RELICENSING STUDY 3.3.9

TWO-DIMENSIONAL MODELING OF THE NORTHFIELD MOUNTAIN PUMPED STORAGE INTAKE/TAILRACE CHANNEL AND CONNECTICUT RIVER UPSTREAM AND DOWNSTREAM OF THE INTAKE/TAILRACE

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

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PREFACE

This study required the development of a model (River2D hydraulic model) of the 10 km reach of the Connecticut River encompassing the Northfield Mountain tailrace/intake (five km upstream and five km downstream of the tailrace/intake). Numerous maps showing the magnitude and direction of water velocity in the 10 km reach are included in this report under a variety of Northfield Mountain Project operations (pumping and generating). The study objectives include assessing the potential for Northfield Mountain Project operations to affect migratory fish relative to velocity barriers, flow reversals, and entrainment. This report includes an assessment of velocity data from the River2D hydraulic model relative to swim speeds of target diadromous fish to determine potential impacts. Four other relicensing studies are currently in progress which utilize empirical radio telemetry data to evaluate the effects of Northfield Mountain Project operations on migratory fish movements; these studies include Study No. 3.3.2 *Evaluate Upstream and Downstream Passage of Adult American Shad,* Study 3.3.3 *Evaluate Downstream Passage of Juvenile American Shad,* Study 3.3.5 *Evaluate Downstream Passage of American Eel,* and Study 3.3.15 *Assessment of Adult Sea Lamprey Spawning within the Turners Falls Project and Northfield Mountain Project Area*. The field work for these studies was conducted in 2015; however, the analysis and results will not be available until 2016. These studies include telemetry data to determine how tagged fish may respond to different operating conditions. These telemetry studies, coupled with the hydraulic evaluation herein, will be used to determine the impact of Project operations on migratory fish movement.

For purposes of this report, the River2D velocity data were compared against fishes' swim speeds to determine the potential for velocity barriers and entrainment. However, this evaluation is based solely on hydraulic modeling; it does not represent how fish will react to *in-situ* conditions. Thus, to fully understand how/if Northfield Mountain Project operations impact migratory fish movement, the results from the radio telemetry studies should be reviewed and used to supplement the discussion provided in this report.

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 the Northfield Mountain and Turners Falls Projects were issued on May 14, 1968 and May 5, 1980, respectively, and both licenses expire on April 30, 2018. On September 13, 2013, FERC issued a study plan determination for the Projects which, among other studies, requires FirstLight to conduct Study No. 3.3.9 *Two-Dimensional Modeling of the Northfield Mountain Pumped Storage Intake/Tailrace Channel and Connecticut River Upstream and Downstream of the Intake/Tailrace* (FERC, 2013). Per the Revised Study Plan (RSP) (filed on August 14, 2013), the goals of the hydraulic study were as follows (FirstLight, 2013):

- Assess velocities and flow fields at, and in proximity to, the Northfield Mountain Project intake/discharge structure, when pumping or generating, and their potential to interfere with fish migration;
- Assess the potential for velocity barriers in the Connecticut River in the vicinity of the Northfield Mountain Project tailrace due to pumping and generation flows alone or in conjunction with generation flows from the upstream Vernon Project;
- Characterize water column velocity profiles in the immediate vicinity of the Northfield Mountain Project tailrace (i.e. inside the boat barrier);
- Assess the potential for Northfield Mountain Project operations to create undesirable attraction flows to the intake/tailrace area that may result in entrainment or delay of migratory fish; and
- Assess potential migratory fish impacts due to flow reversals under:
    - Pumping conditions, such that river flows move upstream to the Northfield tailrace; and
    - Generating conditions, such that river flows move upstream above the Northfield tailrace toward Vernon Dam.

A two-dimensional (River2D) model of the Northfield tailrace and Connecticut River five km upstream and five km downstream of the Northfield Mountain Project tailrace was developed to evaluate hydraulic (depth, velocity, water surface elevation) conditions in the 10 km reach over a range of flow and Northfield Mountain Project operating conditions (two units pumping, four units pumping, two units generating, four units generating).

The methodology and scope for the hydraulic study outlined in the RSP was approved with modification by the Commission in its September 13, 2013 Study Plan Determination Letter (SPDL) (FERC, 2013). The modification to the RSP outlined by the FERC were as follows:

- In addition to simulating hydraulic conditions under the proposed 25% and 75% exceedance flows of the Connecticut River as measured at Turners Falls Dam, FERC required that 5%, 50%, and 95% exceedance flows be added to the scenarios.
- Add another transect equidistant between the Northfield Mountain Project's intake/tailrace and FirstLight's proposed Transect 1.

In its 2014 Initial Study Report (ISR) for Study 3.3.9 (FirstLight, 2014), FirstLight stated that water column velocity data were only collected at the originally proposed three transects, as the additional transect requested by FERC would cross the top of the intake/discharge structure. In its January 22, 2015

Determination on Requests for Study Modifications Letter (FERC, 2015), FERC concluded that the fourth transect was not necessary.

Per the RSP, FirstLight used the 2D hydraulic model called River2D. This finite element, depth-averaged hydrodynamic and fish habitat model was developed for use in streams and rivers, and calculates water surface elevations (WSEL), river depths, and depth-averaged velocities at various locations under a range of flows, Northfield Mountain Project operating conditions and starting downstream WSELs at Turners Falls Dam. Per the RSP, the River2D model was run using unsteady-state (i.e. transient) conditions.

To assist in calibrating the hydraulic model to observed flows and WSELs throughout the 10 km study reach, the following data were obtained:

- WSEL data were collected over a range of flows and operating conditions. In addition to permanent water level loggers maintained by FirstLight, loggers were installed throughout the study reach at various locations during parts of 2014 for this study.
- Flow data were obtained from TransCanada (Vernon discharge), the United States Geological Survey (USGS) from gaged rivers entering the Turners Falls Impoundment (Millers, Ashuelot River), and FirstLight (Northfield Mountain pump/gen flows).
- Bathymetric data were collected in the 10 km study reach and topographic survey data [Light Detection and Ranging (LiDAR)] were obtained from TransCanada.
- Water column velocity data were collected at three transects within the intake/tailrace channel.

The River2D model was calibrated to the WSELs measured at the water level loggers under steady-state conditions. To calibrate to steady state conditions, the goal was to identify periods where WSEL fluctuations were as minor as possible. In general, the calibration procedure consisted of adjusting the roughness coefficient such that the observed and modeled WSELs at the water level loggers were reasonably close[1]. After initial calibration to steady state conditions, the model was verified to unsteady conditions. This was performed in order to verify a reasonable correlation of the modeled flow velocities (i.e. direction and magnitude) to the observed water column velocity profiles.

After model calibration was completed, 60 scenarios were evaluated as shown in Table E-1. It should be noted that scenarios 41 through 60 used the median Turners Falls Impoundment (TFI) elevation of 181.3 feet; these scenarios are more representative of the TFI elevation at the Turners Falls Dam and were included despite not being part of the study plan. Combinations of the following three major variables comprised the 60 scenarios

- Northfield Mountain Project operations (two units pumping, four units pumping, two units generating, four units generating).
- Starting WSEL as measured at the Turners Falls Dam (either 176 feet or 185 feet, the lower and upper FERC licensed ranges; or 181.3 feet, the median elevation at Turners Falls Dam for the period 2000-2010).
- Flow through the TFI (i.e. the annual 5%, 25%, 50%, 75%, and 95% exceedance flow as computed at Turners Falls Dam).

With 300 velocity vector maps (60 scenarios x five maps per scenario as shown in Appendix B) over a 10 km reach, emphasis was placed on the evaluating velocity ranges and flow direction at three locations/sites as follows:

[1] Generally less than 0.15 ft.

- Site 1: this site is located approximately 2.5 miles upstream of the Northfield tailrace/intake near Kidds Island.

- Site 2: this site extends just upstream and downstream of the Northfield tailrace/intake. As discussed below, under some conditions velocity vector*s below* the tailrace/intake point in an upstream direction, against the natural river flow. Similarly, under some conditions velocity vectors *above* the tailrace/intake point in an upstream direction (against the natural river flow).

- Site 3: this site is located in the French King Gorge area.

Velocities

Water velocities at each site were generally higher at low impoundment levels, due to shallower water and more river gradient. The velocities predicted for many scenarios were often greatest at Site 3 in the French King Gorge, with the exception of scenarios where the WSEL at Turners Falls Dam was 181.3 feet or higher and Northfield Mountain was in pumping mode. During these scenarios, Site 3 exhibited similar or slightly lower velocities than Site 2 near the Northfield tailrace area. Velocities at Site 3 reached >10 ft/s in some areas during the most extreme scenarios when river flow was high, impoundment elevation at the dam was low, and the Northfield Mountain Project was generating.

The maximum velocity does not extend across the entire width of the river. Velocity is high in many areas across the channel, but there are areas along the river margins with lower velocities that migrating fish can utilize.

Flow Reversals

Flow reversals upstream of the Northfield Mountain tailrace occur during two unit generation and low river flow, and the greatest extent of reversals during these low flow scenarios occurred when the impoundment level was high (i.e. Scenarios 2, 10, and 45). Flow reversals up to or beyond Kidds Island were observed for scenarios of inflows up to 4,900 cfs, and low impoundment levels tended to reduce the extent of reversals under similar flow conditions. Similar patterns were observed for full generation, except that flow reversals to, or beyond, Kidds Island were present at incoming flows up to 8,440 cfs.

Flow reversals downstream of the Northfield intake were predicted during pumping scenarios under low incoming flow conditions, with reversals predicted only at the lowest incoming flow (1,760 cfs) under 7,600 cfs of pumping, and primarily up to 4,900 cfs incoming flow during full pumping at 15,200 cfs. One exception to this was that flow reversals were predicted under an inflow of 8,440 cfs under full pumping and high (185 ft) impoundment elevation.

The effects of flow reversals on upstream and downstream migrating fish are poorly understood in upriver areas. Fish that encounter flow reversals may change direction, similar to how migratory fish sometimes respond to tide changes when entering estuarine areas (i.e. Grote *et al.*, 2014; Stich *et al.*, 2015), resulting in migration delay, though directional changes documented in the literature are normally thought to be related to salinity. Eddies in the vicinity of the Northfield tailrace also have the potential to confuse fish and delay their migration.

Migrating fish that move during the daytime may encounter flow reversals upstream of the tailrace due to generation and low incoming flow, in the event that these conditions actually occur during migration periods. Alternatively, migrating fish that move at night may encounter flow reversals downstream of the tailrace due to pumping and low incoming flow from upstream.

Attraction

Similar to the attraction of downstream migrating fish that could result in entrainment during pumping, upstream migrating fish such as adult American Shad, Sea Lamprey, and juvenile American Eel could be attracted to the flow from Northfield Mountain during generation. These fish could be delayed in their upstream migration if they are attracted to the tailrace area and stay there for extended periods; however, it should be noted that generation at Northfield Mountain is typically followed by idle and pumping cycles, during which fish should be able to pass upstream of Northfield in a relatively short amount of time and resume their course upstream.

Potential for Entrainment

As part of the field data collection, three transects were located across the tailrace between the intake and boat barrier. Velocity and bathymetric data were collected at these three transects with two units pumping, four units pumping, two units generating and four units generating. Transect 3 (closest to the intake racks) was located approximately 25 ft in front of the intake rack. Under the four pump scenario the measured velocities at Transect 3 ranged between 0.5 and 3 ft/sec within the water column.

Because pumping operations at Northfield Mountain primarily occur during the night, fish that move through the area at night may be susceptible to entrainment. Additionally, drifting eggs or larval fish could also become entrained.

Adult shad possess sufficient swimming speed to avoid entrainment. Out-migrating adult eel and juvenile shad could be attracted to and potentially follow the flow into the intake. Given a relatively low burst speed of 2.5 ft/s, it is unlikely that a juvenile shad that was attracted to the intake structure would be able to escape entrainment if it traveled too close to the structure, particularly during pumping at full capacity. Juvenile eel within the tailrace area could also potentially become entrained if pumping is initiated. Sea Lamprey, while nocturnal, likely have sufficient swim speeds, and a tendency to find resting areas where they will latch onto substrate such that they will avoid becoming entrained.

This hydraulic modeling, coupled with a literature review, and the results of telemetry studies will allow evaluation of potential effects of Northfield Mountain Pumped Storage Project on migratory fish.

Table E-1: List of River2D Hydraulic Modeling Scenarios

Scenario No.	Northfield Mountain Generation Flow (cfs)	Northfield Mountain Pumping Flow (cfs)	Turners Falls Impoundment Elevation at Turners Falls Dam (ft)	Turners Falls Dam Flow (cfs)
1	10,000	0	176.0	1,760 (95% exceedance flow)
2	10,000	0	185.0	1,760
3	20,000	0	176.0	1,760
4	20,000	0	185.0	1,760
5	0	7,600	176.0	1,760
6	0	7,600	185.0	1,760
7	0	15,200	176.0	1,760
8	0	15,200	185.0	1,760
9	10,000	0	176.0	4,900 (75% exceedance flow)
10	10,000	0	185.0	4,900
11	20,000	0	176.0	4,900
12	20,000	0	185.0	4,900
13	0	7,600	176.0	4,900
14	0	7,600	185.0	4,900
15	0	15,200	176.0	4,900
16	0	15,200	185.0	4,900
17	10,000	0	176.0	8,440 (50% exceedance flow)
18	10,000	0	185.0	8,440
19	20,000	0	176.0	8,440
20	20,000	0	185.0	8,440
21	0	7,600	176.0	8,440
22	0	7,600	185.0	8,440
23	0	15,200	176.0	8,440
24	0	15,200	185.0	8,440
25	10,000	0	176.0	15,700 cfs (25% exceedance flow)
26	10,000	0	185.0	15,700
27	20,000	0	176.0	15,700
28	20,000	0	185.0	15,700
29	0	7,600	176.0	15,700
30	0	7,600	185.0	15,700
31	0	15,200	176.0	15,700
32	0	15,200	185.0	15,700
33	10,000	0	176.0	40,100 (5% exceedance flow)
34	10,000	0	185.0	40,100
35	20,000	0	176.0	40,100
36	20,000	0	185.0	40,100
37	0	7,600	176.0	40,100
38	0	7,600	185.0	40,100
39	0	15,200	176.0	40,100
40	0	15,200	185.0	40,100
41	10,000	0	181.3	1,760
42	20,000	0	181.3	1,760
43	0	7,600	181.3	1,760
44	0	15,200	181.3	1,760
45	10,000	0	181.3	4,900
46	20,000	0	181.3	4,900
47	0	7,600	181.3	4,900
48	0	15,200	181.3	4,900

Scenario No.	Northfield Mountain Generation Flow (cfs)	Northfield Mountain Pumping Flow (cfs)	Turners Falls Impoundment Elevation at Turners Falls Dam (ft)	Turners Falls Dam Flow (cfs)
49	10,000	0	181.3	8,440
50	20,000	0	181.3	8,440
51	0	7,600	181.3	8,440
52	0	15,200	181.3	8,440
53	10,000	0	181.3	15,700
54	20,000	0	181.3	15,700
55	0	7,600	181.3	15,700
56	0	15,200	181.3	15,700
57	10,000	0	181.3	40,100
58	20,000	0	181.3	40,100
59	0	7,600	181.3	40,100
60	0	15,200	181.3	40,100

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ADCP	Acoustic Doppler Channel Profiler
cfs	cubic feet per second
cm	centimeters
cms	cubic meters per second
ft	feet
ft/s	feet per second
FERC	Federal Energy Regulatory Commission
FirstLight	FirstLight Hydro Generating Company
GIS	Geographic Information Systems
GPS	Global Positioning System
HEC-RAS	Hydrologic Engineering Center River Analysis System
ILP	Integrated Licensing Process
km	kilometers
LiDAR	Light Detection and Ranging
MA	Massachusetts
mi^2	square mile
NH	New Hampshire
NOI	Notice of Intent
Northfield Mountain Project	Northfield Mountain Pumped Storage Project
PAD	Pre-Application Document
PSP	Proposed Study Plan
QA/QC	Quality Assurance/Quality Control
QI	Quality Index
RSP	Revised Study Plan
RTK	Real-Time Kinematic
RTK-GPS	Real-Time Kinematic- Global Positioning System
SD1	Scoping Document 1
SD2	Scoping Document 2
SPDL	Study Plan Determination Letter
the Commission	Federal Energy Regulatory Commission
the Project	Northfield Mountain Pumped Storage and Turners Falls Hydroelectric Projects
TFI	Turners Falls Impoundment
Turners Falls Project	Turners Falls Hydroelectric Project
USGS	United States Geological Survey
Vernon	Vernon Hydroelectric Project
VT	Vermont
WSEL	water surface elevation

1 INTRODUCTION

1.1 Background

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 the 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. This report documents the results of Study No. 3.3.9 *Two-Dimensional Modeling of the Northfield Mountain Pumped Storage Intake/Tailrace Channel and Connecticut River Upstream and Downstream of the Intake/Tailrace*.

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.[2] 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 and addressed stakeholder comments. Included in the RSP was Study No. 3.3.9 *Two-Dimensional Modeling of the Northfield Mountain Pumped Storage Intake/Tailrace Channel and Connecticut River Upstream and Downstream of the Intake/Tailrace* (hereinafter referred to as the Northfield Intake Study). The methodology and scope for the Northfield Intake Study outlined in the RSP was approved with modification by the Commission in its September 13, 2013 SPDL (FERC, 2013).

FERC made two (2) modifications to the RSP. The first recommendation was to include scenarios which included discharges at the Turners Falls Dam of 5% (40,100 cfs), 50% (8,440 cfs), and 95% (1,760 cfs) exceedance to the already proposed 25% (15,700 cfs) and 75% (4,900 cfs) exceedance flows.

FERC also recommended that a fourth transect be added to the three proposed transects for water column velocity data collection at a location equidistant between the Northfield intake structure and the closest proposed transect. In FirstLight's Initial Study Report (ISR) meeting summary filed with FERC on October 15, 2014, it noted that the fourth transect is technically on top of the intake structure. As such, FirstLight noted that a variance from the RSP was required as obtaining velocity data atop the intake structure would not provide meaningful information. In FERCs Determination on Requests for Study Modifications and New Studies, issued on January 22, 2015, it states *"Based on this new information, we conclude that the fourth transect is not necessary and recommend that FirstLight only be required to sample transects 1-3*".

[2] The ten meetings were held on May 14, 15, 21, and 22, and June 4, 5, 11, 12, and 14 and August 8.

