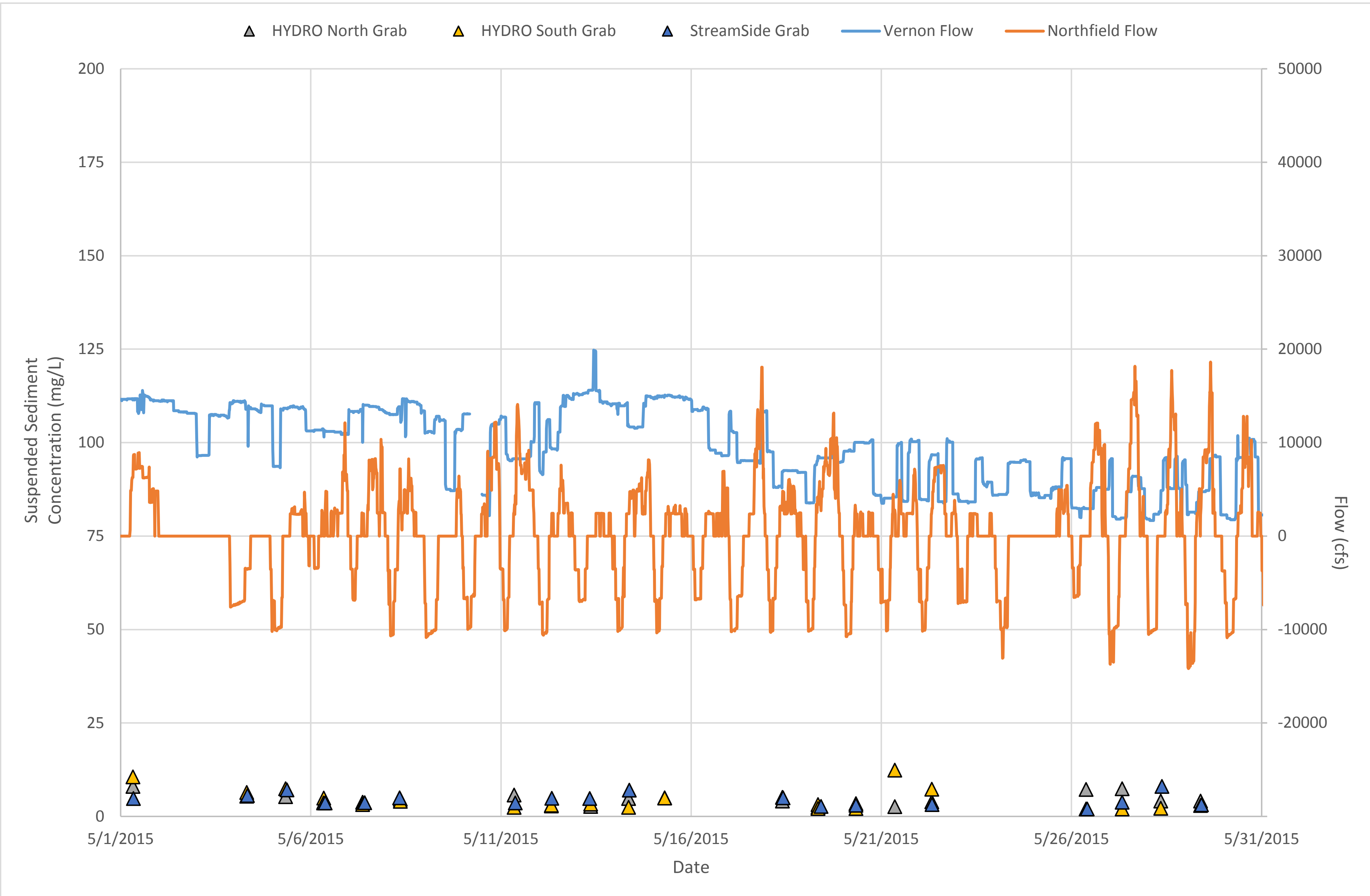
Streamside LISST
StreamSide Grab
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
Flow (cfs)
Date
200
175
150
125
100
75
50
25
0
50000
40000
30000
20000
10000
0
-10000
-20000
7/21/2015
7/22/2015
7/23/2015
7/24/2015
7/25/2015
7/26/2015
7/27/2015
7/28/2015
7/29/2015
7/30/2015
7/31/2015

APPENDIX E – GRAB SAMPLE SSC, FLOW, AND PROJECT OPERATIONS TIMESERIES PLOTS MG/L (2015)

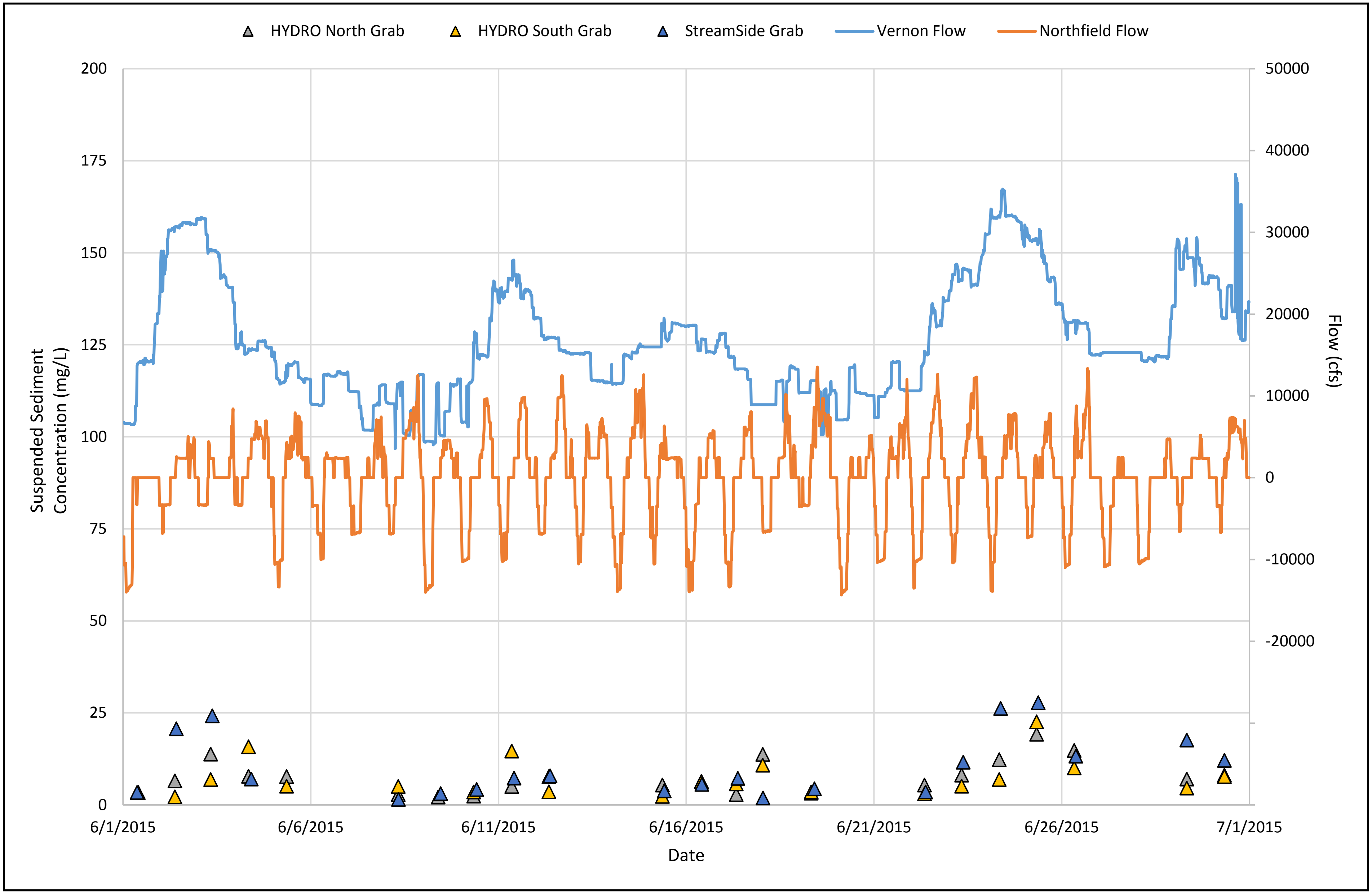
2015 GRAB SAMPLE TIMESERIES-MONTHLY



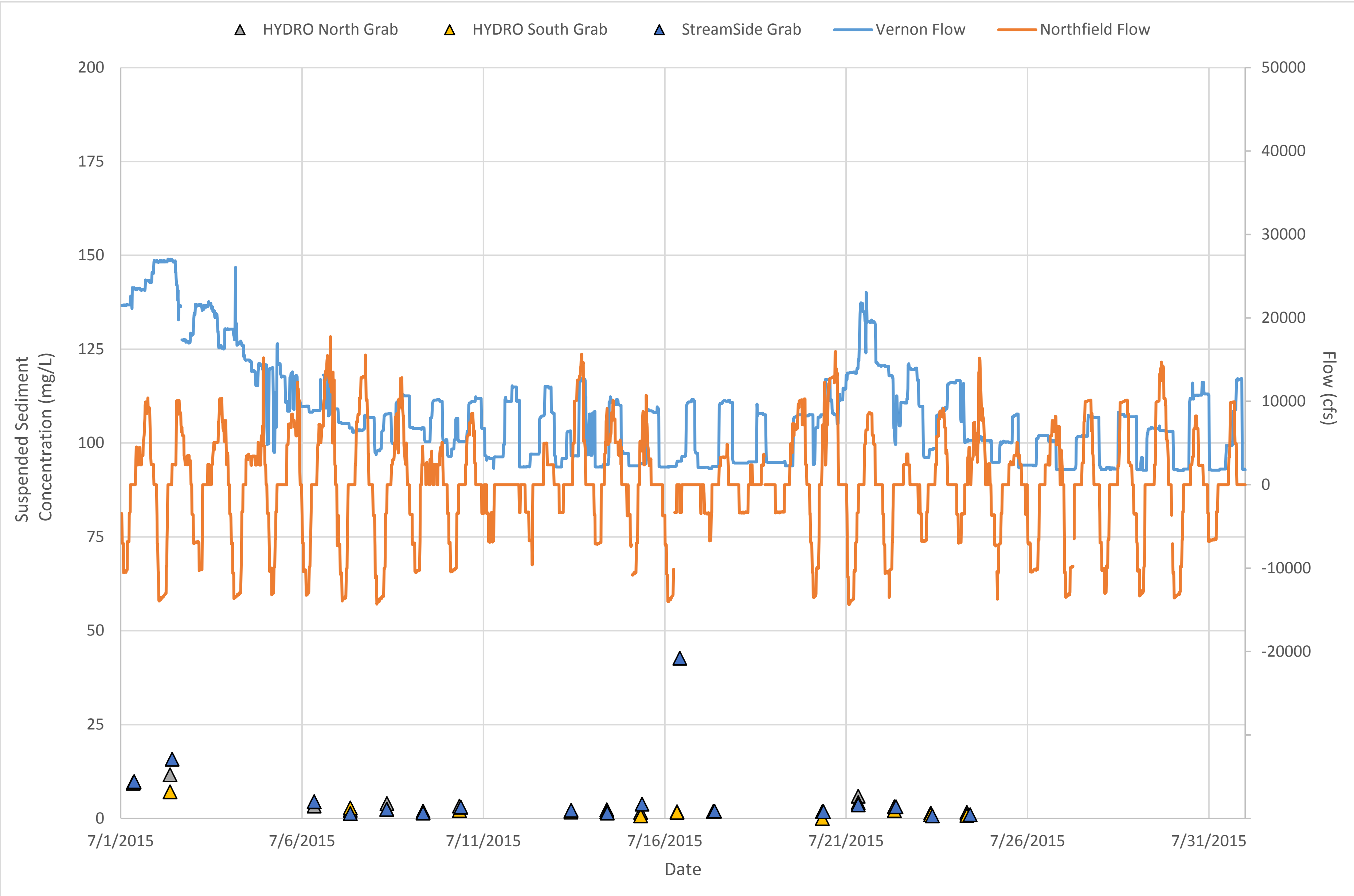
HYDRO North Grab
HYDRO South Grab
StreamSide Grab
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
Flow (cfs)
Date
500
450
400
350
300
250
200
150
100
50
0
70000
60000
50000
40000
30000
20000
10000
0
-10000
-20000
4/1/2015
4/6/2015
4/11/2015
4/16/2015
4/21/2015
4/26/2015
5/1/2015



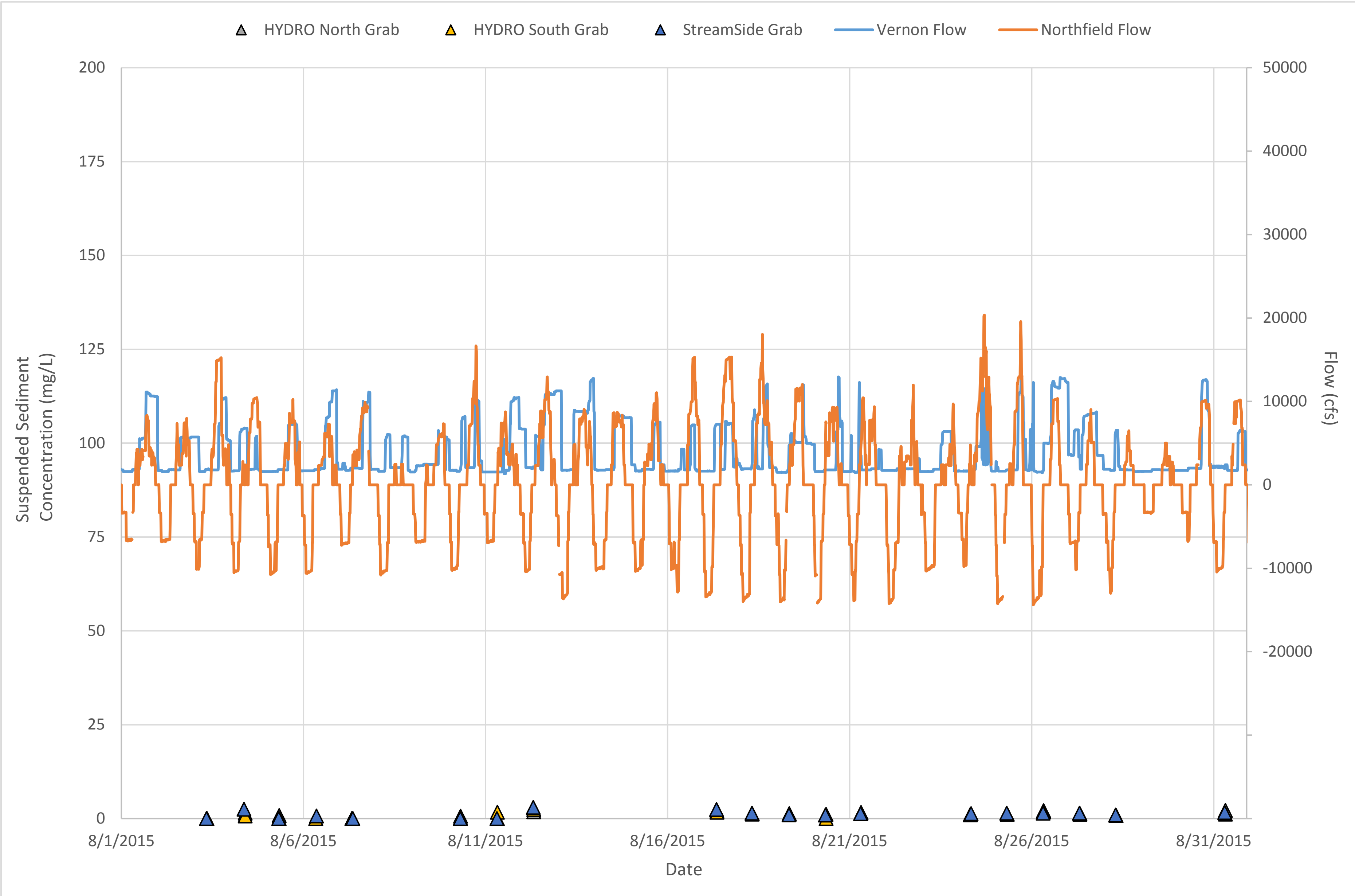
HYDRO North Grab
HYDRO South Grab
StreamSide Grab
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
Flow (cfs)
Date
200
175
150
125
100
75
50
25
0
50000
40000
30000
20000
10000
0
-10000
-20000
5/1/2015
5/6/2015
5/11/2015
5/16/2015
5/21/2015
5/26/2015
5/31/2015