As noted in the RSP, the specific study objectives of the Northfield Intake Study were as follows:

- Assess velocities and flow fields at, and in proximity to, the Northfield Mountain Project intake/discharge structure, when pumping or generating, and their potential to interfere with fish migration.
- Assess the potential for velocity barriers in the mainstem river to develop from pumping and generation flows at the Northfield Mountain Project, alone or in combination with generation flows from the upstream Vernon Project[3] and downstream Turners Falls Project.
- Characterize water column velocity profiles in the immediate vicinity of the Northfield tailrace (i.e. inside the boat barrier).
- Assess the potential for Northfield Mountain Project operations to create undesirable attraction flows to the intake/discharge area that may result in entrainment or delay of migratory fish.
- Assess potential migratory fish impacts due to flow reversals under:
    - Pumping conditions, such that the river flows from the Turners Falls Dam toward the Northfield tailrace; and
    - Generating conditions, such that the river flows from the Northfield tailrace toward Vernon Dam.

1.2 Geographic Scope

The geographic scope of this study is shown in Figure 1.2-1. As shown on the figure, the model starts approximately five kilometers (km) (i.e. 3.1 miles) upstream and extends to a point approximately five km downstream of the Northfield tailrace. This 10 km segment is hereinafter referred to as the study reach. Figure 1.2-2 provides a detailed overview of the Turners Falls Dam, including the bypass reach, and Cabot Canal, which supplies flow to the generating facilities (i.e. Station No. 1 and Cabot Station).

1.3 Vertical Datum

Note that the datum used in this study is the National Geodetic Vertical Datum of 1929 (NGVD29). Although a more up-to-date datum is available[4], FirstLight has used the NGVD29 datum in reporting dam elevation data, water level data, etc. over numerous years. Thus, all water level logger data, and hydraulic modeling was based on the same NGVD29 datum.

Note: All figures and larger tables appear at the end of each Section.

[3] The Vernon Hydroelectric Project is owned and operated by TransCanada. TransCanada is also in the process of relicensing three hydroelectric projects in series upstream of the Turners Falls Dam including from south to north the Vernon Hydroelectric Project (FERC No. 1904), Bellows Falls Hydroelectric Project (FERC No. 1855) and Wilder Hydroelectric Project (FERC No. 1892). All three TransCanada projects have the same license expiration date as the Northfield Mountain and Turners Falls Projects- April 30, 2018.
[4] NAVD88- North American Vertical Datum of 1988 (NAVD88).

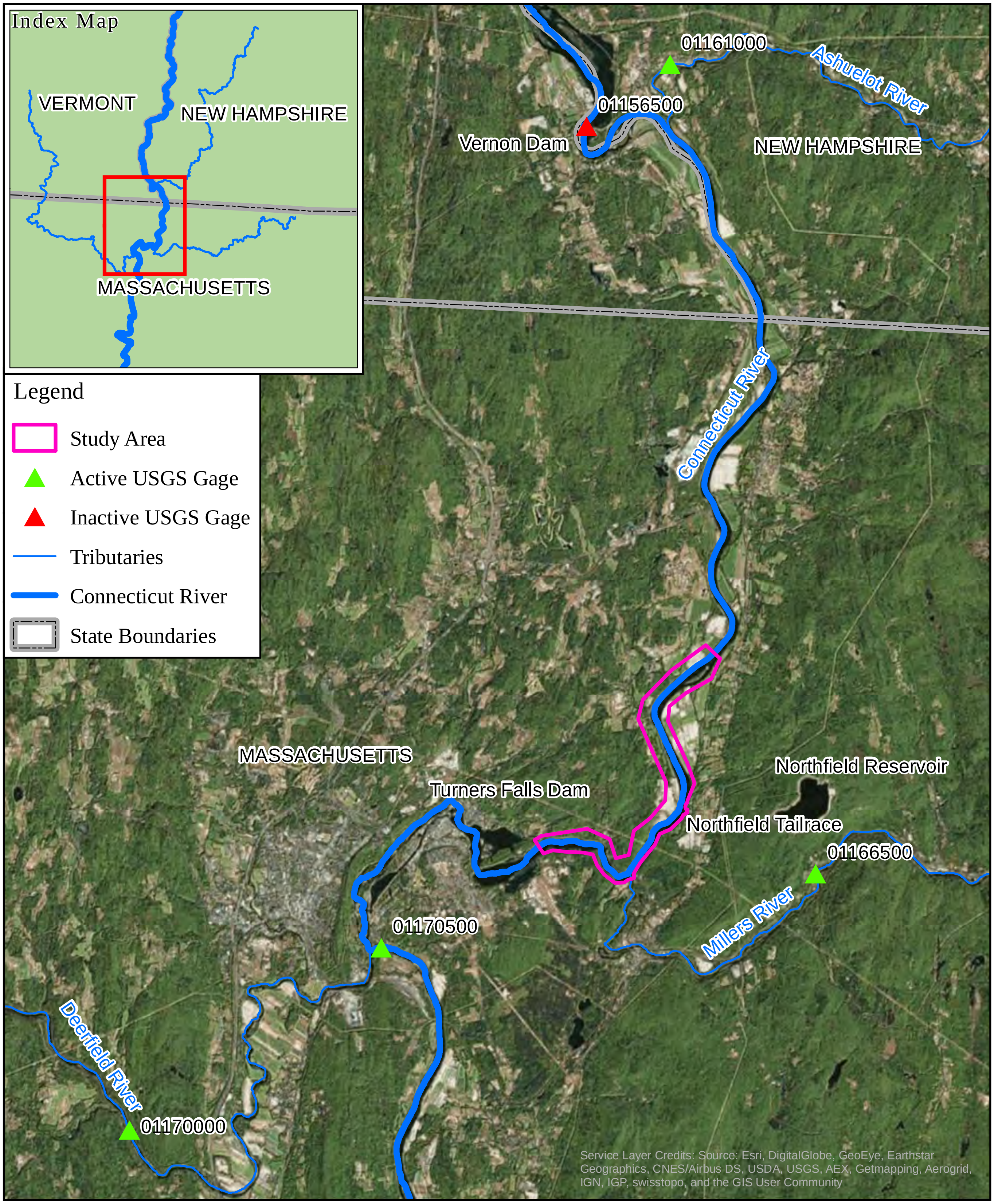

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Figure 1.2-1
Northfield Intake
Study Overview

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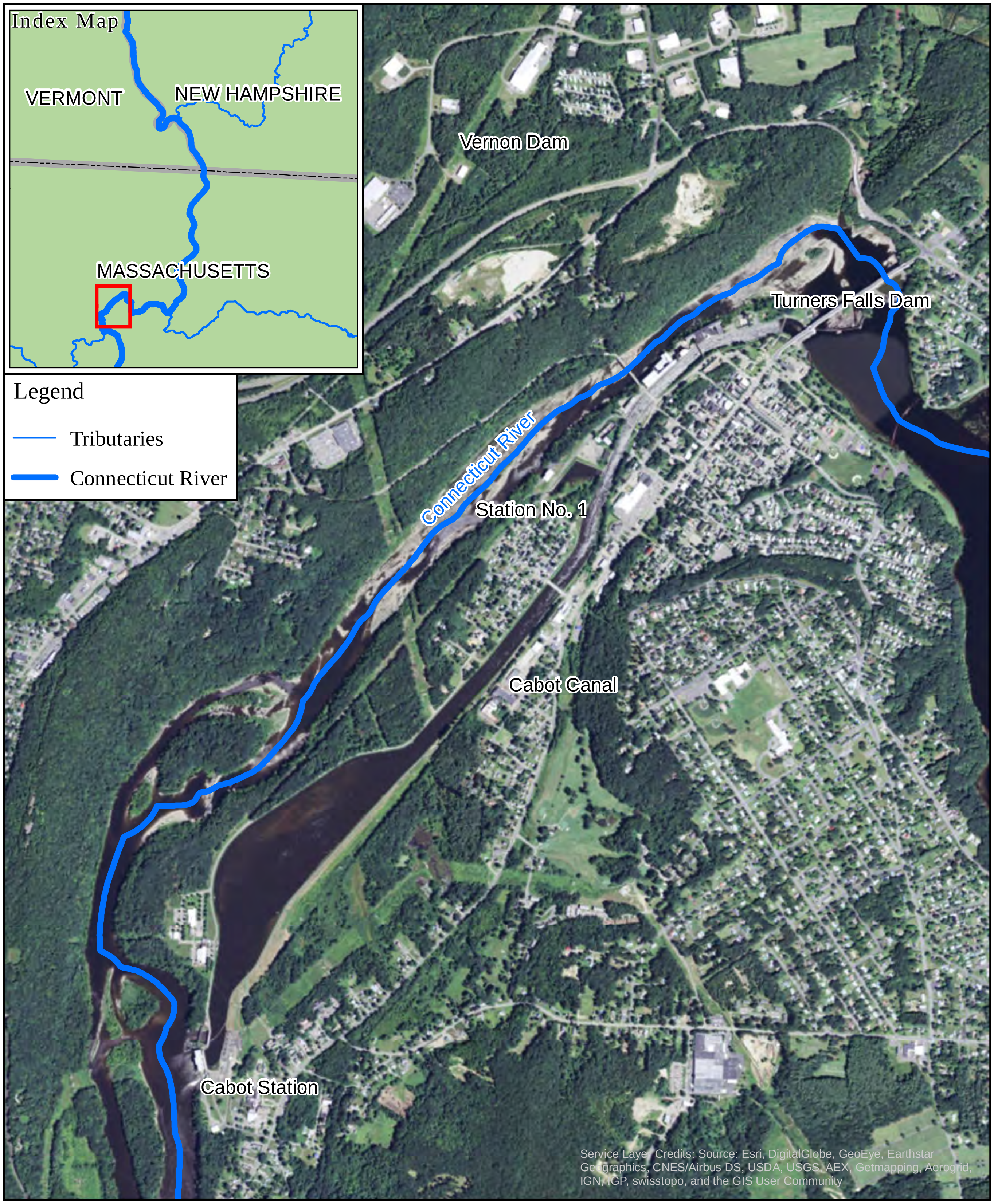

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Figure 1.2-2
Turners Falls Dam and Hydro Facilities Overview

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2 SUMMARY OF FIELD DATA COLLECTION

Considerable field data were collected to develop a calibrated hydraulic model of the study reach. The following data were collected:

- Measured water surface elevations (WSELs) within the study reach of the Turners Falls Impoundment (TFI).
- Measured or computed flows upstream and downstream of the study reach.
- Measured riverbank topography based on Light Detection and Ranging (LiDAR) data and measured bathymetry in the study reach.
- Measured water column velocities in the Northfield tailrace under pumping and generating conditions.

The following sections describe the data collected for this study.

2.1 Water Level Loggers

2.1.1 Study Reach Water Level Loggers

To aid in the hydraulic model calibration process, per the RSP, five (5) water level loggers were installed in the study reach as shown in Figure 2.1.1-1

- five km upstream and downstream of the tailrace,
- one km upstream and downstream of the tailrace,
- in the Northfield tailrace.

In addition to these loggers, one (1) additional logger was installed across from the Northfield tailrace.

The loggers used for this study were Onset HOBO Water Level Logger Model U20. These loggers record pressure, which is proportional to the height of the water above the instrument, and are non-vented, thus must be barometrically compensated using an atmospheric pressure logger; an atmospheric pressure logger was placed near the Northfield tailrace. When installed, the loggers were set to record data on a 15-minute time increment, and were surveyed to the NAVD88, using a Real-Time Kinematic- Global Positioning System (RTK-GPS) unit, and later converted to the NGVD29. The data were downloaded periodically and the logger re-installed.

Listed in Table 2.1.1-1 and shown in Figure 2.1.1-1 are the locations of water level loggers placed in the study reach. Table 2.1.1-1 lists the dates each logger was installed/retrieved, and provides an abbreviated name in parenthesis. These abbreviated names were used in the labeling of water level loggers on numerous plots as described later. Note that the raw water level logger data underwent a rigorous QA/QC procedure before the data were considered “good”. The QA/QC procedure resulted, in some cases, questionable data being eliminated. In general, the QA/QC process involved plotting the WSELs of each water level logger in synchrony with WSELs from other loggers for viewing and identification of any broad-scale elevation issues (i.e. a WSEL much higher or lower than expected based on the WSEL at other water level loggers). These issues were often resolved by re-checking survey data for data entry errors or by re-calibrating to a different RTK GPS survey at the same location. If the issue could not be resolved, as was the case if the logger shifted or moved, these data were flagged to avoid use. Finer-scale data issues were also flagged using a combination of visualization and inspection of the raw data parameters such as depth, pressure, and temperature. Questionable values were examined via plotting and, if deemed incorrect, were flagged to avoid use. All values, flagged and normal data, were uploaded into the database. Export of values from the database is automatically set to include only “Normal” values, and does not export values that were flagged during QA unless specifically requested.

Table 2.1.1-1: Location of Water Level Loggers in the Turners Falls Impoundment

Description	Date Installed	Date Retrieved
5 km Upstream of Tailrace (5 km Upstream)	5/21/2014	11/7/2014
1 km Upstream of Tailrace (1 km Upstream)	4/6/2014	11/7/2014
Across from Northfield Tailrace (Across Tailrace)	5/21/2014	11/7/2014
Within Northfield Tailrace Boat Barrier (Northfield Tailrace)	4/6/2014	11/7/2014
Gate Structure for Northfield Intake (Atmospheric)	4/6/2014	11/7/2014
1 km Downstream of Tailrace (1 km Downstream)	5/21/2014	11/7/2014
5 km Downstream of Tailrace (5 km Downstream)	5/21/2014	11/7/2014

Some loggers were installed on April 6, 2014 when water column velocity data were collected at the three transects in the tailrace. The remaining loggers were installed on May 21, 2014 after the spring freshet when the study reach could be safely accessed by boat (i.e. during high flow conditions, the velocity is too high through the French King Gorge area, creating safety concerns). All of the loggers were retrieved November 7, 2014.

2.1.2 FirstLight Water Level Loggers

FirstLight maintains permanent water level loggers associated with the Project. This study utilized information from the logger located immediately upstream of the Turners Falls Dam to aid in calibrating the hydraulic model. All of the FirstLight water level logger information utilized for calibration of the model was provided on a 15-minute time increment.

2.2 Flow Data

2.2.1 United States Geological Survey (USGS)

The USGS maintains gages throughout the country, for which it estimates flow in cubic feet per second (cfs) based on rating curves (river stage versus flow) developed for each site. Shown in Figure 1.2-1 and listed in Table 2.2.1-1 are the USGS gages in the Project area. The period of record indicated in Table 2.2.1-1, represents the time frame for which mean daily flow data were available, whereas only since 1990 has data been readily available on a 15-minute time increment at these gages.

Table 2.2.1-1: USGS gages utilized in the Northfield Intake Study[5]

Gage No.	Gage Name	Period of Record	Drainage Area	Regulated
01156500	Connecticut River at Vernon, VT	1945 - 1973	6,266 mi^2	Regulated by Wilder and Bellows Falls Dam peaking operations and seasonally regulated by Moore and Comerford Reservoirs
01161000	Ashuelot River at Hinsdale, NH	1907 - current	420 mi^2	Regulated by Corps Storage Reservoirs
01166500	Millers River at Erving, MA	1915 - current	372 mi^2	Regulated by Corps Storage Reservoirs
01170000	Deerfield River near West Deerfield, MA	1904 - current	557 mi^2	Regulated by peaking hydroelectric projects and two (2) seasonal storage reservoirs
01170500	Connecticut River at Montague City, MA	1904 - current	7,860 mi^2	Regulated by Turners Falls Dam, as well as facilities on the Deerfield River

[5] Data for these gages can be downloaded from the USGS Website.

Historically, there was a USGS gage located immediately below the Vernon Dam – USGS Gage No. 011565000 Connecticut River at Vernon, VT. The gage was active from 1936 to 1973, but was retired in 1973 due to the raising of Turners Falls Dam and hence upstream water levels. With the gage inactive, TransCanada, owners of the Vernon Hydroelectric Project (FERC No. 1806), estimates the Vernon discharge. The Vernon discharge estimate includes both generation flow and spill; spill is computed using rating curves.

The drainage areas at Vernon Dam and Turners Falls Dam are 6,266 mi^2 and 7,163 mi^2, respectively, a difference of 897 mi^2. The combined gaged drainage area of the Ashuelot and Millers Rivers is 792 mi^2 or 88% of the drainage area between the Vernon Dam and Turners Falls Dam. The Ashuelot River drains into the TFI just below the Vernon Dam and the Millers River drains into the TFI approximately 7,000 ft below the Northfield Project Tailrace; immediately below the French King Highway Bridge (Route 2), see Figure 1.2-1. The Deerfield River drains into the Connecticut River approximately 3.2 miles downstream of Turners Falls Dam and below Cabot Station. The USGS gage on the Connecticut River at Montague is located approximately 900 feet downstream of where the Deerfield River enters the Connecticut River.

2.2.2 Vernon Hydroelectric Project Discharge

With the USGS gage below Vernon Dam inactive, TransCanada estimates the Vernon discharge, which includes both generation flow (generation is converted to discharge via a MWh vs cfs curve) and spill (spill is computed using rating curves). TransCanada provided information to FirstLight from 2000 through 2010 and 2012 on a 1-hour time increment, and on a 15-minute time increment since 2013[6].

FirstLight records on its log sheets the sum of the Vernon computed discharge plus tributary inflow from the Ashuelot and Millers River. The sum is referred to by FirstLight as the “naturally routed flow”.

2.2.3 Northfield Mountain Pumping and Generating Flows, Turners Falls Discharge, Gatehouse Discharge

The Northfield Mountain Project has four equally-sized pump-turbine units with a total pumping hydraulic capacity of approximately 15,200 cfs, and a total generation hydraulic capacity of approximately 20,000 cfs. FirstLight measures the pump and generation discharge via Accusonic equipment; the flow measurements are accurate within 3% based on the equipment standards. Other flow information obtained from FirstLight includes discharge at Turners Falls Dam and discharge through the gatehouse into the power canal. The Turners Falls Dam discharge and the gatehouse discharge are estimated using rating curves. All of the FirstLight flow data utilized for model calibration were provided on a 15-minute time increment.

2.3 Bathymetric and Upland Survey Data

2.3.1 Bathymetric Data

FirstLight conducted bathymetric mapping in the study reach, excluding inside the Northfield tailrace boat barrier (i.e. for safety reasons). The bathymetric survey of the study reach was completed over four days (May 27, 2014, and June 2-4, 2014). The bathymetric survey was collected using an Acoustic Doppler Channel Profiler (ADCP) linked to a GPS unit, and included the collection of both bathymetry and velocity data during the survey dates. Bathymetric data inside the Northfield tailrace boat barrier were collected along the same three (3) transects and at the same time as the water column velocity data described in Section 2.4, below. All information was collected in the NAVD88, and later converted to the NGVD29. A thorough review of the data were performed during post-processing to remove outliers from the dataset due

[6] The 2011 data was not available at the time of this study. Inclusion of the 2011 data has little impact on the results of the annual flow duration curves used to this project (i.e. maximum difference approximately 100 cfs).

to loss of satellite communication (i.e. this can be caused by overhead obstructions such as the French King Gorge Bridge and trees along the bank).

2.3.2 Light Detection and Ranging (LiDAR) Data

TransCanada provided FirstLight with Light Detection and Ranging (LiDAR) data of the TFI riverbanks. The LiDAR[7] was flown from April 26-28, 2013 (leaf off) during normal river flows (flow at the Montague USGS Gage on these days ranged from 15,600 to 21,000 cfs). One seamless bathymetric/topographic map of the TFI was developed using the 2014 bathymetry data described above and the LiDAR data.

2.4 Water Column Velocity Data

Per the RSP, water column velocity data were collected at three (3) transects within the Northfield Mountain Project tailrace under four different operating scenarios. Velocity profiles and channel bed data were collected for two (2) units generating and pumping on April 6, 2014 and April 7, 2014 respectively. Likewise the same data for four (4) units generating and pumping were collected on July 12, 2014.

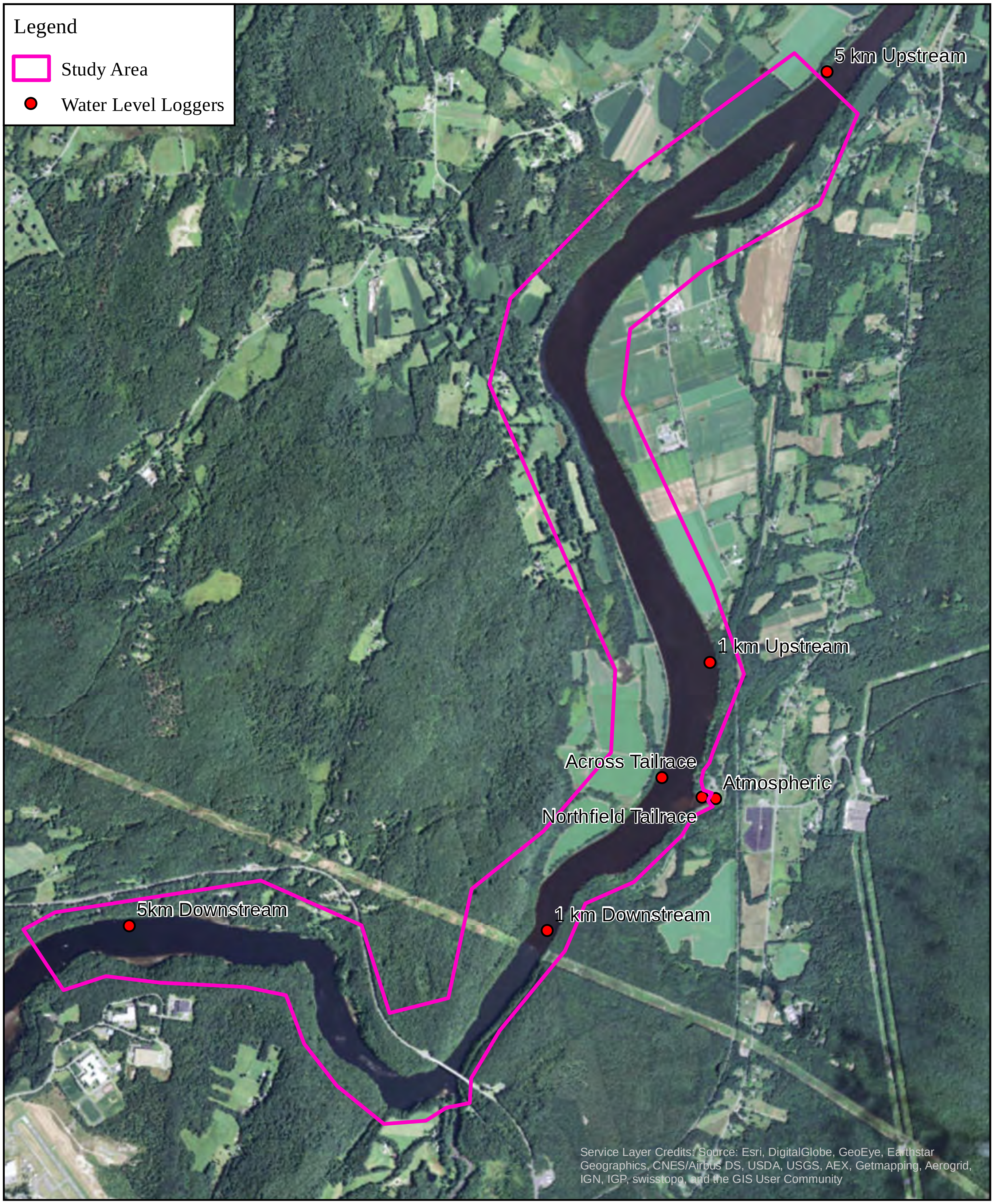
An ADCP linked to a GPS unit was utilized for the collection of these data. All information was collected in the NAVD88, and later converted to the NGVD29.

Due to the location of the field data collection relative to the intake structure, all work was conducted with a tethering system; no workers or boats were used in the water. Headpins and tailpins were established at the ends of each transect and a rope was drawn taut between the pins. Using a tethering system, the ADCP was mounted on a floating platform and then pulled across each transect under the four operating conditions described above. A picture of the set-up is shown in the inset.

In its September 13, 2013 SPD, FERC recommended a fourth transect be included, which was to be located equidistant from the intake and the closest proposed transect. In FirstLight's Initial Study Report (ISR) meeting summary filed with FERC on October 15, 2014, it noted that the fourth transect is technically on top of the intake structure and provided Figure 2.4-1. The upper half of Figure 2.4-1 indicates the approximate face of the intake structure (red dashed line) compared to the location of transects proposed in the RSP (green lines), while the face of the intake structure is faintly visible in the aerial imagery (dated 9/18/2011) provided in the lower half of Figure 2.4-1. The distance from the face of the intake structure to the closest transect is approximately 25 feet. As such a fourth transect was not collected as it would cross the top of the intake structure and provide meaningless data. In FERCs Determination on Requests for Study Modifications and New Studies, issued on January 22, 1015, it states *"Based on this new information,*

[7] The data were collected by US Imaging using an Optech M-300 Orion LiDAR Sensor and Integrated CS-10000 Digital CameraAircraft– Cessna T210N – N6258YQA. The LiDAR data were checked against the independently obtained QA/QC points throughout the project area and was found to have a Root Mean Square Error (RMSE) for the sample (RMSEz) of 6.1cm (vertical). The digital imagery was checked against more than 60 photo targets and Photo ID points along the project corridor and was found to have better than 12 cm horizontal standard deviation.

we conclude that the fourth transect is not necessary and recommend that FirstLight only be required to sample transects 1-3".



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N

0 0.25 0.5 1 Miles

Figure 2.1.1-1
Water Level Logger Locations

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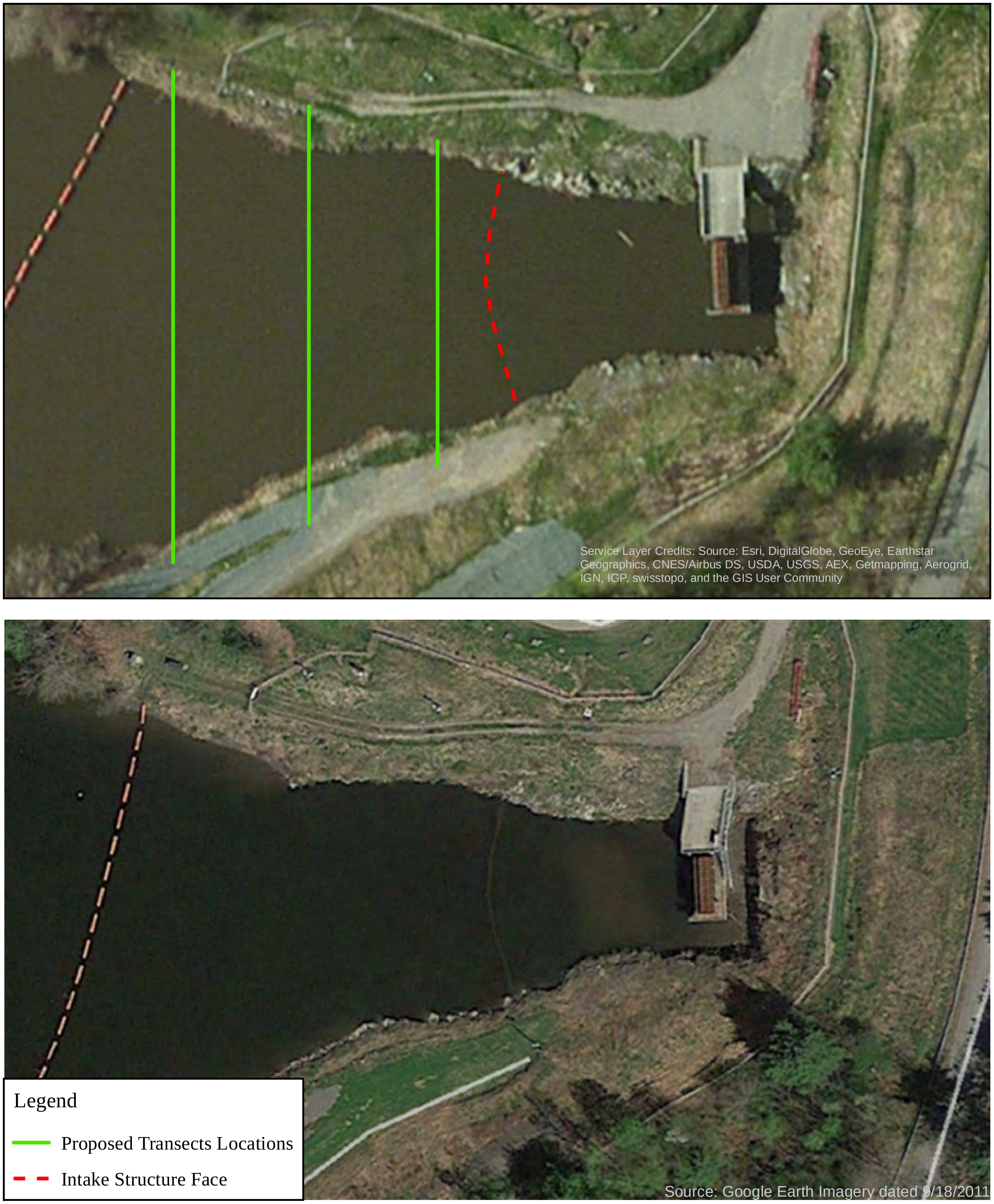

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0 0.005 0.01 0.02 Miles

Figure 2.4-1
Location of Proposed Transects with Respect to Face of Intake Structure

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3 MODEL DEVELOPMENT

3.1 River2D Model Background

Per the RSP, FirstLight used the two-dimensional hydraulic model, River2D, developed at the University of Alberta with funding from the Natural Sciences and Engineering Research Council of Canada, the Department of Fisheries and Oceans, Government of Canada, Alberta Environmental Protection, and the USGS. River2D is a suite of programs, which is publicly available and free-of-charge[8], which includes R2D_Bed and R2D_Mesh. This section provides a brief technical background on the development of a River2D model, which contains technical terms relating to hydraulics and hydrology. Whenever possible, effort has been made to simplify hydraulic concepts presented; however, if further clarification or explanation is desired, the reader is referred to the Users Manuals for each respective program[9].

The River2D model is a two-dimensional finite element depth averaged hydrodynamic and fish habitat model developed for use in natural streams and rivers. River2D solves for mass conservation and momentum balance in two dimensions using the St. Venant flow equations. River2D is designed to perform both steady (flow does not change over time) and unsteady (flow changes over a time) flow routing. The software predicts WSELs, river depths, and depth-averaged velocities at various locations under a range of flows.

The River2D model utilizes a bed topography file and overlays a computational mesh file. R2D_Bed is an interactive and graphical bed topography file editor, which defines points with horizontal and vertical locations as well as an associated roughness value for use in the River2D model. This file is usually comprised of bathymetry, LiDAR, or other observed elevation data. It should be noted that the roughness values in River2D are not the same as the Manning's n values typically used in one-dimensional modeling. This two-dimensional resistance term, roughness, only accounts for the direct bed shear, and represents the height of the bed roughness in meters. Therefore observations of bed material and bedform size are usually sufficient to establish reasonable initial roughness estimates. While the program provides a tool which estimates an appropriate roughness value based on a Manning's n roughness and a hydraulic radius, it is always better to develop roughness values through calibration where possible, as was done for this study (see Section 4, below). R2D_Mesh is an interactive and graphical mesh file editor, which is used to build a finite element mesh in order to generate an input file for River2D. R2D_Mesh defines a set of spatially distributed points or "nodes" throughout the study area, which extract an elevation and roughness value from the underlying bed file. It then creates a linearly-interpolated triangulated mesh from the set of nodes, with each triangle referred to as an "element". The boundary conditions including the computational extents are also defined in R2D_Mesh. Inflow boundaries can be either constant or time-varying, while outflow boundaries can be fixed or time-varying elevations, a stage-total discharge relationship, or a depth-unit discharge relationship. Many of the functions in R2D_Mesh are available within River2D. Transient, or unsteady, boundary conditions must be defined within the River2D user interface, rather than R2D_Mesh.

The processes utilized in the development of the bed and mesh files for this study are presented in Sections 3.2 and 3.3, below. It should be noted that while the River2D requires the use of the metric system for all inputs (i.e. meters and cubic meters per second), this study will report everything using the U.S. Customary system of units (i.e. ft and cfs).

3.2 River2D Bed

One seamless bathymetric/topographic surface was developed for the study reach using the bathymetric and LiDAR data described in Section 2.3. Figure 3.2-1 shows the surface, which was developed through

[8] Main Page of River2D website: http://www.river2d.ca/
[9] River2D User's Manual (Steffler & Blackburn, 2002), R2D_Bed User's Manual (Steffler, 2002), and R2D_Mesh User's Manual (Waddle & Steffler, 2002).

the use of the Geographic Information System (GIS), ArcGIS. Hundreds of thousands of points were used to develop the surface within the study reach. The use of all of these points would create a cumbersome bed file. Therefore, a series of steps were taken to thin the points to just over 93,000 for the bed file as follows:

- Remove points outside of the elevation 190 foot contour line;
- Convert the 190 and 185 foot elevation contours to points with 10 foot spacing; and,
- Convert the tin to a raster with a 20 foot cell size within the mainstem of the TFI and three (3) foot cell size within the Northfield tailrace, then creating points from this raster.

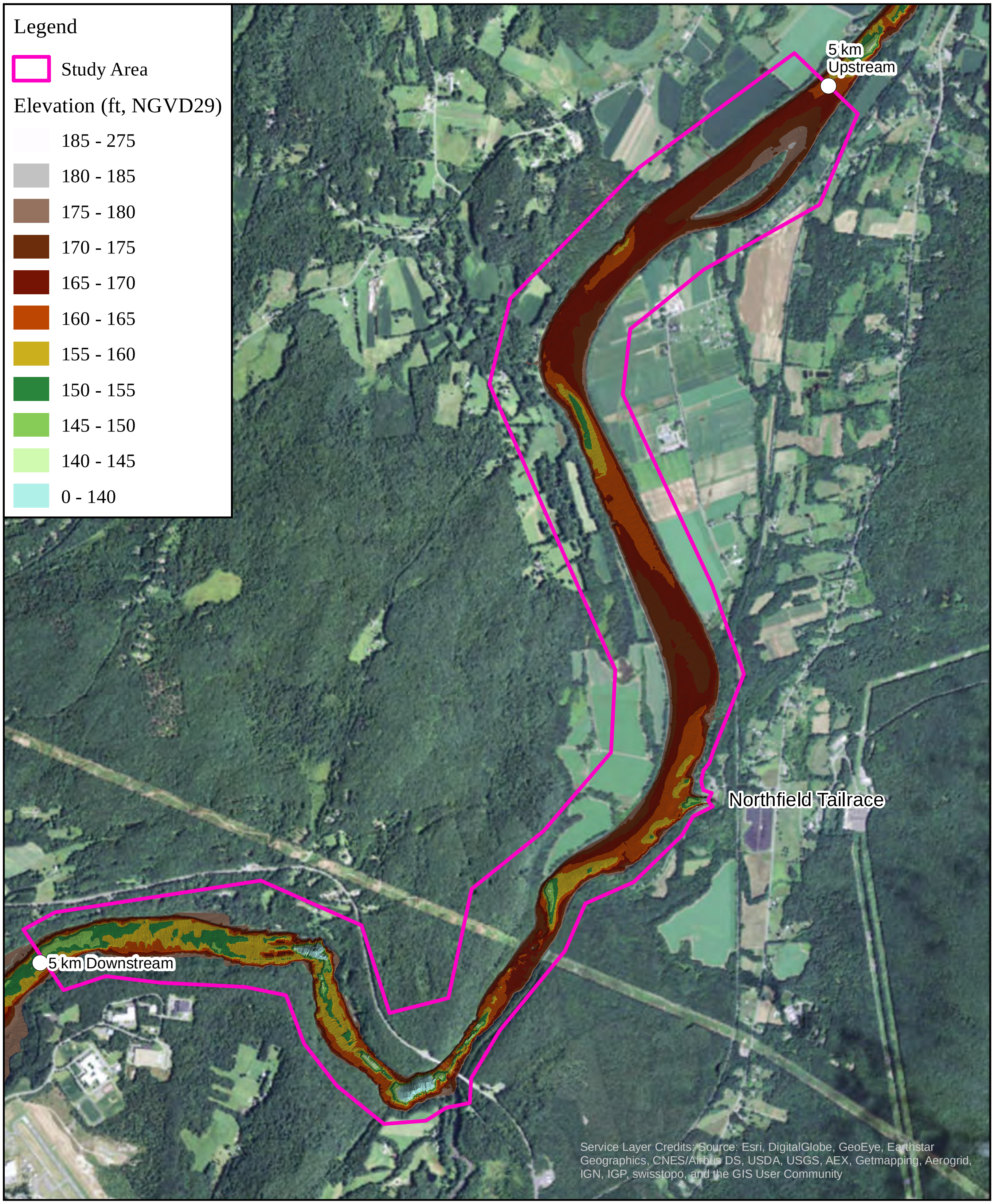
In this manner the horizontal and vertical attributes of the bed file points were defined. These steps also had the effect of smoothing the surface created in the bed file. The roughness values for the bed file were adjusted throughout the calibration process as described in Section 4, below. Figure 3.2-2 shows the final calibrated roughness values within the study area.