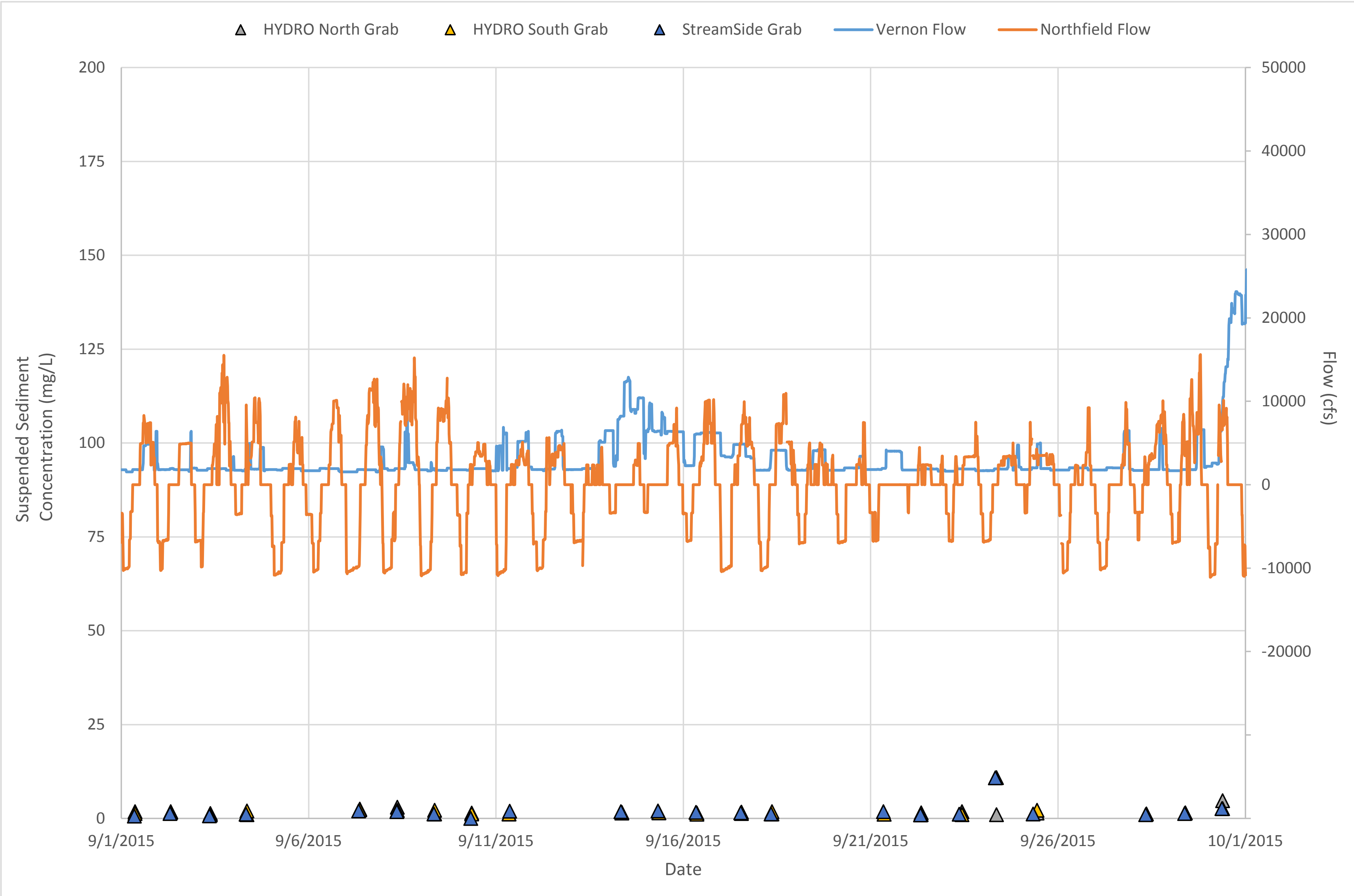
HYDRO North Grab
HYDRO South Grab
StreamSide Grab
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
200
175
150
125
100
75
50
25
0
Flow (cfs)
50000
40000
30000
20000
10000
0
-10000
-20000
6/1/2015
6/6/2015
6/11/2015
6/16/2015
6/21/2015
6/26/2015
7/1/2015
Date



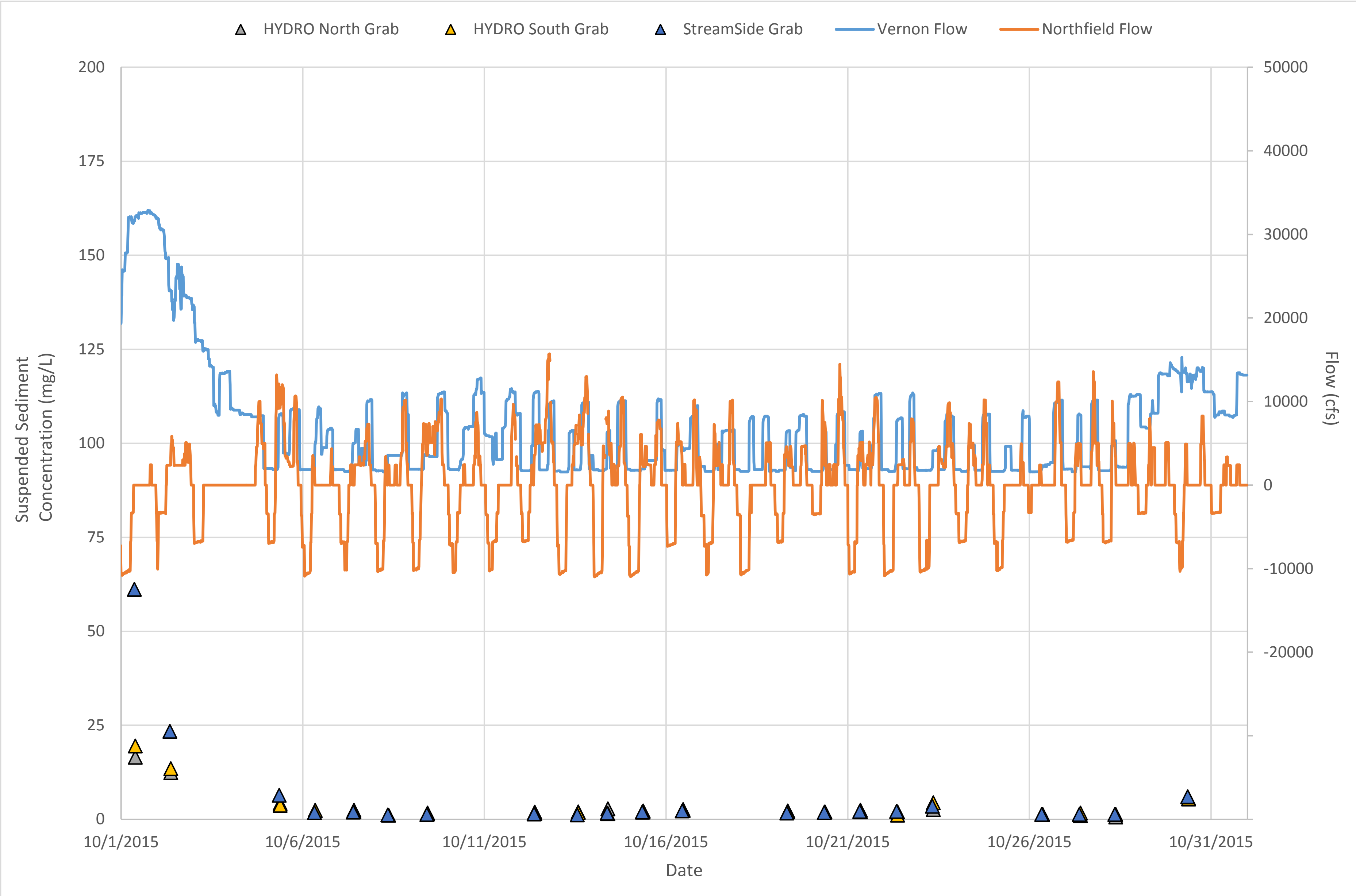
HYDRO North Grab
HYDRO South Grab
StreamSide Grab
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
200
175
150
125
100
75
50
25
0
Flow (cfs)
50000
40000
30000
20000
10000
0
-10000
-20000
7/1/2015
7/6/2015
7/11/2015
7/16/2015
7/21/2015
7/26/2015
7/31/2015
Date



HYDRO North Grab
HYDRO South Grab
StreamSide Grab
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
200
175
150
125
100
75
50
25
0
50000
40000
30000
20000
10000
0
-10000
-20000
Flow (cfs)
8/1/2015
8/6/2015
8/11/2015
8/16/2015
8/21/2015
8/26/2015
8/31/2015
Date



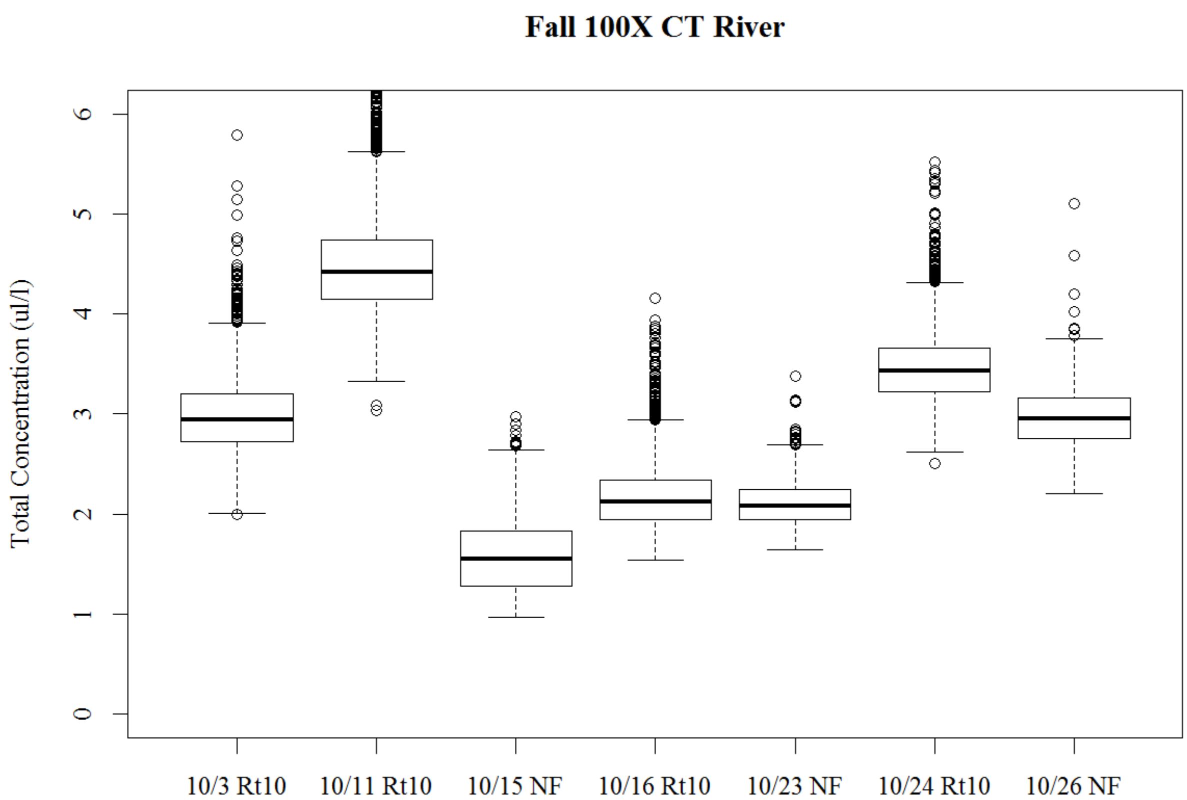
HYDRO North Grab
HYDRO South Grab
StreamSide Grab
Vernon Flow
Northfield Flow
Suspended Sediment Concentration (mg/L)
Flow (cfs)
Date
200
175
150
125
100
75
50
25
0
50000
40000
30000
20000
10000
0
-10000
-20000
9/1/2015
9/6/2015
9/11/2015
9/16/2015
9/21/2015
9/26/2015
10/1/2015