3.3 River2D Mesh

A proper mesh not only aims to adequately represent the topography of the bed file, but aims to create mesh elements which are reasonably close to equilateral, as this is a preference of the River2D software. Additionally, the model runtime increases significantly for meshes with a significant number of elements, because they require the use of the slower "iterative" solver, rather than the "direct" solver. The mesh quality index (QI) is a measure of how close a triangle is to being equilateral, while the difference in elevation between the center of the triangle and the underlying bed is evaluated by the "dz" parameter. A QI of one (1) represents a perfect equilateral triangle (e.g., values of 0.15 to 0.5 are considered acceptable), while a dz of zero (0) is optimal. During mesh development, greater emphasis was placed on evaluating the QI and dz values for areas within the main channel and areas closer to the tailrace, rather than the banks and tributaries. The mesh was generated with an initial node spacing of approximately 75 feet within the mainstem channel, and then further refined as needed to obtain acceptable values for dz and QI. The mesh was adjusted throughout the calibration process, as described in Section 4, below. The final mesh utilized 18,310 nodes and 36,592 elements with a QI value of 0.216. The values of dz are generally less than 0.5 feet, with greater values seen at areas with steep and/or irregular slopes such as the top of banks and deep cuts/depressions in the channel not indicative of the general topology. Figure 3.3-1 shows the surface created by the final mesh surface, while Figure 3.3-2 provides a comparison of the final mesh surface with the final bathymetric/topographic surface.

3.4 River2D Input Parameters

A variety of options are available within River2D when performing steady and unsteady hydraulic analyses. All runs performed for this study utilize the "direct" Analytical Jacobian Matrix for the linear solver. An upwinding coefficient of 0.5 was selected for all model runs. The transmissivity and storativity parameters for groundwater flow were each set to 0.1 in order to reduce the impact of groundwater movement as this phenomena is not usually expected to have a major influence during model simulation times of less than a day. For unsteady runs, a value of 0.5 was selected for the solution tolerance, a value of one (1) was selected for the implicitness, and the "goal time step" was selected to be 100 seconds. Further explanation regarding the selection of some of these parameters is provided with model calibration in Section 4, below.



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N

0 0.25 0.5 1 Miles

Figure 3.2-1
Bathymetric/Topographic Surface

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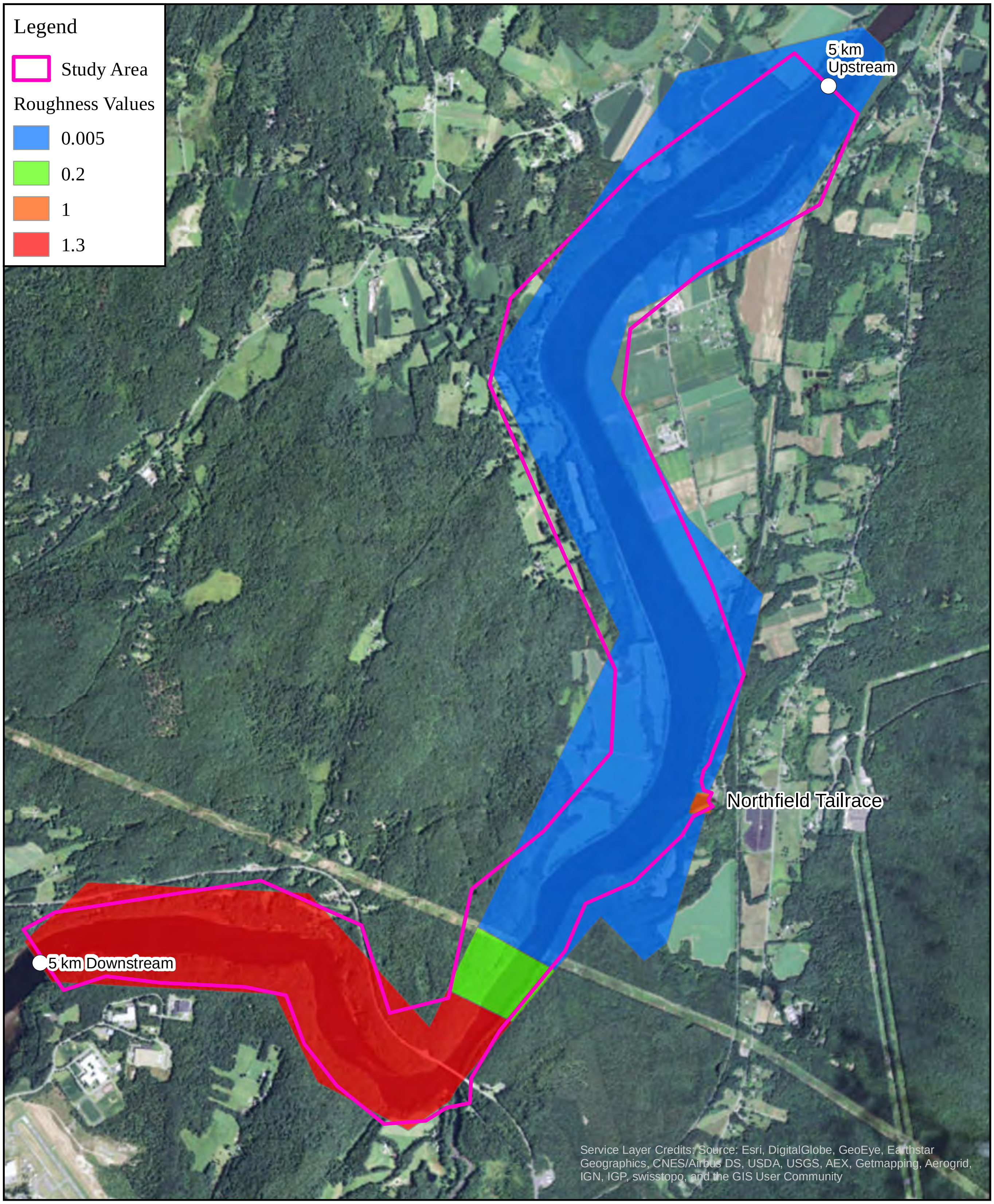

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Figure 3.2-2
Calibrated Roughness Values

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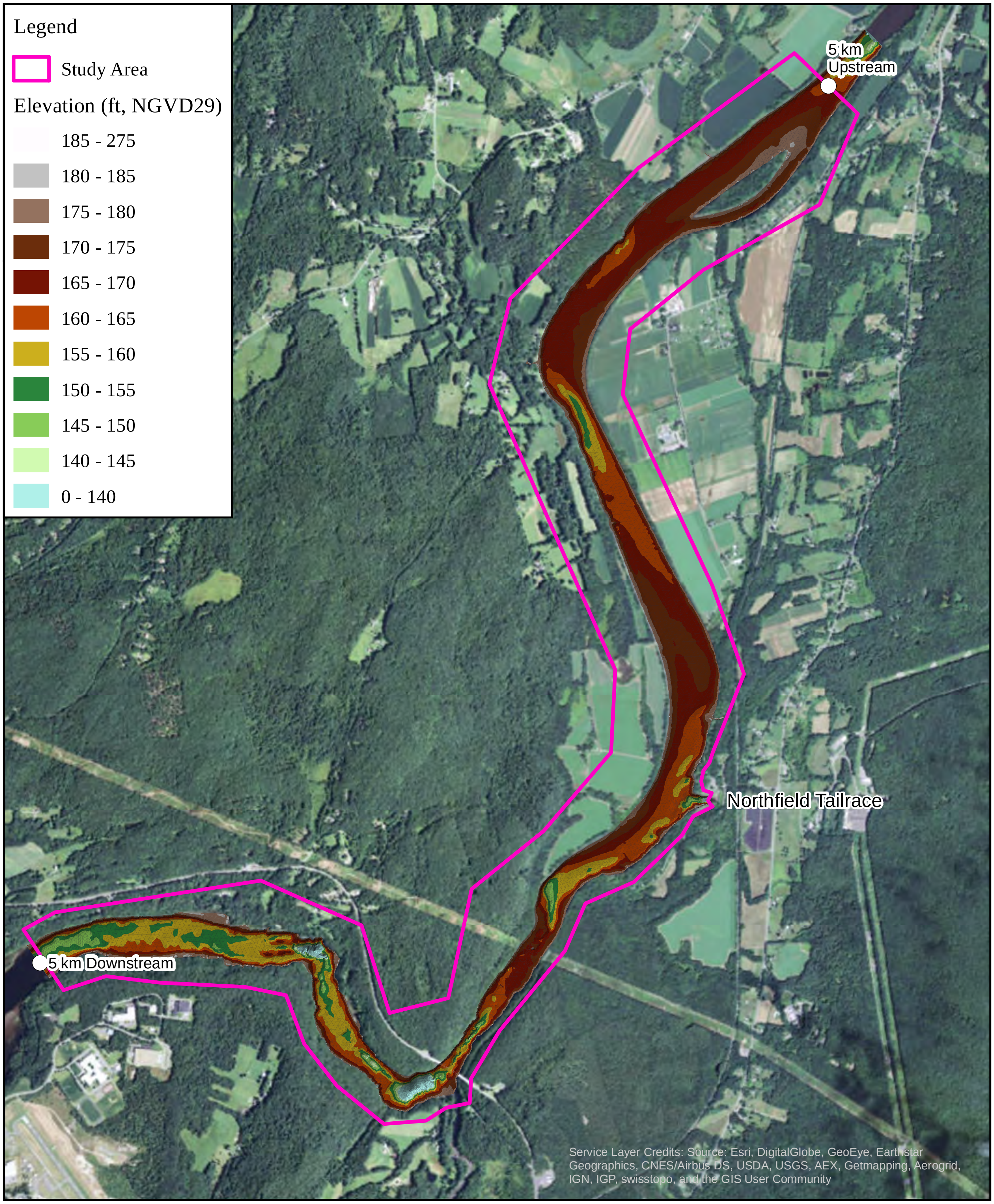

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N

0 0.25 0.5 1 Miles

Figure 3.3-1
Mesh Surface

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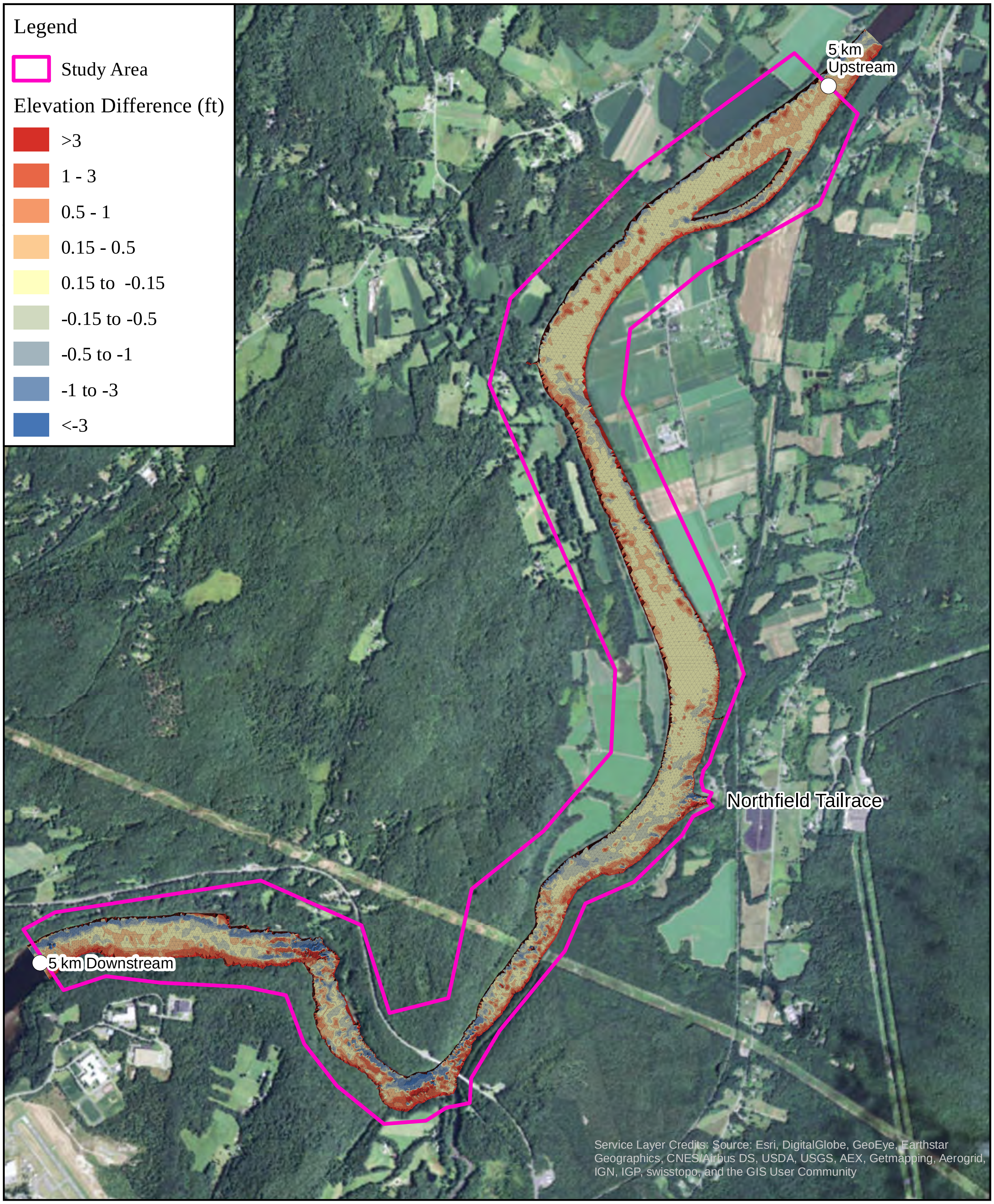

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Figure 3.3-2
Comparison of Mesh Surface to Bathymetric Surface

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4 MODEL CALIBRATION

4.1 Developing Model Boundary Conditions

Calibration of a model requires the use of observed data. This section describes the development of the boundary conditions from various observed data sources. Boundary conditions are needed at the Northfield tailrace (near the intake/tailrace structure) and at the end of the study reach (or 5 km downstream of the Northfield tailrace).

4.1.1 Northfield Tailrace

The RSP stated that the boundary immediately below the Northfield intake/tailrace would be defined with the flow condition being spread evenly across the boundary. The water column velocity data collected in the field suggested that this may not adequately represent the flow distribution at this boundary. Therefore, the boundary was split into five (5) sections of approximately equal length across the width of the intake/tailrace. Figures 4.1.1-1 and 4.1.1-2 show the distribution of flow across the tailrace from south to north, along with the percent of the total flow represented by each boundary segment, for the generating and pumping scenarios, respectively. The x-axis for these figures is shown as a percent of the total distance across the transect since transects 1, 2, and 3 represent three different lengths (see Figure 2.4-1). It should be noted that this distribution was also utilized for the scenarios.

All steady runs (i.e. both calibration and scenarios) were developed without operation of the Northfield pump-turbines (i.e. zero (0) flow through the Northfield tailrace boundary). The initial conditions for unsteady runs require that a steady run be performed to stabilize the model to the initial conditions. The total flow through the boundary for the unsteady calibration runs was obtained from the FirstLight database as described in Section 2.2.3, above. The values utilized for the Northfield tailrace boundary condition for steady calibration runs, and the text file inputs utilized for the Northfield tailrace boundary condition for unsteady calibration runs are provided in Appendix A.

4.1.2 Downstream

The RSP stated that the downstream boundary (5 km downstream of the Northfield tailrace) would be defined using a stage-discharge relationship with a nearly constant discharge over the range of stages. The intention of this boundary condition is to present a scenario in which the discharge from the Turners Falls Dam is constant. Since the boundary condition is located a distance upstream of Turners Falls Dam (or 5 km downstream of the Northfield tailrace), use of the stage-discharge relationship as described in the RSP may indicate a faster drawdown or filling of the TFI than would otherwise occur due to the storage in the portions of the TFI not defined in the study area. Therefore, the downstream boundary was defined as a stage utilizing the observed values from the water level logger installed five (5) km downstream of the Northfield tailrace, as described later. The stage is constant for steady runs, and time-varying for unsteady runs. The values utilized for the Downstream boundary condition for steady calibration runs, and the text file inputs utilized for the Downstream boundary condition for unsteady calibration runs are provided in Appendix A.