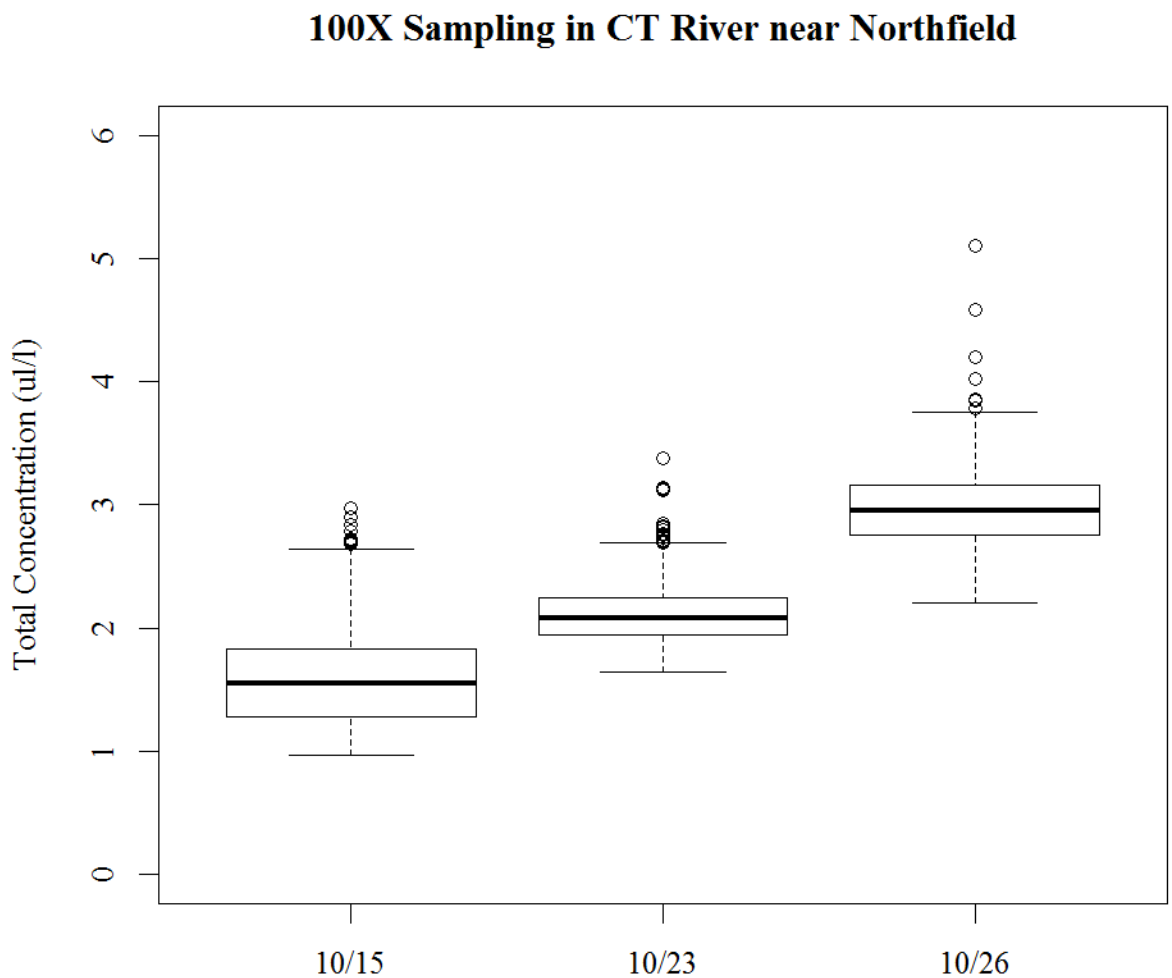
HYDRO North Grab
HYDRO South Grab
StreamSide Grab
Vernon Flow
Northfield Flow
200
175
150
125
100
75
50
25
0
Suspended Sediment Concentration (mg/L)
50000
40000
30000
20000
10000
0
-10000
-20000
Flow (cfs)
10/1/2015
10/6/2015
10/11/2015
10/16/2015
10/21/2015
10/26/2015
10/31/2015
Date

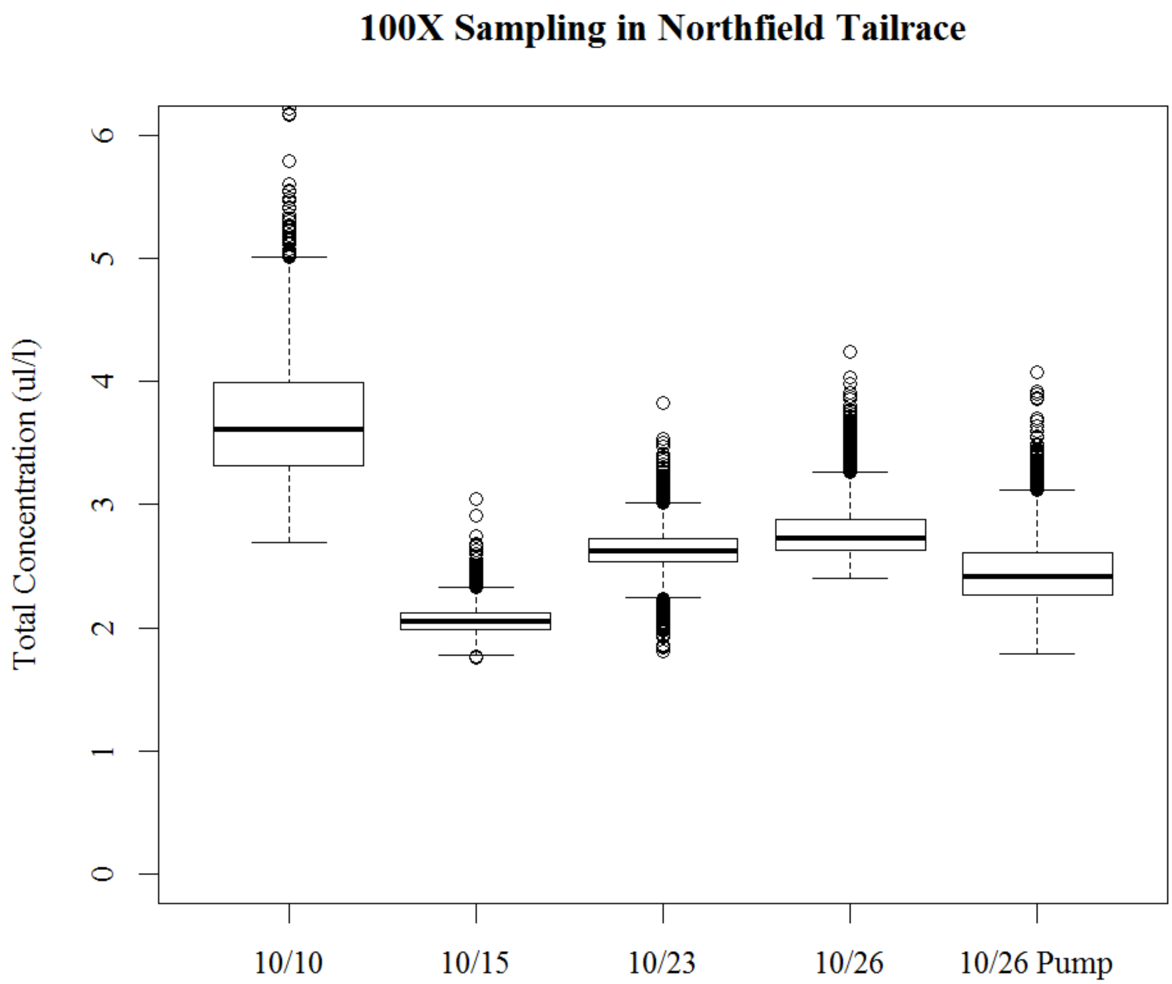
APPENDIX F – LISST-100X ROUTE 10 BRIDGE & NORTHFIELD MOUNTAIN TAILRACE CROSS-SECTION PLOTS (2013)

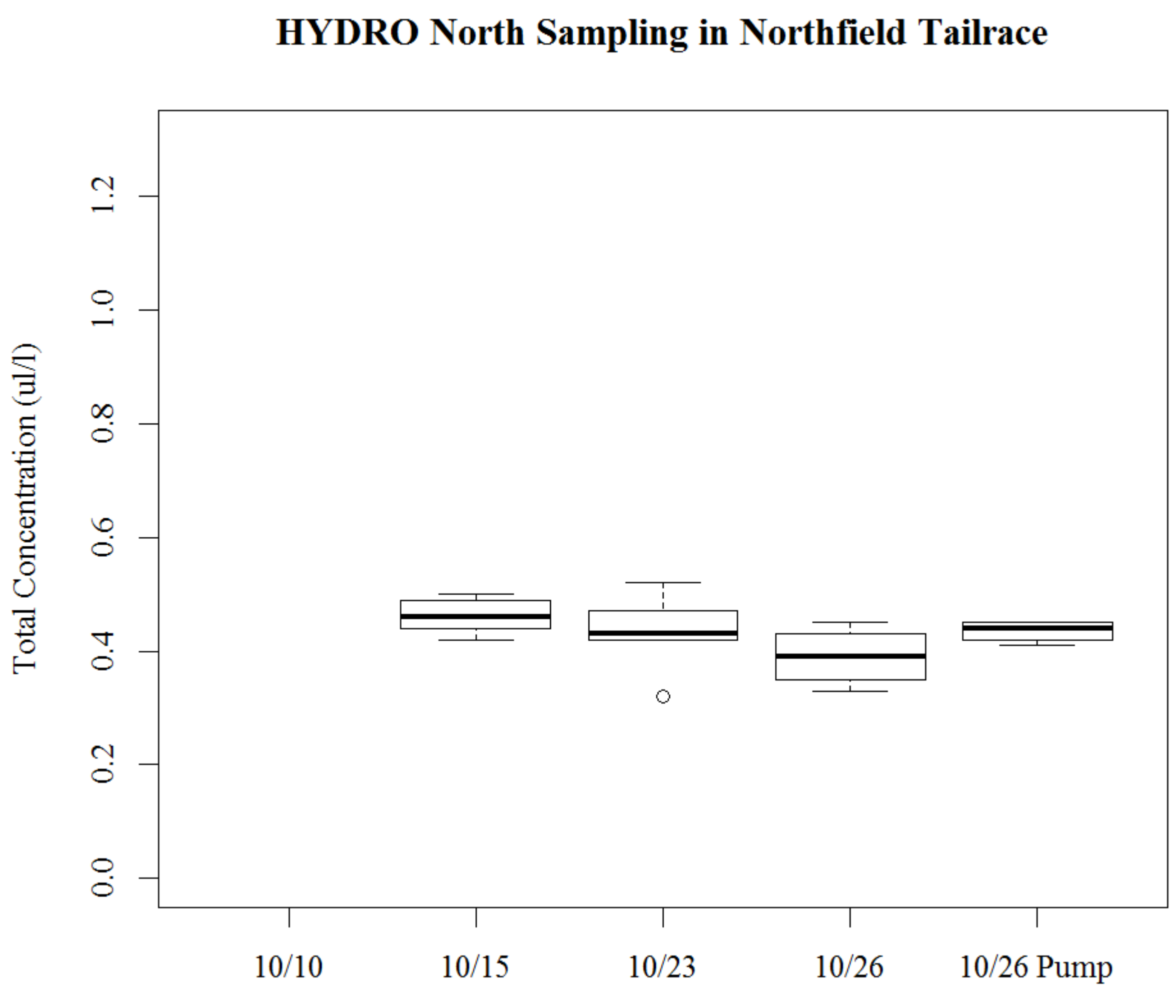
2013 LISST 100X PLOTS- HYDRO AND 100X ANALYSIS

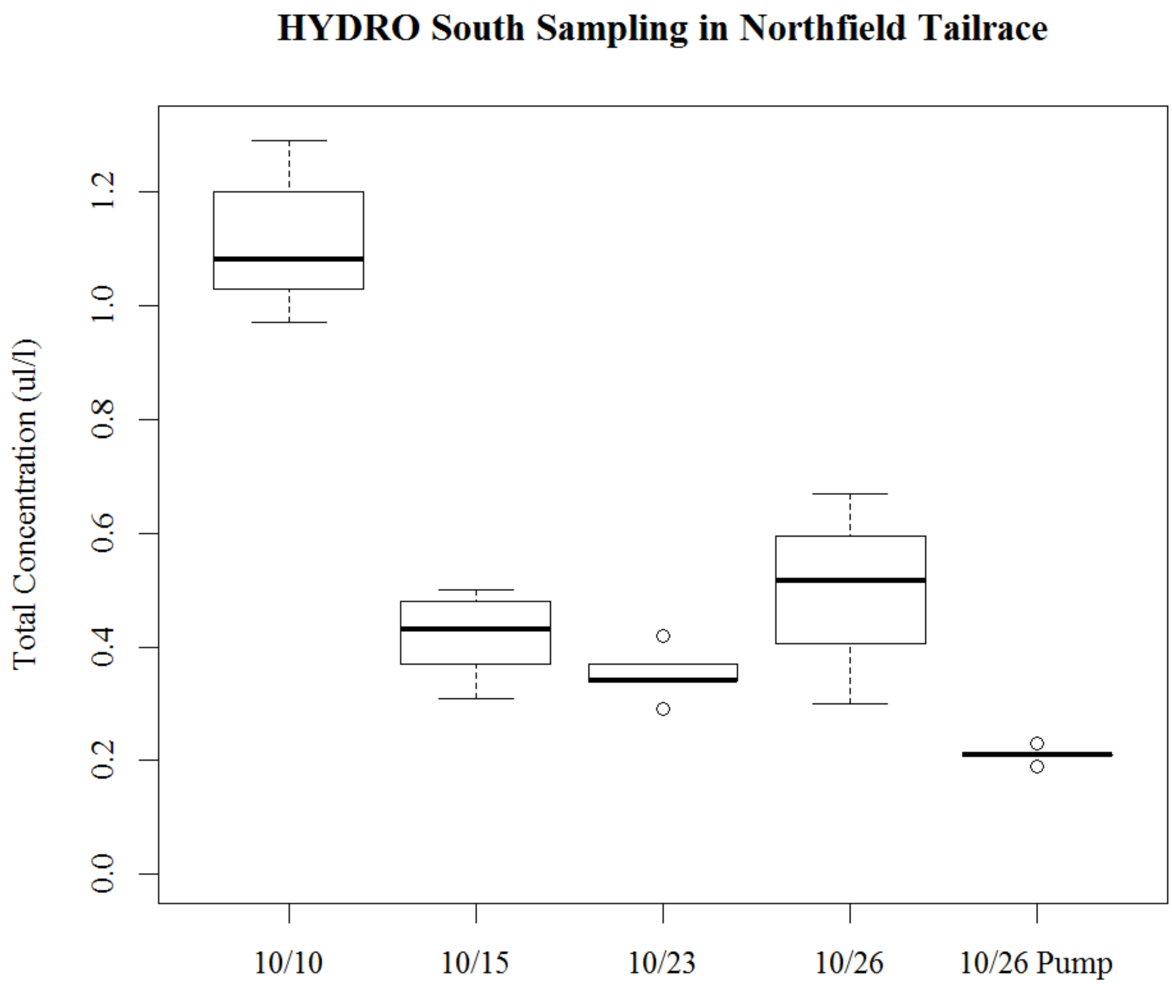


Fall 100X CT River
Total Concentration (ul/l)
0
1
2
3
4
5
6
10/3 Rt10
10/11 Rt10
10/15 NF
10/16 Rt10
10/23 NF
10/24 Rt10
10/26 NF