4.1.3 Base Flow

The base flow for the mainstem of the Connecticut River was applied at two locations (i.e. upstream end of the model and the Millers River confluence). The inflow at the Millers River confluence was derived by prorating the Millers River gage flow (Gage No. 01166500), based on the difference in drainage area along the Connecticut River between the Turners Falls Dam and the Northfield tailrace divided by the Millers River drainage area at the gage, see Equation 4.1.3-1. The inflow to the upstream end of the model was derived by adding to the Vernon flow (i.e. reported by TransCanada), a prorated Ashuelot River gage flow (Gage No. 01161000), based on the difference in drainage area along the Connecticut River between the

Northfield tailrace and Vernon Dam divided by the Ashuelot River drainage area at the gage, see Equation 4.1.3-2.

$$\text{Millers River Boundary Flow} = \text{Millers River Gage Flow} * \frac{(7{,}163 - 6{,}766)}{372} \qquad (4.1.3\text{-}1)$$

$$\text{Upstream Boundary Flow} = \text{Vernon Flow} + \text{Ashuelot River Gage Flow} * \frac{(6{,}766 - 6{,}266)}{420} \qquad (4.1.3\text{-}2)$$

Where,

7,163 = Connecticut River Drainage Area at Turners Falls Dam, as reported in the Pre-Application Document (PAD)

6,766 = Connecticut River Drainage Area at Northfield tailrace, as measured from USGS Streamstats[10]

6,266 = Connecticut River Drainage Area at Vernon Dam, as reported in the PAD

420 = Ashuelot River Drainage Area at USGS Gage No. 01161000, as reported by USGS

372 = Millers River Drainage Area at USGS Gage No. 01166500, as reported by USGS

Although the base flow into the TFI remains constant throughout the calibration run, the flow at the upstream model boundary may not remain constant due to influences from operations at the Northfield Mountain Project. Since observed flows are not available at the upstream boundary, a time-varying flow hydrograph was generated for the Upstream boundary condition using the HEC-RAS[11] hydraulic model of the TFI developed under Study No. 3.2.2 of the RSP. The time-varying upstream boundary flow computed using the above equations was entered into the most upstream transect in the HEC-RAS model (i.e. just downstream of Vernon Dam), as appropriate for each unsteady calibration run scenario, while the computed Millers River boundary flow was entered in to the nearest transect to the confluence of the Millers River with the Connecticut River. The most downstream transect in the HEC-RAS model is located upstream of the Turners Falls Dam (i.e. at the boat barrier for the dam) and is considered representative of conditions at the dam. As such, the downstream condition for the HEC-RAS model was set as a stage/flow hydrograph utilizing observed data provided by FirstLight. The stage was taken from the water level logger at Turner Falls Dam (TF_Pond), and the flow was taken as the sum of the Turner Falls Dam (TF_Dam) and gatehouse (Cabot_Canal) flows. The HEC-RAS model was run with the appropriate Northfield operations (pump or generate as reported by Northfield_CFS) for each calibration run scenario. Results from the HEC-RAS model were retrieved at a transect located near the upstream end of the River2D model in order to develop the time-varying flow hydrograph for the River2D calibration run. The values utilized for the Upstream and Millers River boundary conditions for steady calibration runs, and the text file inputs utilized for the Upstream and Millers River boundary conditions for unsteady calibration runs are provided in Appendix A.

4.2 Steady Runs

4.2.1 Low Flow

The difference in WSELs throughout the TFI under any flow condition increases as the WSEL at Turners Falls Dam is lowered. Under low flows, the WSEL throughout the entire TFI is dependent on the WSEL at Turners Falls Dam. The water level logger and flow data described in Section 4.1, above, were reviewed to identify a period of time with low inflows, no Northfield operations, and a low TFI elevation. The time period best meeting these criteria (i.e. 9/7/2014 10:00) only indicated a 0.07 foot difference (i.e. less than

[10] USGS Streamstats website: http://water.usgs.gov/osw/streamstats/
[11] HEC-RAS: Hydrologic Engineering Center River Analysis System

one (1) inch) in the WSEL from the downstream to upstream end of the study area under a total inflow of approximately 2,500 cfs, as measured downstream of the confluence with Millers River. This is not ideal for trying to calibrate roughness values under low flow conditions, as a wide range of roughnesses could lead to acceptable results. Therefore, the high flow event was primarily used to determine appropriate roughness values, although the low flow scenario was still utilized for identifying areas of the mesh in need of refinement and a check to ensure that the final roughness values are appropriate. The modeled WSELs were within 0.02 feet of the observed WSEL throughout the model for the low flow calibration run.

4.2.2 High Flow

Calibration results for steady flow runs are more reliable when the observed inflows and WSELs were steady for a longer period of time rather than during an unsteady event (e.g., rising or falling limb of a storm event). The water level logger and flow data described in Section 4.1, above, were reviewed to identify a period of time with high inflows, no Northfield operations, and a fairly steady TFI elevation. The time period best meeting these criteria (i.e. 5/24/2014 21:30) indicated approximately 3.0 feet of difference in the WSEL from the downstream to upstream end of the study area under a total inflow of approximately 31,360 cfs. The water level loggers indicated that most of this change in WSEL (i.e. approximately 2.2 feet) occurs in the downstream 4 km of the study area. The model confirmed that a majority of the change in WSEL occurs within the French King Gorge, a naturally constricted river reach downstream of the Northfield tailrace that causes high velocities and higher upstream WSELs. The calibrated roughness values were thus significantly higher in the downstream portion of the model. The modeled WSEL were generally within 0.1 feet of the observed WSELs throughout the model for the high flow calibration run.

4.3 Unsteady Runs

The observed values during the unsteady runs were based on the same time period for which the water column velocity data were collected for four (4) units pumping and generating (July 12, 2014), as described in Section 2.4, above. The steady runs performed to determine the initial conditions for each of the unsteady calibration runs indicated that there was not enough change in the modeled WSEL to match the observed WSEL for the upstream portion the model (i.e. upstream of the Northfield tailrace). However, there was less confidence in these runs due to the higher variability in the inflows during the time leading up to pumping and generation operations. Additionally, the inflows for these runs are significantly smaller than those used for the high flow calibration run. As such, any changes in roughness values for the unsteady runs, would have a much greater impact on the WSELs for the high flow calibration run. Therefore the roughness values in the mainstem of the Connecticut River determined during the high flow calibration run were not altered. It should be noted that further refinement to the mesh within the tailrace was performed as part of the unsteady calibration runs in order to improve model stability.

4.3.1 4-Units Generating

The total inflow of approximately 9,710 cfs, excluding Northfield operations, was fairly steady throughout the unsteady event. The simulation was run for approximately 5.5 hours, during which time the Northfield operations varied from zero (0) flow at the beginning of the simulation to a peak generation flow of approximately 20,500 cfs. The sensitivity analyses shows a reasonable correlation with the observed flow direction and magnitude, as indicated in Figure 4.3.1-1.

4.3.2 4-Units Pumping

The total inflow of approximately 3,640 cfs, excluding Northfield operations, was fairly steady throughout the unsteady event. The simulation was run for approximately 3 hours, during which time the Northfield operations varied from zero (0) flow at the beginning of the simulation to a peak pumping flow of approximately 13,500 cfs. The sensitivity analyses shows a reasonable correlation with the observed flow direction and magnitude, as indicated in Figure 4.3.2-1.

4.4 Sensitivity Analyses

A variety of sensitivity analyses were performed with the unsteady runs in order to decrease the time it took to run the model. Use of the default parameters in River2D required more than one (1) day to complete the three (3) to five (5) hours of simulation time. As parameters are altered to decrease the run time, there is some loss in accuracy. Efforts were made to provide a reasonable balance of model run time and accuracy when selecting the final parameters.

Many values were evaluated including the upwinding coefficient, solution tolerance, implicitness, goal time step, and more. The upwinding coefficient is recommended to be set to 0.5 for steady state simulations and 0.25 for unsteady simulations. In the end, an upwinding coefficient of 0.5 was utilized for all runs because it greatly decreased the run time with little variation in results. Similarly the final selected values described in Section 3.4, above, provided essentially the same WSELs with little impact on the velocity magnitude and direction when compared to the default parameters. The differences in the velocity magnitude and direction are primarily in areas of low velocity (i.e. along the banks, in the center of eddy formations), and in areas of significant mixing (i.e. where the tailrace flow mixes with the main stem river flow). A larger degree of uncertainty was expected in these areas, and the overall flow direction and velocity magnitude remained reasonable.

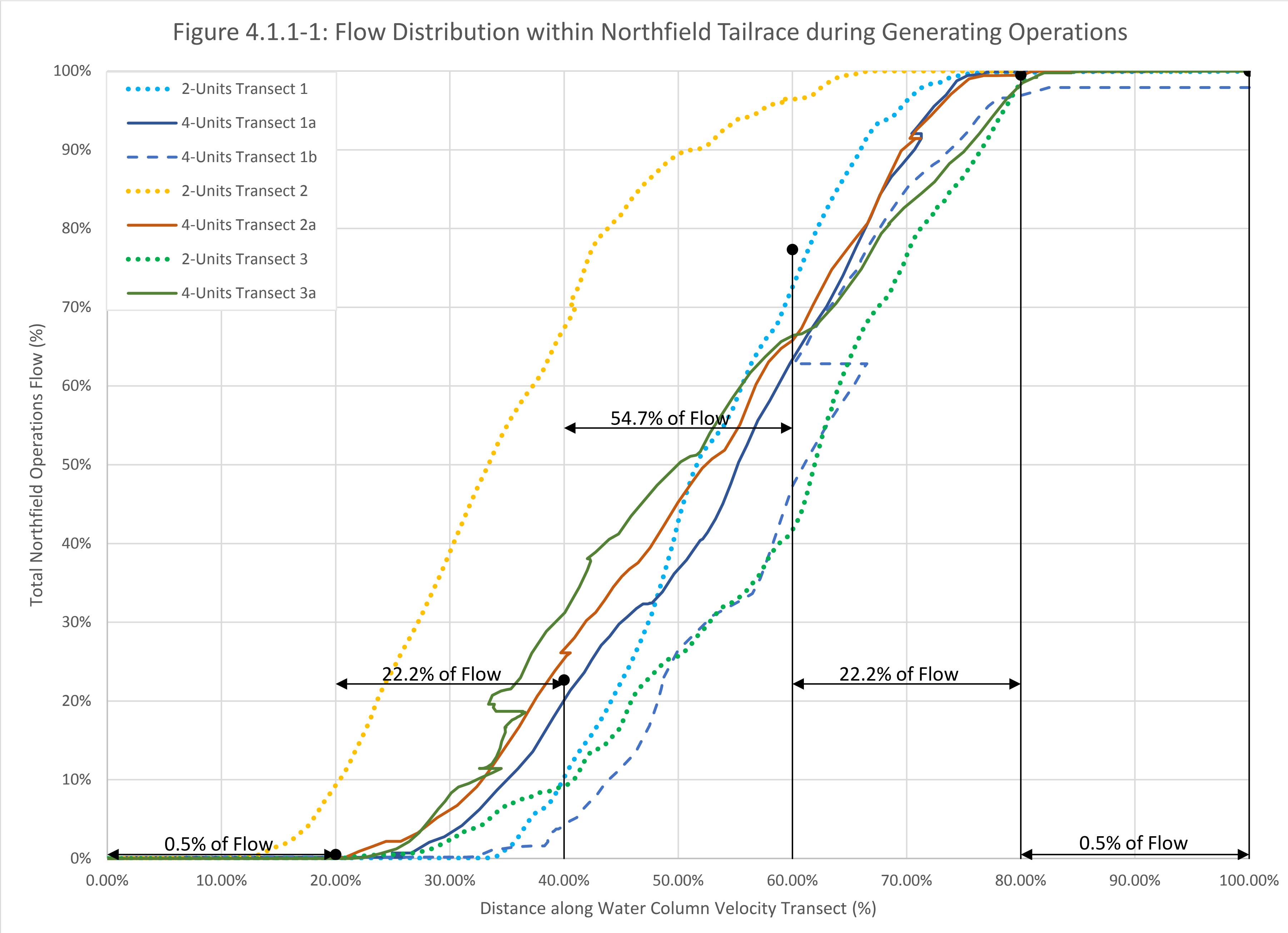


Figure 4.1.1-1: Flow Distribution within Northfield Tailrace during Generating Operations
2-Units Transect 1
4-Units Transect 1a
4-Units Transect 1b
2-Units Transect 2
4-Units Transect 2a
2-Units Transect 3
4-Units Transect 3a
54.7% of Flow
22.2% of Flow
22.2% of Flow
0.5% of Flow
0.5% of Flow
Total Northfield Operations Flow (%)
Distance along Water Column Velocity Transect (%)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0.00%
10.00%
20.00%
30.00%
40.00%
50.00%
60.00%
70.00%
80.00%
90.00%
100.00%

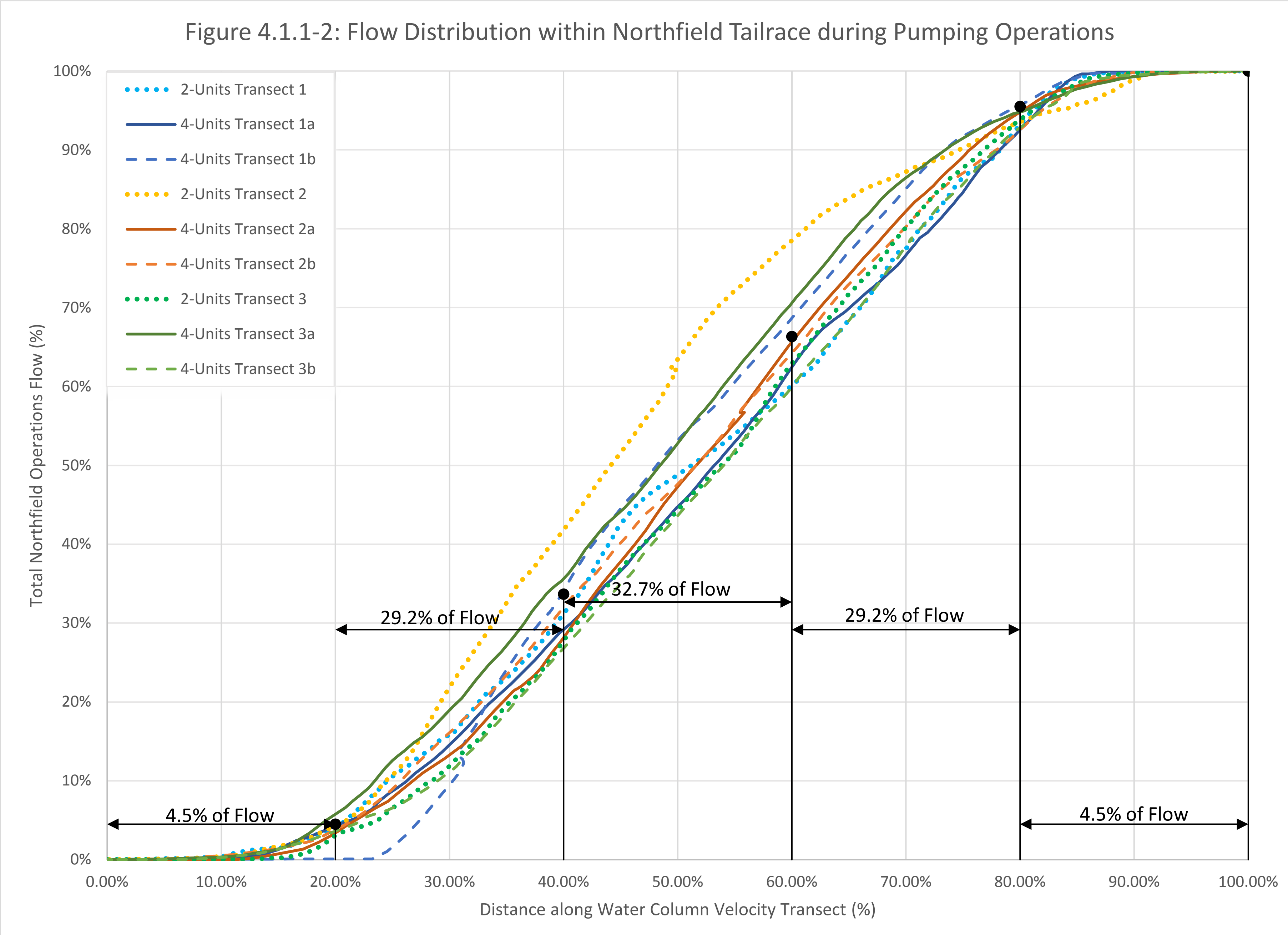
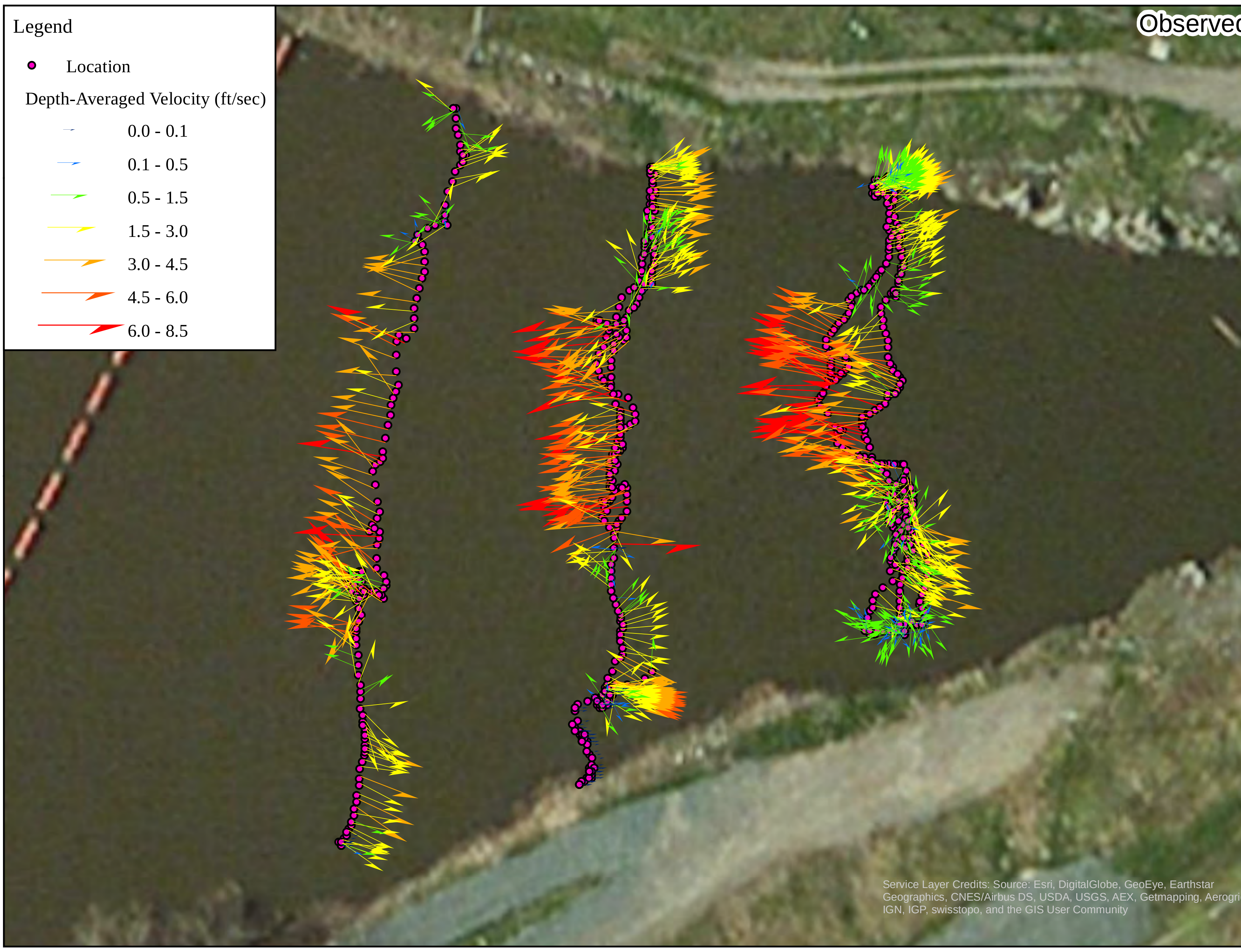
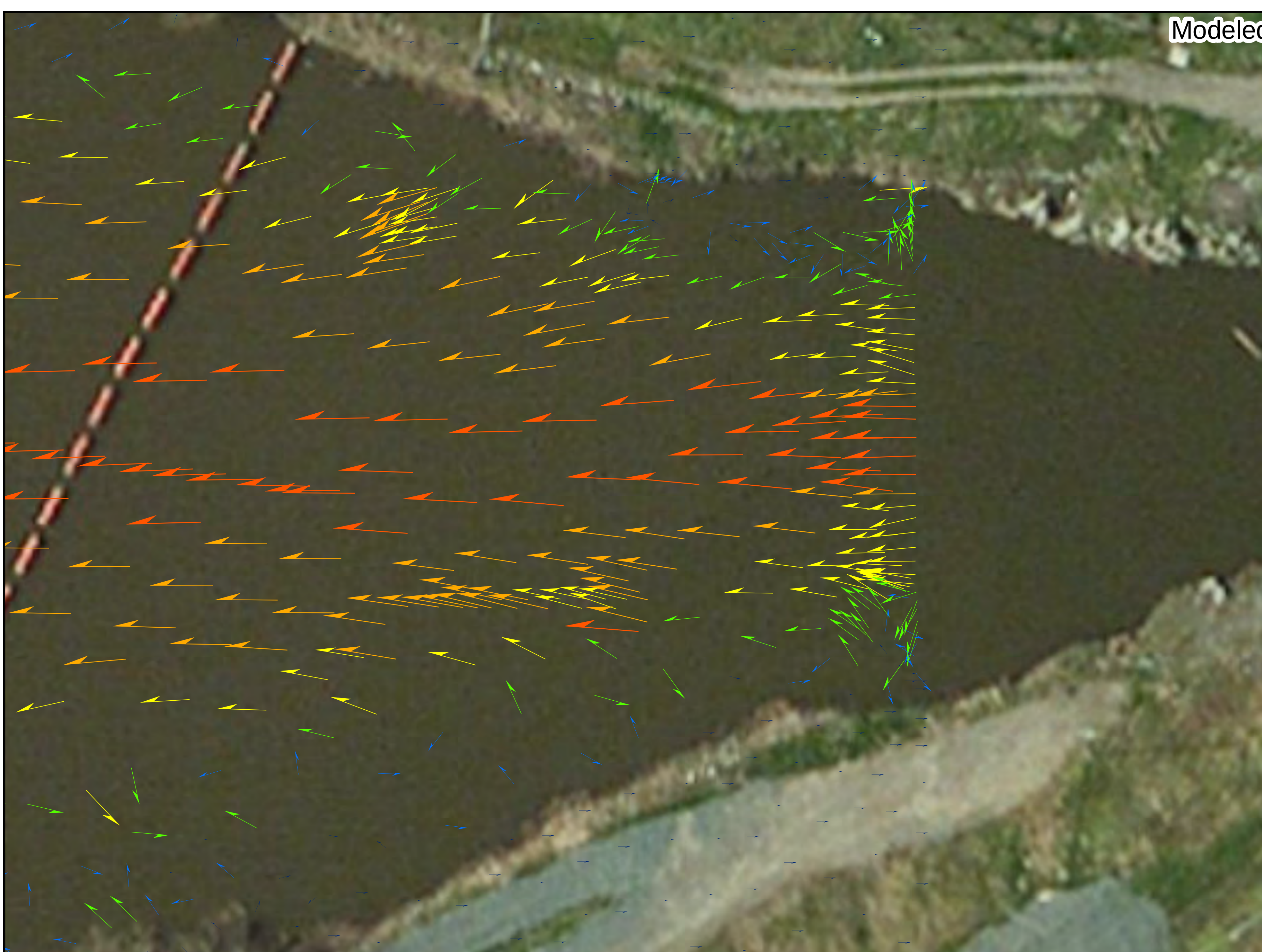