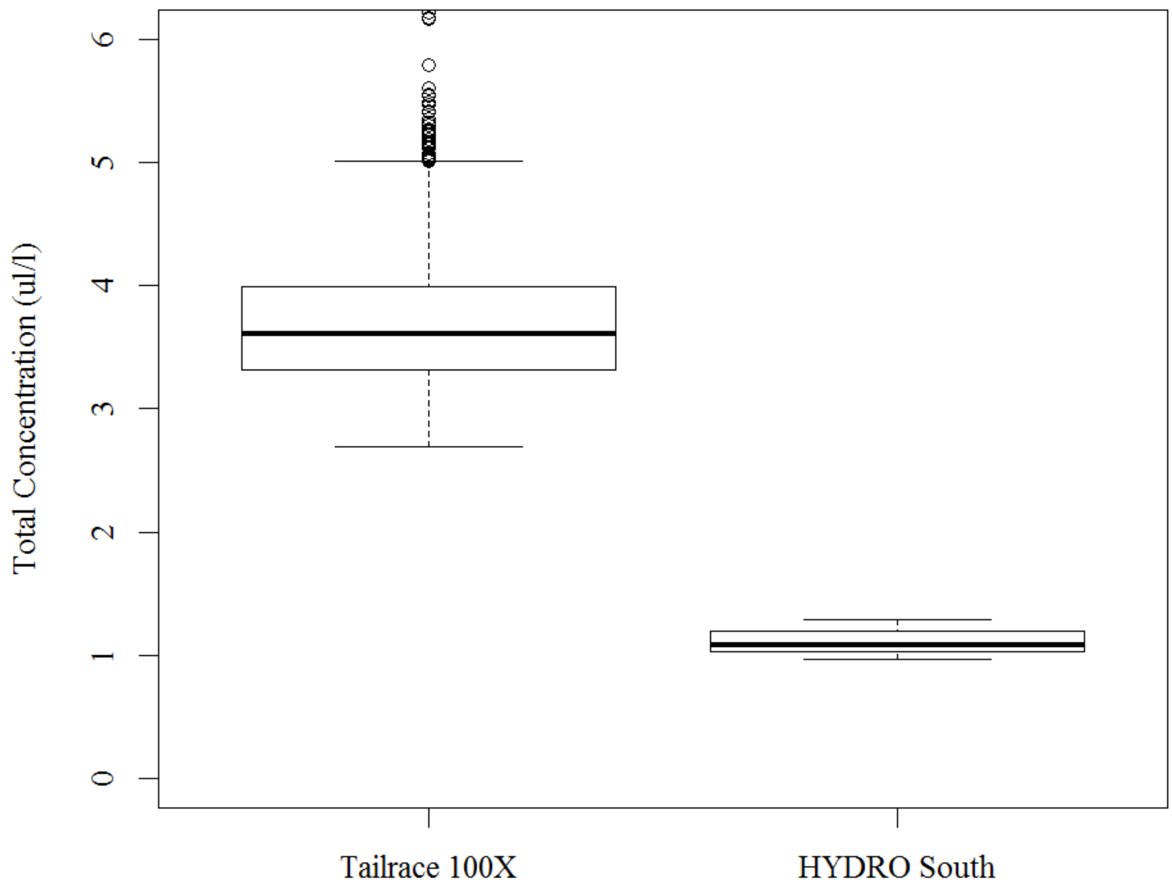

100X Sampling in CT River near Northfield
Total Concentration (ul/l)
0
1
2
3
4
5
6
10/15
10/23
10/26

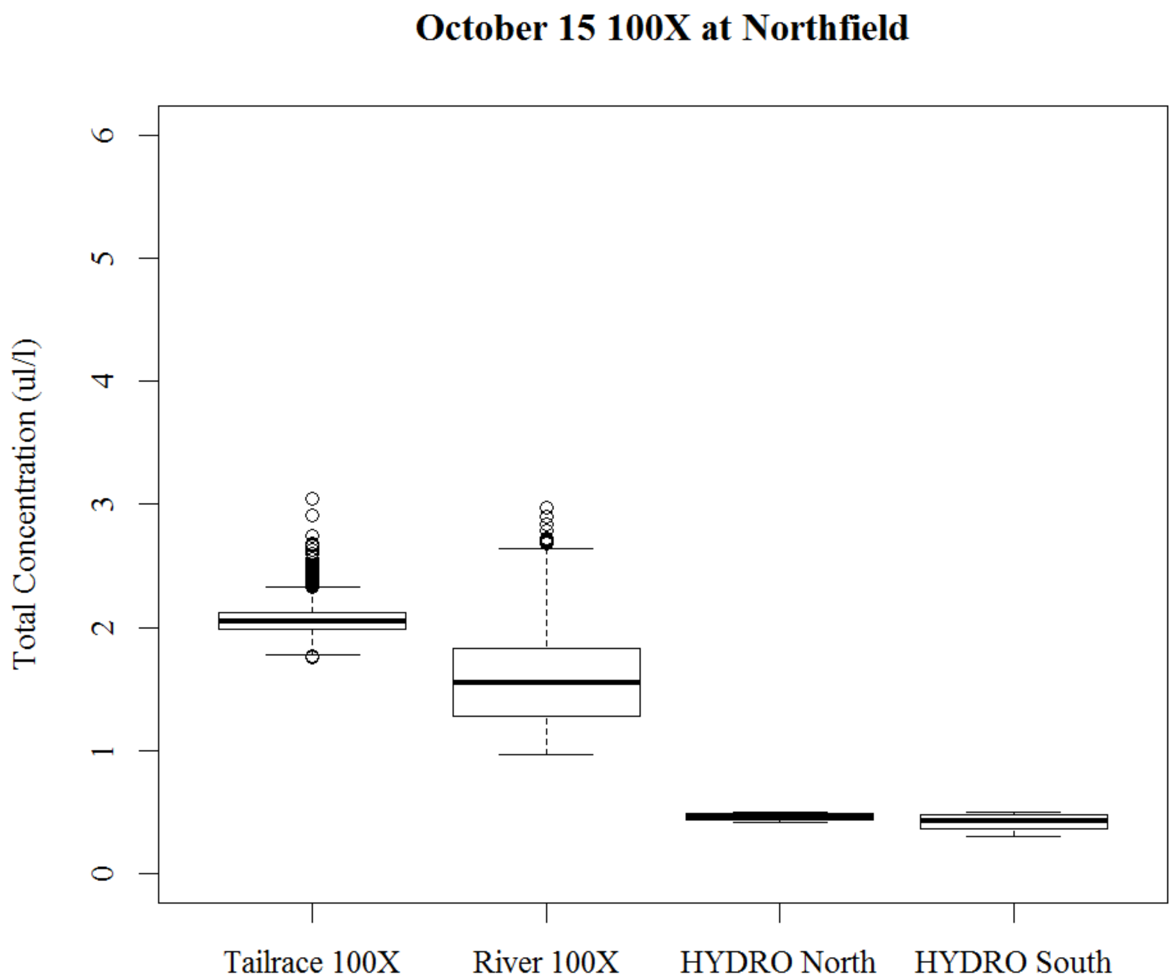

100X Sampling in Northfield Tailrace
Total Concentration (ul/l)
0
1
2
3
4
5
6
10/10
10/15
10/23
10/26
10/26 Pump


HYDRO North Sampling in Northfield Tailrace
Total Concentration (ul/l)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
10/10
10/15
10/23
10/26
10/26 Pump

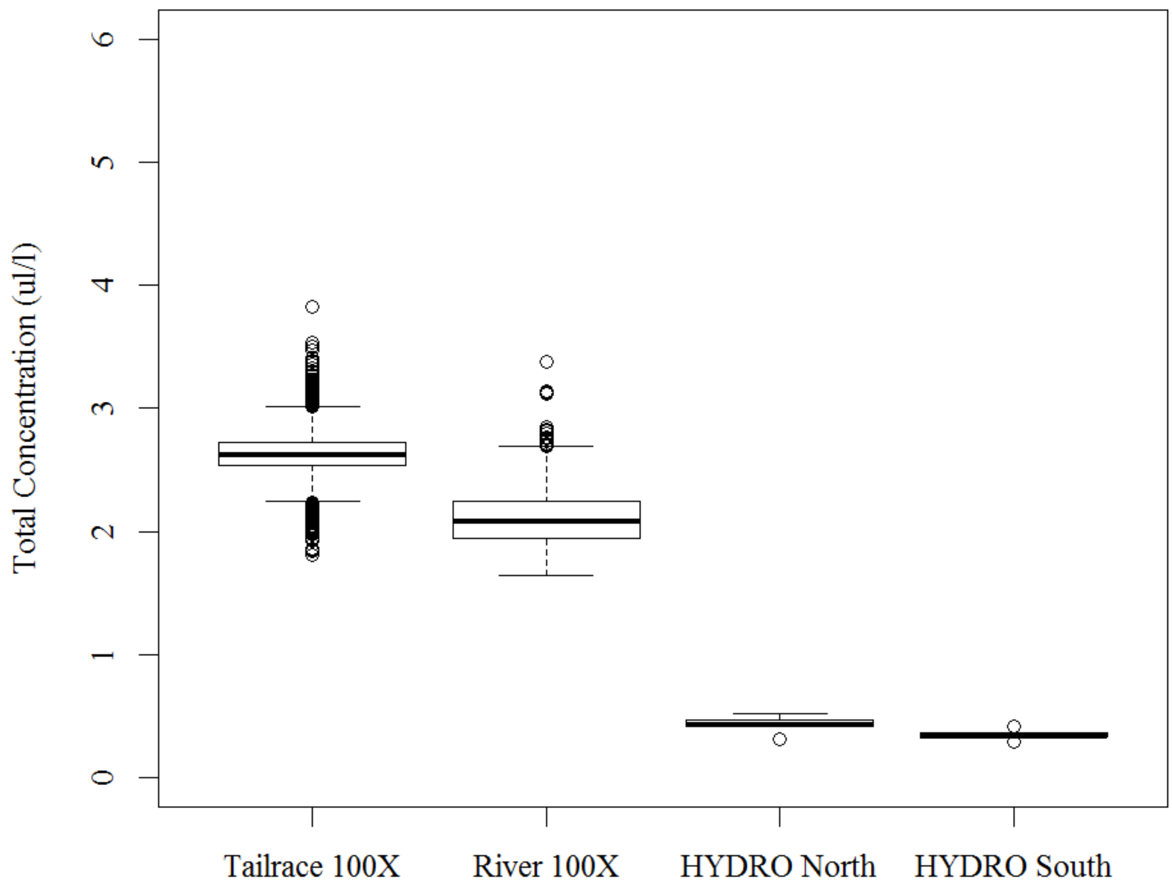

HYDRO South Sampling in Northfield Tailrace
Total Concentration (ul/l)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
10/10
10/15
10/23
10/26
10/26 Pump

October 10 100X at Northfield

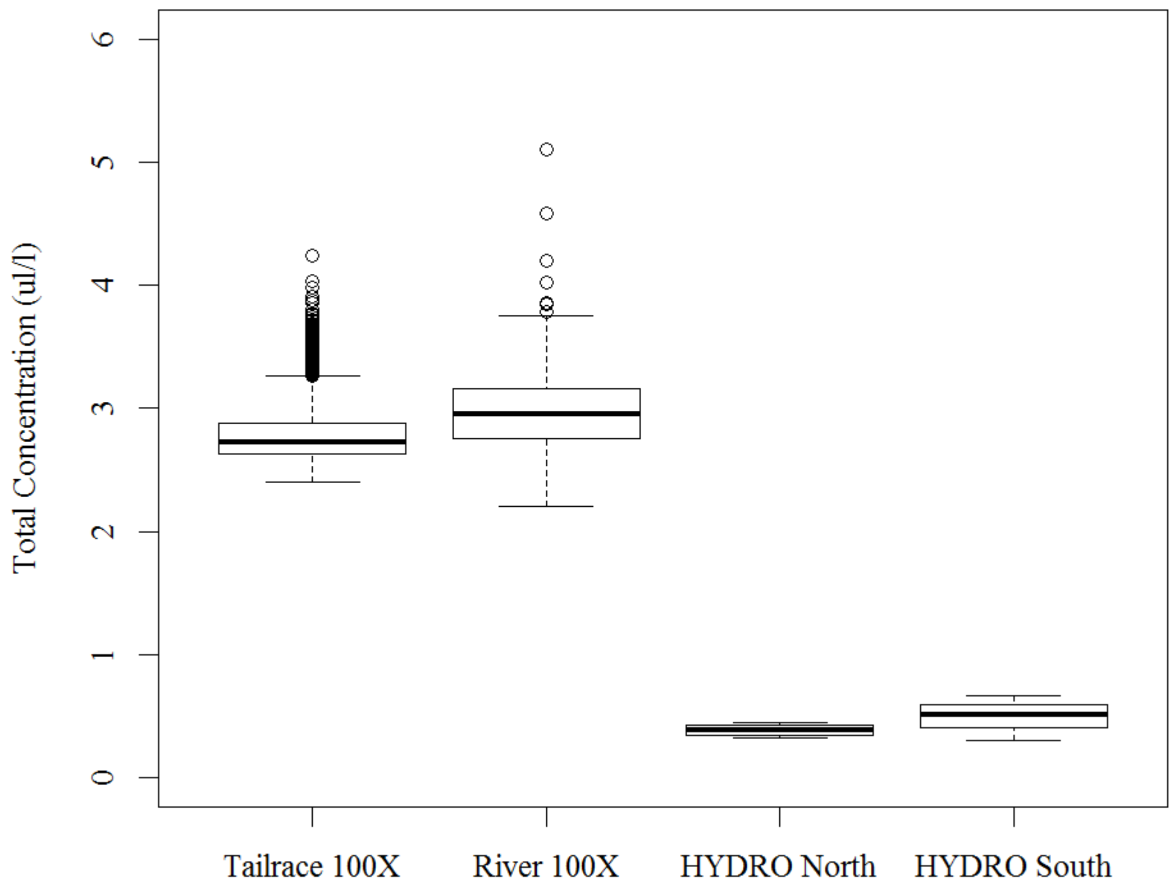


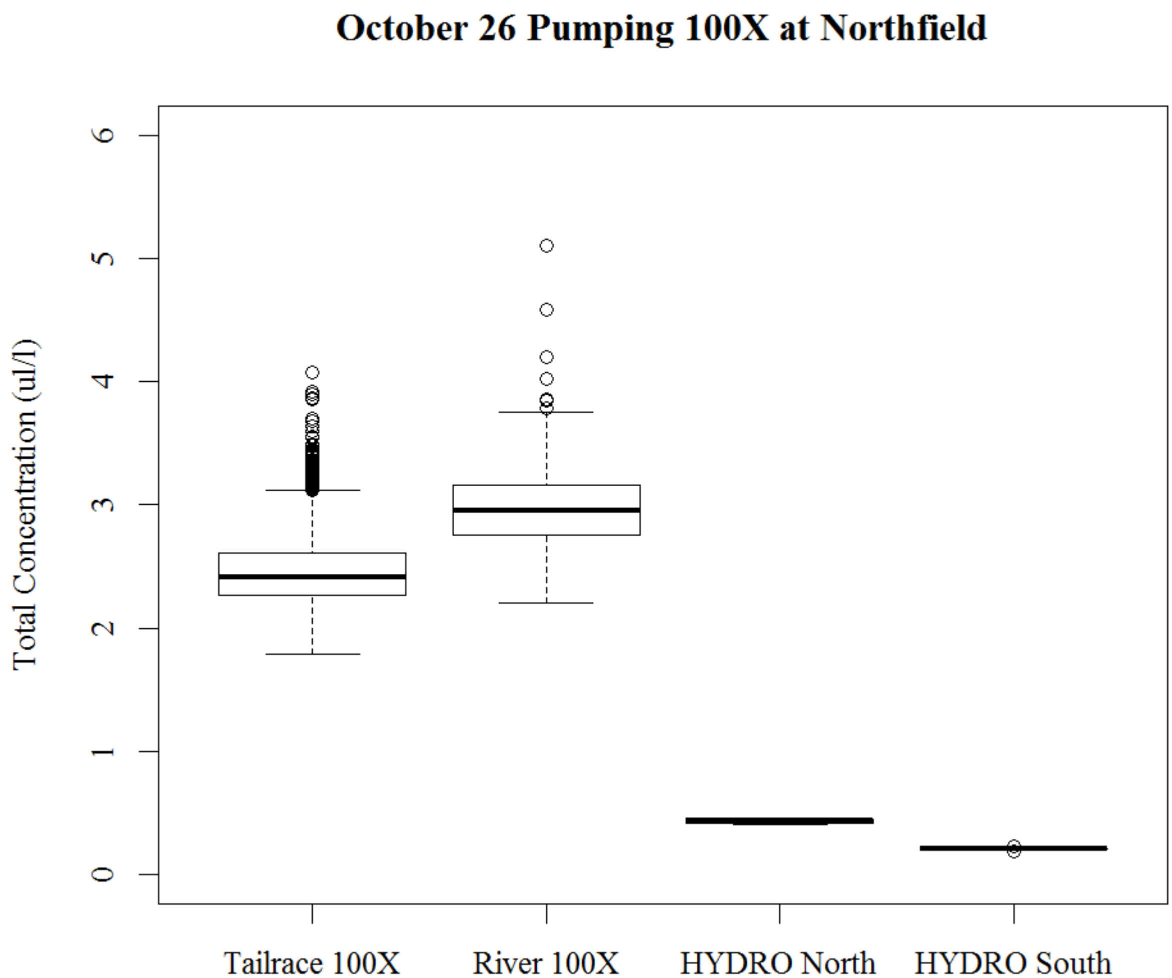

October 15 100X at Northfield
Total Concentration (ul/l)
0
1
2
3
4
5
6
Tailrace 100X
River 100X
HYDRO North
HYDRO South