Figure 4.1.1-2: Flow Distribution within Northfield Tailrace during Pumping Operations
2-Units Transect 1
4-Units Transect 1a
4-Units Transect 1b
2-Units Transect 2
4-Units Transect 2a
4-Units Transect 2b
2-Units Transect 3
4-Units Transect 3a
4-Units Transect 3b
4.5% of Flow
29.2% of Flow
32.7% of Flow
29.2% of Flow
4.5% of Flow
Total Northfield Operations Flow (%)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0.00%
10.00%
20.00%
30.00%
40.00%
50.00%
60.00%
70.00%
80.00%
90.00%
100.00%
Distance along Water Column Velocity Transect (%)





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

STUDY REPORT
RELICENSING STUDY 3.3.9

0 0.005 0.01 0.02 Miles

Figure 4.3.1-1
Comparison of Observed and Modeled Velocities with 4-Units Generating

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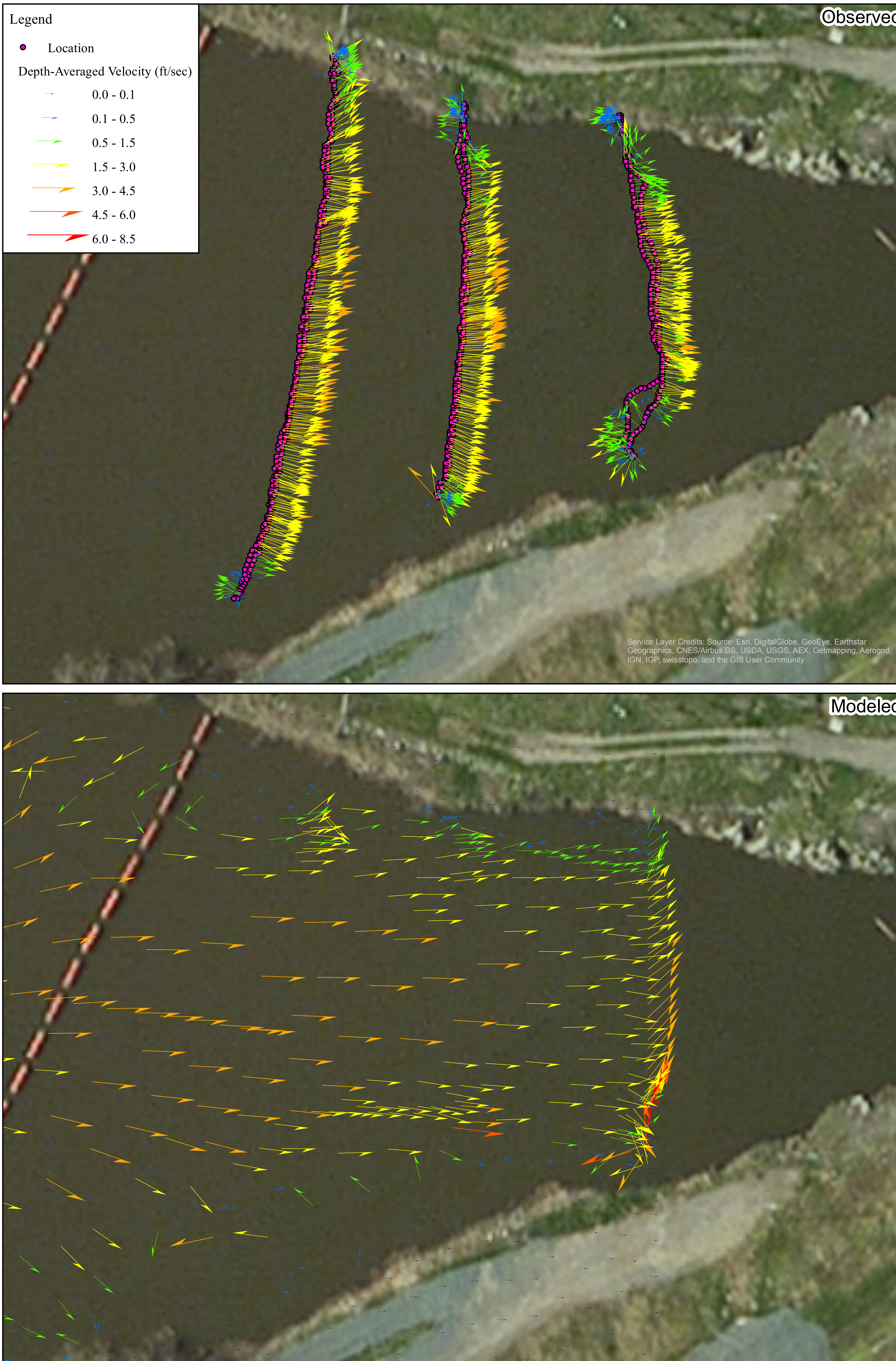

FirstLight GDF SUEZ

Northfield Mountain Pumped Storage Project (No. 2485)
and Turners Falls Hydroelectric Project (No. 1889)
STUDY REPORT
RELICENSING STUDY 3.3.9

N

0 0.005 0.01 0.02 Miles

Figure 4.3.2-1
Comparison of Observed and Modeled Velocities with 4-Units Pumping

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5 MODEL INPUTS FOR SCENARIOS

The scenarios varied the following three model variables:

- Northfield Mountain Project flow (pumping or generating at full or half hydraulic capacity).
- TFI elevation, as measured at Turners Falls Dam (either 176 feet or 185 feet, the lower and upper FERC licensed ranges, or 181.3 feet (the median TFI elevation for the period 2000-2010).
- Connecticut River flow (base flow) as measured at Turners Falls Dam.

Table 5.0-1 lists all of the scenarios. It should be noted that scenarios 41 through 60 are considered to be more representative of normal operating conditions, and were included despite not being part of the study plan.

Table 5.0-1: List of River2D Hydraulic Modeling Scenarios

Scenario No.	Northfield Mountain Generation Flow (cfs)	Northfield Mountain Pumping Flow (cfs)	Turners Falls Impoundment Elevation at Turners Falls Dam (ft)	Turners Falls Dam Flow (cfs)
1	10,000	0	176.0	1,760 (95% exceedance flow)
2	10,000	0	185.0	1,760
3	20,000	0	176.0	1,760
4	20,000	0	185.0	1,760
5	0	7,600	176.0	1,760
6	0	7,600	185.0	1,760
7	0	15,200	176.0	1,760
8	0	15,200	185.0	1,760
9	10,000	0	176.0	4,900 (75% exceedance flow)
10	10,000	0	185.0	4,900
11	20,000	0	176.0	4,900
12	20,000	0	185.0	4,900
13	0	7,600	176.0	4,900
14	0	7,600	185.0	4,900
15	0	15,200	176.0	4,900
16	0	15,200	185.0	4,900
17	10,000	0	176.0	8,440 (50% exceedance flow)
18	10,000	0	185.0	8,440
19	20,000	0	176.0	8,440
20	20,000	0	185.0	8,440
21	0	7,600	176.0	8,440
22	0	7,600	185.0	8,440
23	0	15,200	176.0	8,440
24	0	15,200	185.0	8,440
25	10,000	0	176.0	15,700 cfs (25% exceedance flow)
26	10,000	0	185.0	15,700
27	20,000	0	176.0	15,700
28	20,000	0	185.0	15,700
29	0	7,600	176.0	15,700
30	0	7,600	185.0	15,700
31	0	15,200	176.0	15,700
32	0	15,200	185.0	15,700
33	10,000	0	176.0	40,100 (5% exceedance flow)
34	10,000	0	185.0	40,100
35	20,000	0	176.0	40,100

Scenario No.	Northfield Mountain Generation Flow (cfs)	Northfield Mountain Pumping Flow (cfs)	Turners Falls Impoundment Elevation at Turners Falls Dam (ft)	Turners Falls Dam Flow (cfs)
36	20,000	0	185.0	40,100
37	0	7,600	176.0	40,100
38	0	7,600	185.0	40,100
39	0	15,200	176.0	40,100
40	0	15,200	185.0	40,100
41	10,000	0	181.3	1,760
42	20,000	0	181.3	1,760
43	0	7,600	181.3	1,760
44	0	15,200	181.3	1,760
45	10,000	0	181.3	4,900
46	20,000	0	181.3	4,900
47	0	7,600	181.3	4,900
48	0	15,200	181.3	4,900
49	10,000	0	181.3	8,440
50	20,000	0	181.3	8,440
51	0	7,600	181.3	8,440
52	0	15,200	181.3	8,440
53	10,000	0	181.3	15,700
54	20,000	0	181.3	15,700
55	0	7,600	181.3	15,700
56	0	15,200	181.3	15,700
57	10,000	0	181.3	40,100
58	20,000	0	181.3	40,100
59	0	7,600	181.3	40,100
60	0	15,200	181.3	40,100

The following sections describe the development of the River2D inputs for these variables.

5.1 Northfield Tailrace Boundary Condition

Four (4) different flow scenarios were evaluated for the Northfield Mountain Project flow (i.e. 4-units pumping, 2-units pumping, 4-units generating, 2-units generating). The reported maximum hydraulic capacity for all four (4) units pumping and generating is approximately 15,200 cfs and 20,000 cfs, respectively. Thus, the maximum hydraulic capacity for two (2) units pumping and generating is approximately 7,600 cfs and 10,000 cfs, respectively. The time series for the Northfield operations holds steady at zero (0) for the first 15 minutes prior to ramping up to the appropriate maximum capacity (pumping or generating) over the next 15 minute period, at which time it was held constant for the remainder of the simulation. The boundary was separated into five (5) segments as described in Section 4.1.1, above. The text file inputs utilized for the Northfield tailrace boundary condition are provided in Appendix A.

5.2 Downstream Boundary Condition

Per the RSP, the model runs (determination of the velocity, depth and WSEL) were to be performed with the TFI at its maximum and minimum elevations permitted under the current FERC License (i.e. 185 ft and 176 ft). Additional runs with the TFI at 181.3 ft were included, as this is more representative of normal operating conditions (i.e. median impoundment level for the period 2000-2010). As described in Section 4.1.2, above, a stage-discharge boundary at the 5 km end of the River 2D model is not appropriate. Instead, a time-varying stage is more appropriate. Since observed stages are not available for the conditions proposed for the scenarios, they were generated using the HEC-RAS hydraulic model of the TFI developed under Study No. 3.2.2 of the RSP. The most downstream transect in the HEC-RAS model is closely located at the Turners Falls Dam (i.e. at the boat barrier for the dam) and is considered representative of conditions at the dam. As such, the downstream condition for the HEC-RAS model was set as a constant outflow (i.e. equal to the base flow as appropriate for each scenario, see Section 5.3, below) with an initial stage of either 176 ft or 185 ft, as appropriate and per the intention of the RSP. The HEC-RAS model was run with the appropriate Northfield operations for each scenario, and results from the HEC-RAS model were retrieved at a transect located closest to the downstream end of the River2D model in order to develop the time-varying stage for the River2D scenario. The text file inputs utilized for the Downstream boundary condition are provided in Appendix A.

5.3 Base Flow Boundary Conditions

Per the FERC's SPDL, the base flow was to be evaluated at five different flows (i.e. the 5%, 25%, 50%, 75%, and 95% exceedance flow at Turners Falls Dam). Therefore an exceedance curve was computed for the Turners Falls Dam using the approved daily average flows for each water year[12] (WY) reported at both the Montague gage (USGS Gage No. 01170500) and the Deerfield gage (USGS Gage No. 01170000). At the time of the analysis the data for both gages were only approved through WY 2012, and were reported as provisional for WY2013 indicating that a quality assurance/quality control review had not yet been performed. Additionally, while the Deerfield gage has spotty data from 1904 and 1905, it does not have any other data until 1940. As such the analysis utilized data from WY-1941 through WY-2012. The average daily flow at Turners Falls Dam was derived by taking the Montague gage flow and subtracting the Deerfield gage flow prorated by the difference in drainage area along the Connecticut between the Montague gage and Turners Falls Dam divided by the Deerfield River drainage area at the gage, see Equation 5.3-1.

$$\text{Turners Falls Dam Flow} = \text{Montague Gage Flow} - \text{Deerfield Gage Flow} * \frac{(7{,}860 - 7{,}163)}{557} \qquad (5.3\text{-}1)$$

Where,

7,860 = Connecticut River Drainage Area at USGS Gage No. 01170500, as reported by USGS

7,163 = Connecticut River Drainage Area at Turners Falls Dam, as reported in the PAD

557 = Deerfield River Drainage Area at USGS Gage No. 01170000, as reported by USGS

Similar to the calibration runs, the base flow for the mainstem of the Connecticut River was applied at two locations (i.e. upstream end of the model and the Millers River confluence). As such, exceedance curves were computed for the Upstream boundary and Millers River boundary as well. The exceedance curve for the Millers River confluence was derived from daily flows at the Millers River gage after being prorated in the same way described in Section 4.1.3, above. A daily flow record for the upstream end of the model was generated by summing the daily flows from the Vernon gage (USGS Gage No. 01156500) and the prorated daily flows from the Ashuelot gage. The Ashuelot gage was prorated in the same way as described in Section 4.1.3, above, and an upstream daily flow was only computed for days in which daily flows for both gages were available. An exceedance curve for the upstream end of the model was thus generated from this derived daily flow record. Since the Upstream boundary and Millers River boundary exceedance curves do not comprise the entire drainage area represented by the Turners Falls exceedance curve, the Upstream boundary and Millers River boundary curves for a given exceedance value do not sum to the flow from the Turners Falls curve for that same exceedance value. As such, the Upstream boundary and Millers River boundary exceedance curves were prorated so that they summed to equal the Turners Falls exceedance curve. In general the Millers River boundary exceedance curve represents approximately 5%

[12] A water year is defined by the USGS as the 12-month period October 1, for any given year through September 30, of the following year. The water year is designated by the calendar year in which it ends and which includes 9 of the 12 months. Thus, the year ending September 30, 2012 is called the "2012" water year.

to 8% of the total inflow to the model. Figure 5.3-1 shows the exceedance curves for the Turners Falls Dam, Upstream boundary and Millers River boundary, as well as the adjusted Upstream boundary and adjusted Millers River boundary exceedance curves.