October 23 100X at Northfield

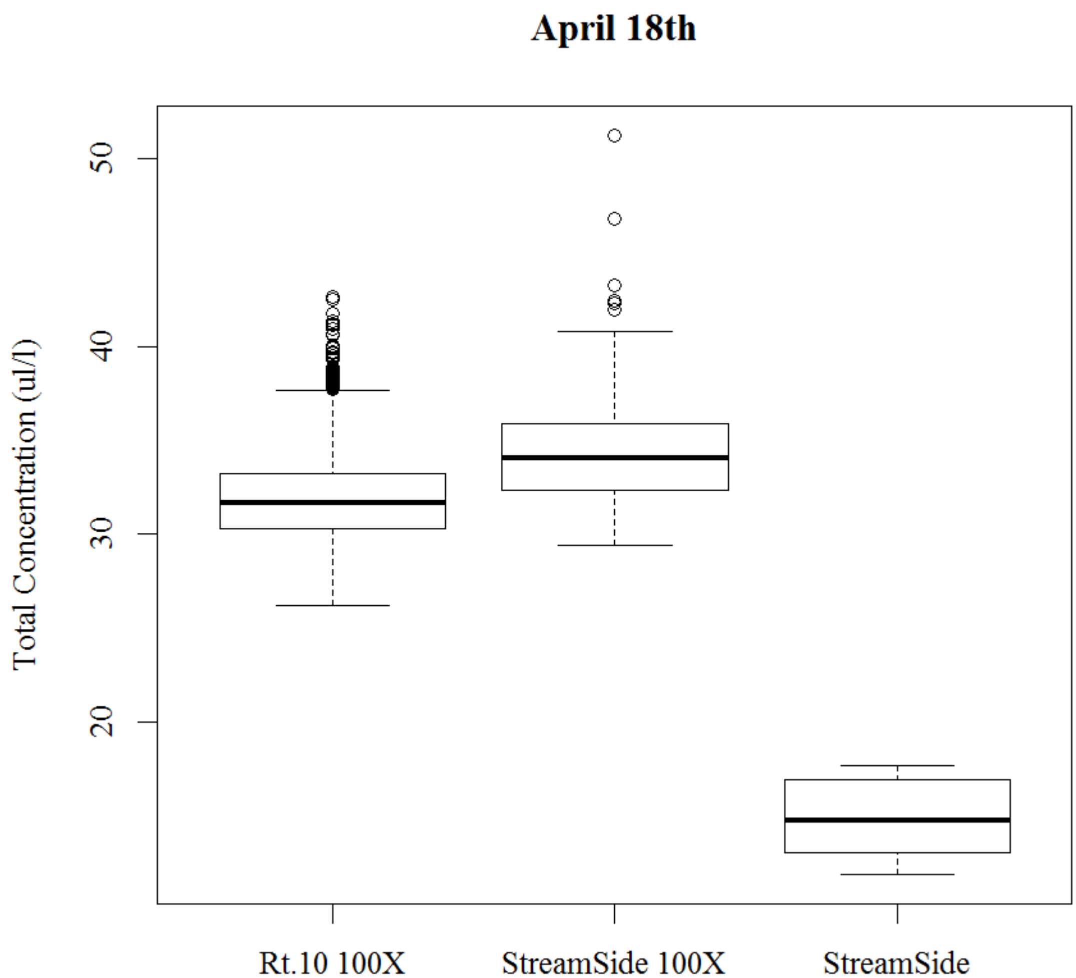


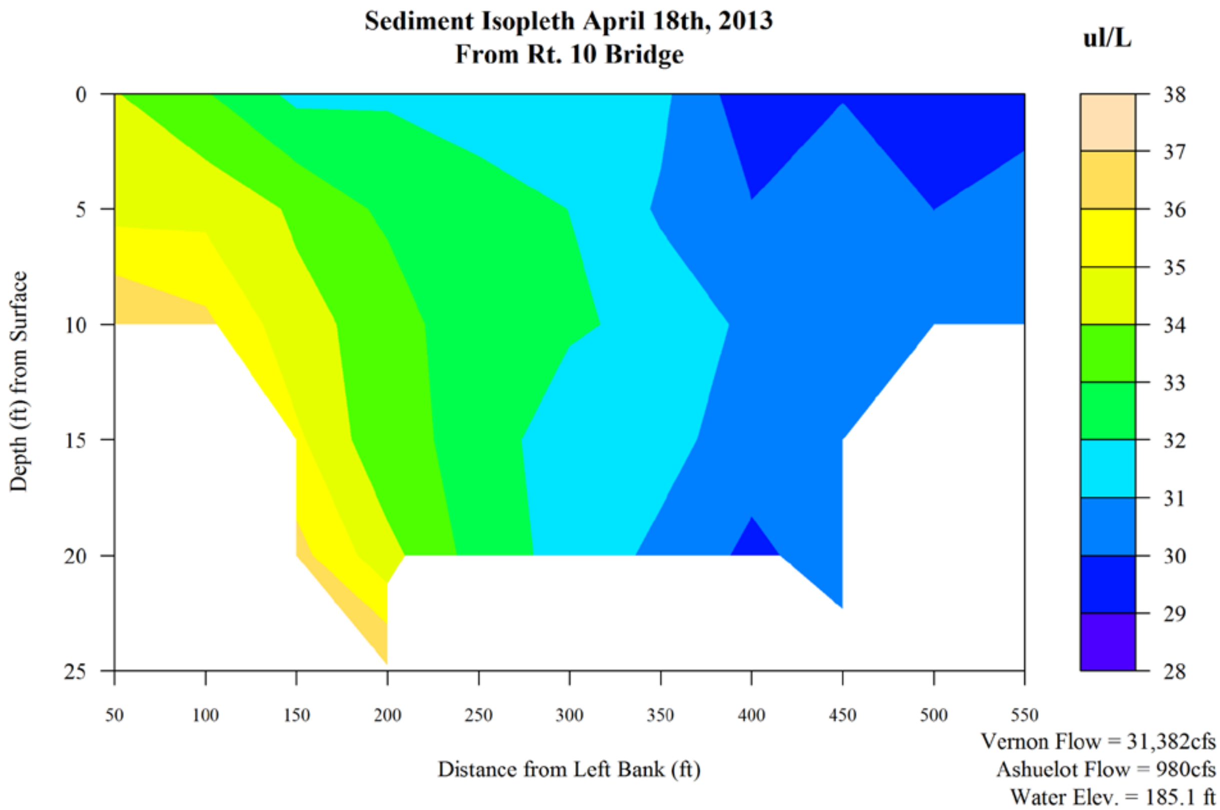
October 26 100X at Northfield

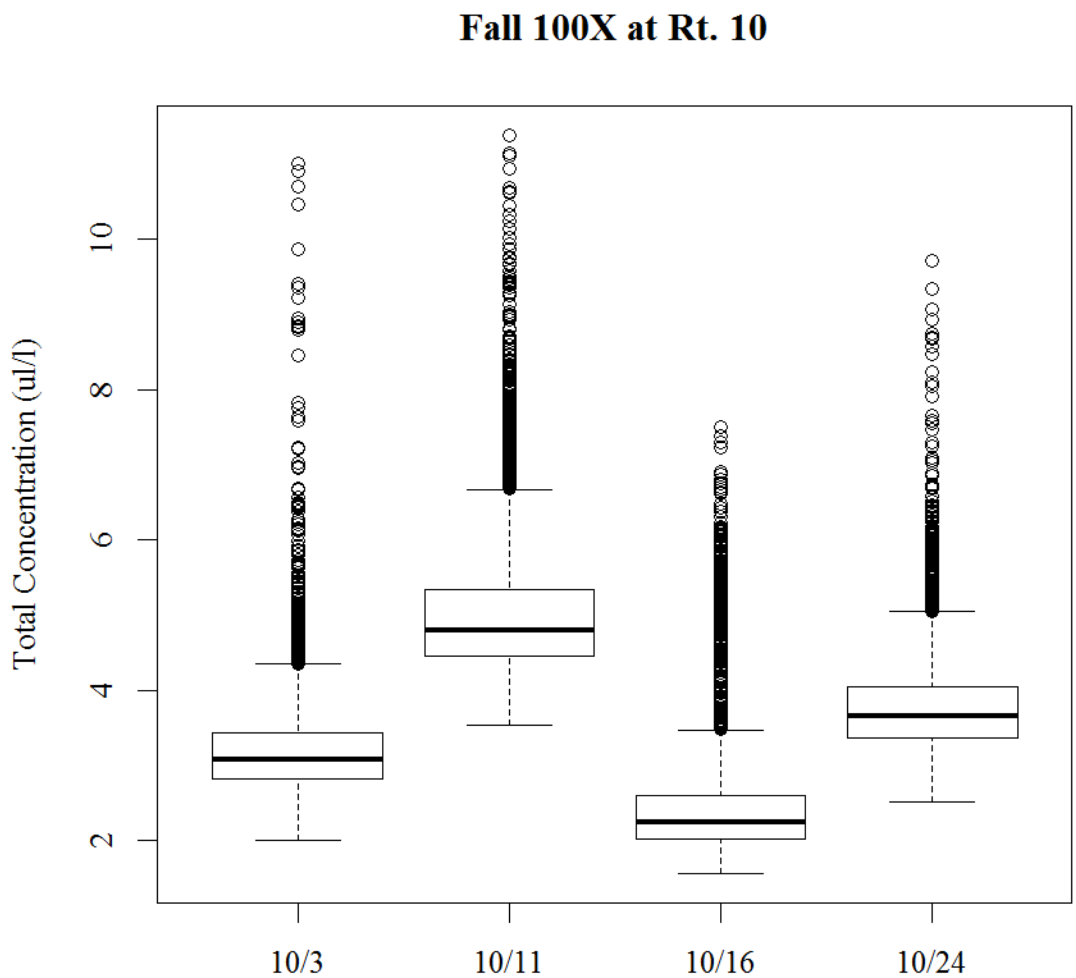



October 26 Pumping 100X at Northfield
Total Concentration (ul/l)
0
1
2
3
4
5
6
Tailrace 100X
River 100X
HYDRO North
HYDRO South

2013 LISST 100X PLOT- STREAMSIDE AND 100X ANALYSIS


April 18th
Total Concentration (ul/l)
50
40
30
20
Rt.10 100X
StreamSide 100X
StreamSide


Sediment Isopleth April 18th, 2013
From Rt. 10 Bridge
ul/L
38
37
36
35
34
33
32
31
30
29
28
Depth (ft) from Surface
0
5
10
15
20
25
50
100
150
200
250
300
350
400
450
500
550
Distance from Left Bank (ft)
Vernon Flow = 31,382cfs
Ashuelot Flow = 980cfs
Water Elev. = 185.1 ft



Fall 100X at Rt. 10
Total Concentration (ul/l)
2
4
6
8
10
10/3
10/11
10/16
10/24

APPENDIX G – SUSPENDED SEDIMENT MONITORING DATA (2013-2015)

CD AVAILABLE UPON REQUEST

DATA POSTED TO RELICENSING WEBSITE DECEMBER 2015