Although the base flow into the TFI remains constant throughout the scenario, the flow at the upstream model boundary may not remain constant due to influences from operations at Northfield. Therefore, similar to the downstream boundary condition, a time-varying flow hydrograph was generated using the HEC-RAS model from Study No. 3.2.2 of the RSP for the upstream boundary condition. The baseflow from the adjusted Upstream boundary exceedance flow was entered into the most upstream transect in the HEC-RAS model (i.e. just downstream of Vernon Dam), as appropriate for each scenario, while the adjusted Millers River boundary exceedance flow was entered in to the nearest transect to the confluence of the Millers River with the Connecticut River. Table 5.3-1 provides the flows utilized for boundaries within the HEC-RAS model. The HEC-RAS model was run with the appropriate Northfield operations for each scenario, and results from the HEC-RAS model were retrieved at a transect located near the upstream end of the River2D model in order to develop the time-varying flow hydrograph for the scenario. The text file inputs utilized for the Upstream and Millers River boundary condition are provided in Appendix A.

Table 5.3-1: Exceedance Flows Utilized for Boundary Conditions

Turners Falls Dam Exceedance	Turners Falls Dam Flow	Upstream Boundary Condition Flow	Millers River Boundary Condition Flow
95%	1,760 cfs	1,620 cfs	140 cfs
75%	4,900 cfs	4,640 cfs	260 cfs
50%	8,440 cfs	7,930 cfs	510 cfs
25%	15,700 cfs	14,730 cfs	970 cfs
5%	40,100 cfs	37,830 cfs	2,270 cfs

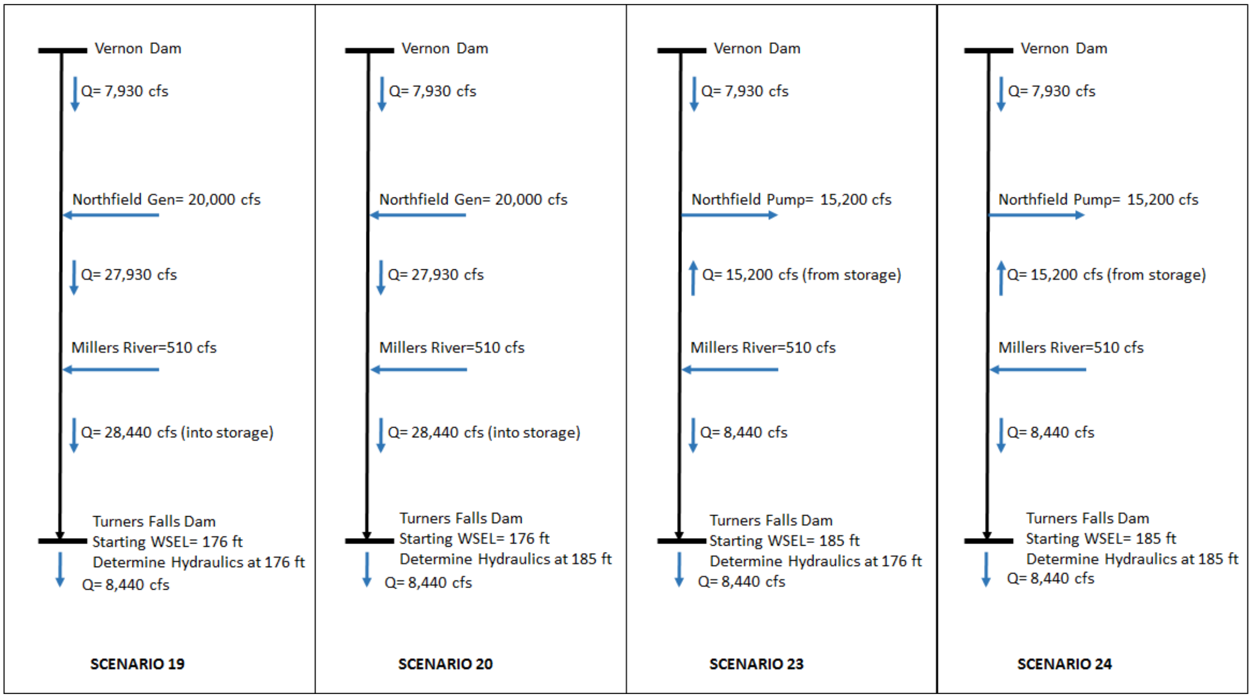
Notes:

- Upstream Boundary Condition Flow = Vernon Discharge + Ashuelot River Flow
- Millers River Boundary Condition Flow = Millers River Flow
- Turners Falls Dam Flow = Upstream Boundary Condition Flow (Vernon Discharge + Ashuelot River Flow) + Millers River Flow

5.4 Summary of Model Runs

To help explain the process of how model runs were conducted, four examples (Scenarios 19, 20, 23, and 24) are provided below representing full pump and full generation conditions under the median flow. A not-to-scale schematic of these scenarios is shown below.

Scenario No.	Northfield Mountain Generation Flow (cfs)	Northfield Mountain Pumping Flow (cfs)	Turners Falls Impoundment Elevation at Turners Falls Dam (ft)	Turners Falls Dam Flow (cfs)
19	20,000	0	176.0	8,440 (50% Exceedance Flow)
20	20,000	0	185.0	8,440
23	0	15,200	176.0	8,440
24	0	15,200	185.0	8,440



Step 1: Run HEC-RAS Model in Unsteady State

The HEC-RAS model developed for Study 3.2.2 was used to simulate WSELs from the Turners Falls Dam up to the Vernon Dam. From this unsteady state model, a WSEL versus time relationship was determined at the transect located 5 km below the Northfield tailrace and a discharge versus time relationship was determined at the transect located 5 km above the Northfield tailrace for the 60 Scenarios outlined in Table 5.0-1. These time varying parameters are needed as input to the River2D model to establish the downstream and upstream boundary conditions in that model.

Note that for those scenarios where Northfield is generating the starting downstream WSEL at the Turners Falls Dam used in the HEC-RAS model was set to 176 ft (TFI allowed to fill). Alternatively, for those scenarios where Northfield is pumping the starting downstream WSEL at the Turners Falls Dam used in the HEC-RAS model was set to 185 feet (TFI allowed to drain).

Scenario 19: In the case of Scenario 19 (Northfield generating), the HEC-RAS model was run with steady flows of 7,930 (in mainstem above Northfield) cfs and 510 cfs (Miller River) to represent a total TFI inflow of 8,440 cfs. The HEC-RAS model was also set up such that the Turners Falls Dam discharge equals the total TFI inflow or 8,440 cfs. For Scenario 19, the starting downstream boundary WSEL at the Turners Falls Dam used in the HEC-RAS model was set to 176 ft. In this case, Northfield's discharge was ramped from 0 cfs to 20,000 cfs over the first 15 minutes (see Section 5.1), at which time it was held steady at 20,000 cfs thereafter (meaning the TFI will fill if inflow exceeds outflow; the TFI elevation is the only unsteady variable). The HEC-RAS model is operated until the TFI elevation at the dam reaches 185 feet. The resulting WSEL versus time relationship at the transect located 5 km downstream and the discharge versus time relationship at the transect located 5 km upstream of the Northfield tailrace from the HEC-RAS model was then used as input as the downstream and upstream boundary conditions in the unsteady state River2D model.

Scenario 20: The time varying parameters (i.e. WSEL and discharge) for Scenario 20 are obtained from the same unsteady HEC-RAS run as Scenario 19, and as such a separate HEC-RAS model run is unnecessary.

Scenario 23: In the case of Scenario 23, the HEC-RAS model is run with steady flows of 7,930 cfs and 510 cfs to represent a total TFI inflow of 8,440 cfs. The HEC-RAS model was also set up such that the Turners Falls Dam discharge equals the total TFI inflow or 8,440 cfs. For Scenario 23, the starting downstream boundary WSEL at the Turners Falls Dam used in the HEC-RAS model was set to 185 ft. In this case, Northfield's pumping (15,200 cfs) is also ramped from 0 cfs to full capacity over the first 15 minutes, and then held constant. The model is operated until the TFI elevation at the dam reaches 176 ft. Once this occurs, the WSEL versus time relationship at the transect located 5 km downstream and the discharge versus time relationship at the transect located 5 km upstream of the Northfield tailrace from the HEC-RAS model was used as input as the downstream and upstream boundary conditions in the River2D model.

Scenario 24: The time varying parameters (i.e. WSEL and discharge) for Scenario 24 are obtained from the same unsteady HEC-RAS run as Scenario 23, and as such a separate HEC-RAS model run is unnecessary.

Step 2 Run River2D Model in Steady State

The "initial conditions" set forth by the River2D model after building a mesh and defining the boundary conditions do not represent the true hydraulic nature of the river. Therefore, the River2D model is first run in steady state until it converges on a solution. This solution will be used as the starting point for the unsteady state model run.

Scenario 19: Similar to the HEC-RAS model for Scenario 19, the River2D model was run in steady state with flows of 7,930 cfs and 510 cfs to represent a total TFI inflow of 8,440 cfs. Since the steady state run is supposed to reflect the initial conditions, the discharge from Northfield was set to 0 cfs. The downstream boundary condition for Scenario 19 was set to 176.07 ft, seeing as this is a generation scenario (i.e. the TFI is allowed to fill). The downstream boundary was not set to elevation 176 ft because the HEC-RAS model indicates that there is 0.07 ft of hydraulic grade between the Turners Falls Dam and the downstream boundary of the River2D model under the 50% exceedance flow conditions.

Scenario 20: The results for Scenario 20 are obtained from the same unsteady run as Scenario 19, as explained further in Step 3, below, and as such a separate River2D steady state model run is unnecessary.

Scenario 23: Similar to the steady state River2D model for Scenario 19, the River2D model was run in steady state with flows of 7,930 cfs and 510 cfs to represent a total TFI inflow of 8,440 cfs, and a Northfield discharge of 0 cfs. However, the downstream boundary condition for Scenario 23 was set to 185.01 ft, seeing as this is a pumping scenario (i.e. the TFI is allowed to drain). The downstream boundary was not set to elevation 185 ft because the HEC-RAS model indicates that there is 0.01 ft of hydraulic grade between the Turners Falls Dam and the downstream boundary of the River2D model under the 50% exceedance flow conditions.

Scenario 24: The results for Scenario 24 are obtained from the same unsteady run as Scenario 23, as explained further in Step 3, below, and as such a separate River2D steady state model run is unnecessary.

Step 3 Run River2D Model in Unsteady State

The unsteady state run is started using the solution from Step 2. The first 15 minutes of simulation time for each unsteady model run holds the starting discharges and WSELs constant in order to ensure that the computational differences between steady and unsteady modeling solution algorithms are resolved. After the first 15 minutes of simulation time, the time-varying parameters from Step 1 are used to define the model boundary conditions. Output is provided every 15 minutes of simulation time, and as such the results shown in the maps may not reflect conditions for which the TFI elevation at the dam is exactly 176 ft or 185 ft. However, the results are generally within 0.1 ft of these target elevations.

Scenario 19: In the case of Scenario 19, the River2D model was run in an unsteady state with flows of 7,930 cfs and 510 cfs to represent a total TFI inflow of 8,440 cfs, and a Northfield discharge of 0 cfs for the first 15 minutes. The inflow from the Millers River (510 cfs) is held constant through the rest of the simulation, while the turbines at Northfield are ramped up to full capacity (20,000) cfs over the next 15 minutes, after which time it is held constant, and the upstream and downstream boundary conditions are defined using the time varying relationships from Step 1. The output from the model at the 30 minute mark was used to generate the maps for Scenario 19 (i.e. once the turbines are at full capacity).

Scenario 20: The unsteady run from Scenario 19 was allowed to operate beyond the time which the HEC-RAS model indicated that the TFI elevation at the dam would reach 185 ft. The output from the model at the 525 minute mark was used to generate the maps for Scenario 20, as this was the 15 minute increment which was closest to the time when the TFI elevation at the dam was closest to 185 ft.

Scenario 23: In the case of Scenario 23, the River2D model was run in an unsteady state with flows of 7,930 cfs and 510 cfs to represent a total TFI inflow of 8,440 cfs, and a Northfield discharge of 0 cfs for the first 15 minutes. The inflow from the Millers River (510 cfs) is held constant through the rest of the simulation, while the pumps at Northfield are ramped up to full capacity (-15,200 cfs) over the next 15 minutes, after which time it is held constant, and the upstream and downstream boundary conditions are defined using the time varying relationships from Step 1. The output from the model at the 30 minute mark is used to generate the maps (i.e. once the pumps are at full capacity).

Scenario 24: The unsteady run from Scenario 23 was allowed to operate beyond the time which the HEC-RAS model indicated that the TFI elevation at the dam would reach 176 ft. The output from the model at the 675 minute mark was used to generate the maps for Scenario 24, as this was the 15 minute increment which was closest to the time when the TFI elevation at the dam was closest to 176 ft.

It should be noted that the HEC-RAS and River2D models compute the reservoir volume within the 10 km study area to be slightly different. This difference may cause issues in River2D as the WSEL defined at the downstream boundary may not sync up with the change in volume computed by River2D. This issue was most notable in the initial results for Simulation 4, as the velocity direction downstream of Northfield did not align with the expected results. As such, a sensitivity analysis was run for some scenarios as described in Step 4.

Step 4 Sensitivity Analysis

River2D scenarios with longer simulation times have a greater chance to propagate the error caused by the reservoir volume difference between HEC-RAS and River2D. Therefore this error is likely to be more prevalent in pumping scenarios corresponding to a TFI elevation at the dam of 176 ft and generating scenarios corresponding to a TFI elevation at the dam of 185 ft. Additionally, the magnitude of this error is likely more prevalent with lower baseflow conditions. Therefore, Steps 1-3 were redone for a select number of Scenarios as a sensitivity analysis. This was performed in a manner which would allow for these scenarios to run for a shorter simulation time prior to the reaching the desired results, and is described in detail for Scenario 4.

Step 1: In the case of Scenario 4, the HEC-RAS model was run with steady flows of 1,620 cfs and 140 cfs to represent a total TFI inflow of 1,760 cfs (95% exceedance flow). The HEC-RAS model was also set up such that the Turners Falls Dam discharge equals the total TFI inflow or 1,760 cfs. However, the starting downstream boundary WSEL at the Turners Falls Dam used in the HEC-

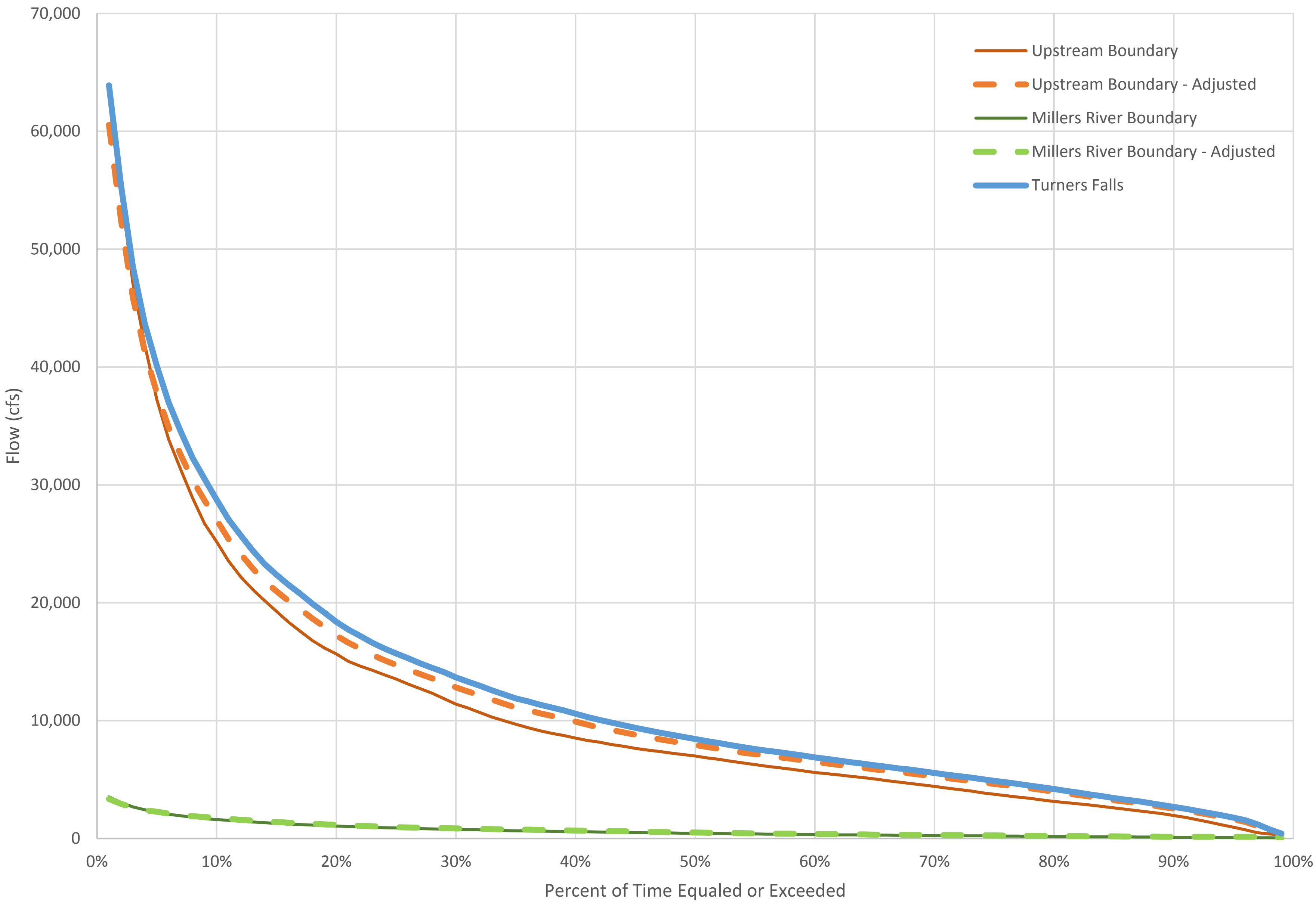
RAS model for the sensitivity analysis was set to 184 ft, instead of the 176 ft originally used. The Northfield's discharge was again ramped from 0 cfs to 20,000 cfs over the first 15 minutes (see Section 5.1), at which time it was held steady at 20,000 cfs thereafter (meaning the TFI will fill if inflow exceeds outflow; the TFI elevation is the only unsteady variable). The HEC-RAS model is operated until the TFI elevation at the dam reaches 185 feet. The resulting WSEL versus time relationship at the transect located 5 km downstream and the discharge versus time relationship at the transect located 5 km upstream of the Northfield tailrace from the HEC-RAS model was then used as input as the downstream and upstream boundary conditions in the unsteady state River2D model.

Step 2: Similar to the HEC-RAS model for Scenario 4, the River2D model was run in steady state with flows of 1,620 cfs and 140 cfs to represent a total TFI inflow of 1,760 cfs. Since the steady state run is supposed to reflect the initial conditions, the discharge from Northfield was set to 0 cfs. The downstream boundary condition for Scenario 4 was set to 184.0 ft, seeing as this is a generation scenario (i.e. the TFI is allowed to fill). The HEC-RAS model does not indicate that there is a hydraulic grade between the Turners Falls Dam and the downstream boundary of the River2D model under the 95% exceedance flow conditions.

Step 3: In the case of Scenario 4, the River2D model was run in an unsteady state with flows of 1,620 cfs and 140 cfs to represent a total TFI inflow of 1,760 cfs, and a Northfield discharge of 0 cfs for the first 15 minutes. The inflow from the Millers River (140 cfs) is held constant through the rest of the simulation, while the turbines at Northfield are ramped up to full capacity (20,000) cfs over the next 15 minutes, after which time it is held constant, and the upstream and downstream boundary conditions are defined using the time varying relationships from Step 1 of the sensitivity analysis. The unsteady run was allowed to operate beyond the time which the HEC-RAS model indicated that the TFI elevation at the dam would reach 185 ft. The output from the model at the 90 minute mark was used to generate the maps for the Scenario 4 sensitivity analysis, as this was the 15 minute increment which was closest to the time when the TFI elevation at the dam was closest to 185 ft.

The results of the sensitivity analysis for Scenario 4 showed that the velocity magnitude in the area of concern remained in the 0-1 ft/s range, but the direction now aligned with expected results. This indicates that the water downstream of Northfield is relatively stagnant for this scenario and the velocity direction may be susceptible to small changes in the model conditions. A more significant change in the velocity field in the immediate vicinity of the Northfield tailrace was observed in the sensitivity analysis, which were again more in line with expected results. Again the velocity magnitude did not differ significantly, but the velocity direction changed quite drastically. As such, the sensitivity analysis was performed for additional scenarios (i.e. Scenarios 5, 7, 12, 13, 15, 23, 42, and 48) in order to identify the extent of the scenarios impacted. Scenarios 5, 42, and 48 did not exhibit any significant changes in the maximum velocity magnitude, but the velocity direction at the downstream end of the model was impacted. Scenarios 7 and 15 exhibited potentially significant changes in velocity magnitude, but no significant changes in velocity direction. These changes were most notable within the area of the French King Gorge. Scenarios 12, 13, and 23 did not exhibit significant changes in velocity magnitude or direction. The remainder of the model runs were thus deemed to not be significantly affected by the issue of reservoir volume differences between the HEC-RAS and River2D models, based on the results of the sensitivity analyses. The results of the initial scenario runs were utilized in all cases, except for Scenarios 4, 5, 7, 15, 42, and 48 in which the results from the sensitivity analysis are reported.

Figure 5.3-1: Annual Flow Duration Exceedence Curves Utilized for Study



6 EVALUATION OF FISH PASSAGE WITH HYDRAULIC MODELING RESULTS

6.1 Overview of Study Objectives Pertaining to Fish

As noted above, the study objectives were to:

- Assess velocities in the TFI above and below the Northfield tailrace/intake and inside the boat barrier line to determine if Northfield Mountain Project operations impact fish migration. More specifically, to evaluate if there are potential velocity barriers during pumping and generation flows at the Northfield Mountain Project.
- Assess the potential for the Northfield Mountain Project to create undesirable attraction flows to the intake/tailrace that could result in entrainment or delay of migratory fish.
- Assess potential impacts to migratory fish due to flow reversals.

6.2 Swim Speeds

Migratory fish that traverse large areas of riverine environments during their upstream migration may encounter zones of high water velocity that are difficult to negotiate. The ability to pass through these high velocity barriers may limit the distribution of, and block potential spawning by, species attempting to migrate upstream. The presence of a velocity barrier is dependent on physical, behavioral, and physiological factors. The hydraulic characteristics of the water body (e.g., river flow) and fish swimming performance are among the most important of these parameters.

Given that the generation flow from the Northfield Project is an additive component to the overall flow system in the TFI, the potential exists for these incremental flows to create areas of high velocity in the vicinity and downstream of the Northfield Mountain discharge. If these high velocity flows are of sufficient intensity and duration, they may present hydraulic barriers to American Shad (and other diadromous migrants) attempting to move upstream past the Northfield Project. In its simplest terms, a velocity barrier may be defined as a reach of a flowing water body where the water velocity exceeds the burst speed of the fish, defined as the speed that can be maintained for a short period of time (e.g., 5-10 seconds). Where velocities exceed the maximum sustained swim speed, defined as the highest swim speed that can be maintained indefinitely, successful passage is possible provided that fish swim at an appropriate speed. Failure to traverse an area at an optimum swim speed and distance-maximizing strategy can prevent fish from successfully negotiating otherwise passable barriers (Castro-Santos, 2005). Typically, barriers are characterized by varying flow velocities, and fish are thought to swim at varying speeds to traverse them (Castro-Santos, 2006).

6.2.1 Target Species

The primary migratory species reaching the Northfield Mountain Project are American Shad, American Eel and Sea Lamprey, and a literature review of juvenile and adult swim speed studies was conducted. Swim speeds were then compared against the velocity data from the River 2D model developed for the Northfield Mountain Project tailrace.

6.2.2 Target Species Swim Speeds

Swim speeds are generally derived from: 1) predictive models or, 2) performance studies of fishes of various sizes in laboratory flumes or other experimental apparatuses that are only approximations of the conditions found in natural rivers and streams.

Three swim speed modes are generally recognized for fishes though terminology differs slightly among authors. Following the nomenclature of Beamish (1978) the following define various swim speeds:

- *Sustained* swim speed – this speed can be maintained for an indefinite period (longer than 200 minutes) and does not involve fatigue;
- *Prolonged* swim speed- this speed can last between 15 seconds and 200 minutes and if maintained will end in fatigue; and,
- *Burst* swim speed- this speed is characterized by rapid movements of short duration and high speed, maintained for less than 15 seconds.

Laboratory testing of *prolonged* swim speeds for specific time intervals, frequently related to an expected or required time to pass through fishways or culverts, results in estimates of critical swim speed (U), accompanied by a time stamp (*e.g*., $Ucrit_2$ = maximum *prolonged* speed for 2 minutes). *Burst* swim speeds (also startle, fast-start, or dart) are the fastest attainable and are also those generally associated with fish well-being or survival (Beamish, 1978; Wardle, 1980), as they are also related to a fish's ability to capture prey and avoid predators. Among the three swim speed modes, *burst* swim speed is harder to quantify in a laboratory and, thus, fewer burst swim speed studies with adequate sample sizes are available (Castro-Santos & Haro, 2005).

In recognition of the role fish size plays in swim performance, information on burst swim speed may also be expressed as fish body lengths per second, termed "relative burst speed". Smaller fish have a higher relative swim speed (more body lengths per second) than larger fish, even though the absolute swim speed (ft/sec) of larger fish is greater (Beamish, 1978).

Turbulence and eddies as well as flow velocity may be integral in impeding upstream migration of fish by disorienting them. Environmental stimuli in a water body on which migrating fish cue, in addition to physical structures, include turbulence, flow acceleration, pressure changes, sound, etc. (Castro-Santos & Haro, 2005). Other conditions which may exacerbate the ability for fish to overcome velocity barriers or flow fields (water intakes) include darkness, turbidity, and reduced swimming ability as water temperatures approach or exceed cold water tolerances.

Work by Castro-Santos (2005) has shown that the maximum distance of ascent through velocity barriers is limited by the swim speed of the fish, time to fatigue, and the speed of flow. Due to both individual variability and life history constraints, fish do not always swim at the distance-maximizing speed. Flow disturbances (e.g., entrained bubbles, turbulence) and high turbidity could lead to reduced willingness to traverse high velocity or turbulent areas, potentially resulting in delayed passage. The distance traversed ultimately results from species-specific physiological capacities and behavior (Castro-Santos & Haro, 2005).

Lower temperatures may also negatively affect swimming performance through velocity barriers by reducing the maximum sustained swimming speed (Dickson *et al*., 2002). However, Haro et al. (2004) reported that adult shad swim performance declined at higher water temperatures, suggesting that shad later in the spawning run may not have the same swimming capability as those arriving early in the run at lower water temperatures. This may also explain the apparent lack of motivation for shad to move upstream as the run continues past peak spawning temperatures in late May and June.

There is considerable variability in the swim speeds reported from the literature. Table 6.2.2-1 presents swim speeds for adult and juvenile American Shad, American Eel and Sea Lamprey in the Connecticut River. Two trends are identifiable for a given species; the absolute swimming speed of larger juveniles or adult fish is faster than smaller juveniles, and swim speed for several species appears maximized at 68-86°F, typically late spring to fall ambient water temperatures. A reduction in swimming ability of 50% may occur at water temperatures outside a preferred range (ASCE, 1995).

Table 6.2.2-1: Literature Based Swimming Performance Data for Target Species in the Project Area

Species	Lifestage	Fish Size (inches)	Swim Speed (ft/sec)			Literature Source-Comments
			Sustained	Prolonged or Critical	Burst or Startle	
American Eel (European Eel used as surrogate)	Juvenile (elver)	2.8-3.9 TL	-	-	2.0-3.0	McCleave, 1980.
	Adult (yellow)	14.0-21.0 TL	-	1.4	-	Quintella *et al*. 2010; U-crit 20 min, 60.8-66.2 °F.
	Adult (silver)	12.5-27.6 TL	-	2.2	-	Quintella *et al*. 2010; U-crit 20 min, 60.8-66.2 °F.
American Shad	Juvenile	2.0-3.0 FL	-	1.5	-	Robbins *et al*. 1970; S/max= maximum swim speed for 3 min (= Beamish's prolonged)
	Juvenile	1.0-3.0 FL		1.75	2.5	Bell, 1991
	Adult	Unknown	2.36-2.47	-	-	Dodson & Leggett 1973; boat speed while following sonic tagged fish, not from laboratory test.
	Adult	Unknown	-	7	-	Bell, 1991.
	Adult	Unknown	-	-	11.5-13.0	Weaver, 1965; Beamish, 1978
Sea Lamprey	Adult	15"	1.2			Beamish, 1974. Non-feeding, migrating adult max sustained speed for 1 minute at 15 °C.
					5-13	Hanson, 1980.
				3.3		Almeida *et al*., 2007

TL= total length
FL= fork length

6.3 Literature Review of Movement Patterns

6.3.1 American Shad

Migration patterns of adult and juvenile American Shad in the TFI are still under investigation (see relicensing study nos. 3.3.2 and 3.3.3). Adult shad generally follow the main river channel during their freshwater migration. Studies of shad migrating upstream in the Connecticut River identified that current velocities were highest in main channel areas where shad predominantly migrated (Leggett, 1976). Shad can detect these changes in current velocity and thus orient to the main river channel. Structure such as channel edges may then be used visually to maintain required ground speed (Castro-Santos, 2005). American Shad are also thought to be visually-oriented, and adults will travel during the day or night, but primarily during the day in areas that are turbulent or difficult to traverse (Keefer *et al*., 2013). At night, they tend to swim more slowly (Castro-Santos & Letcher 2010) and because they spawn at night, they may move to areas with spawning habitat. Out-migrating juvenile shad tend to migrate in the afternoon and evening (O'Leary & Kynard, 1986).

6.3.2 American Eel

Upstream migration patterns of juvenile eel in the TFI are still under investigation (see relicensing study no. 3.3.5). Some young eels are expected to reach the Northfield Mountain tailrace/discharge area and continue upstream to the Vernon tailrace and spillway area. Just as likely, some percentage of juveniles is anticipated to leave the main body of the TFI and ascend the numerous tributaries to grow and mature.

Juvenile eels typically must pass upstream through areas with current velocities that exceed their swimming capability, whether in a natural or regulated stream course. To successfully pass through these areas, eels utilize areas of low velocity in near-stream bed refugia created by substrate roughness to maintain upstream migration progress. Areas off-channel (stream edges) may offer similar, low velocity conditions. The coarse substrate on the channel bottom or near-shore provides areas of reduced current in which eels can rest between swimming bursts (Barbin & Krueger, 1994). The faster the current, the longer the duration of intervening rest periods, hence slower upstream progress. The end result is that upstream progress is slow in most natural systems with fast-flowing reaches (Dutil *et al.,* 1989; Jessop, 2003).

Juvenile eels move mainly at night, therefore they will typically be subject to effects of hydroelectric operations that occur during the night such as pumping or reduced generation.

6.3.3 Sea Lamprey

Upstream migration patterns of Seam Lamprey in the TFI are still under investigation (see relicensing study no. 3.3.15). Anadromous Sea Lamprey generally tend to migrate at night during their spawning migration (Almeida *et al.,* 2002). When the mainstem flow is rapid, lampreys move upstream near the edges (Hardisty & Potter, 1971) where they may be assisted by eddy currents. In high flow areas lamprey alternate between short activity periods and rest periods, and they will attach to surfaces during passage (Quintella *et al.,* 2009).

7 RESULTS

7.1 Turners Falls Impoundment Velocities and Vectors

7.1.1 Maps for All Scenarios

Shown in Appendix B are a total of 420 plan maps showing the following for the 60 scenarios outlined in Table 5.0-1:

- 60 color-coded depth maps over the entire reach (5 km upstream to 5 km downstream of the Northfield tailrace/intake).
- 60 color-coded WSEL maps over the entire reach (5 km upstream to 5 km downstream of the Northfield tailrace/intake).
- 300 color-coded average channel velocities and velocity vectors maps. The velocity vectors are represented by an elongated triangle with the tip of the triangle showing the direction of flow. Because it is difficult to see the velocity vectors if only one map were developed, five (5) maps covering the 10 km reach were developed (60 scenarios x 5 maps/scenario or a total of 300 maps).

Note that the average channel velocities inside the Northfield tailrace boat barrier line from the River2D model are not accurate[13], thus velocity data inside the boat barrier line were purposely removed from the plan maps above. As described below, the observed velocity data obtained inside the boat barrier line represents the best available data.

7.1.2 Velocities

In relation to the maps outlined above, emphasis was placed on the velocity ranges at three sites/locations (Tables 7.1.2-1 to 7.1.2-4) that were determined to be relevant to fish migration.

- Site 1: this site is located approximately 2.5 miles upstream of the Northfield tailrace/intake near Kidds Island (shown on Map 1 for each scenario). This site was primarily selected to evaluate the extent of flow reversals caused by generation at the Northfield Mountain project.
- Site 2: this site extends just upstream and downstream of the Northfield tailrace/intake (shown on Map 3 for each scenario). This site was selected to determine the magnitude of velocity and velocity direction in close proximity to the tailrace area.
- Site 3: this site is located in the French King Gorge area (shown on Map 4 for each scenario) and is a swift-flowing river segment. This site was selected to determine the extent of flow reversals that may occur during pumping and if high velocities that could result in velocity barriers were predicted by the model.

Downstream velocities at each site were generally higher at low impoundment levels due to shallower water and higher river gradient (or slope of the WSEL). The velocities predicted for many scenarios were often greatest at Site 3 in the French King Gorge, with the exception of scenarios where the WSEL at Turners Falls Dam was 181.3 or 185 feet and Site 3 exhibited similar or slightly lower velocities than Site 2 near the Northfield tailrace area. Velocities at Site 3 exceeded 10 ft/s in some areas during the most extreme scenarios when river flow was high, impoundment elevation at the dam was low, and Northfield was generating (Scenarios 33 and 35).

[13] The inaccuracies of the River2D model within the Northfield tailrace boat barrier are most likely caused by the complicated boundary conditions. It is not uncommon for models to have irregular results near boundaries, and to therefore exclude results in the vicinity of a boundary.

7.1.3 Flow Reversals

Flow reversals upstream of Northfield caused by operating at half generation were predicted by the model during low river flow, and the greatest extent of reversals during these low flow scenarios occurred when the TFI elevation was high (i.e. Scenarios 2, 10, and 45). Flow reversals to, or beyond, Kidds Island were observed for scenarios with incoming flows up to 4,900 cfs, and low TFI elevations tended to reduce the extent of reversals under similar flow conditions. Similar patterns were observed for full generation, except that flow reversals to, or beyond, Kidds Island were present at incoming flows up to 8,440 cfs.

Flow reversals downstream of Northfield were predicted during pumping scenarios under low incoming flow conditions, with reversals predicted only at the lowest incoming flow (1,760 cfs), under 7,600 cfs of pumping, and primarily up to 4,900 cfs incoming flow during full pumping at 15,200 cfs. One exception to this was that flow reversals were predicted under an incoming flow of 8,440 cfs under full pumping and high (185 ft) TFI elevation. Additionally, at the lowest flows, the higher reversal velocities were observed in the French King Gorge under low TFI water levels.

Table 7.1.2-1: Range of Velocities at Key Locations when Northfield is Generating at 10,000 cfs (2 units)

Scenario	Flow through TFI (cfs)	Site 1: Velocity Range near Kidds Island- magnitude and velocity direction (ft/sec)	Site 2: Velocity Range near Northfield Tailrace/Intake (ft/sec)			Site 3: Velocity Range near French King Gorge- magnitude and direction (ft/sec)
			Magnitude range (ft/sec)	Velocity Direction above tailrace/intake	Velocity Direction below tailrace/intake	
1 (Elev 176 ft)	1,760 (95%)	0-1 (u/s & d/s)	0-4	u/s	d/s	0-4 (d/s)
41 (Elev 181.3 ft)		0-1 (u/s)	0-3	u/s	d/s	0-2 (d/s)
2 (Elev 185 ft)		0-1 (u/s)	0-3	u/s	d/s	0-2 (d/s)
9 (Elev 176 ft)	4,900 (75%)	0-2 (d/s)	0-4	u/s	d/s	0-5 (d/s)
45 (Elev 181.3 ft)		0-1 (d/s)	0-3	u/s (eddies)	d/s	0-3 (d/s)
10 (Elev 185 ft)		0-1 (u/s)	0-3	u/s (eddies)	d/s	0-2 (d/s)
17 (Elev 176 ft)	8,440 (50%)	0-4 (d/s)	0-4	d/s (eddies)	d/s	0-6 (d/s)
49 (Elev 181.3 ft)		0-1 (d/s)	0-3	d/s	d/s	0-3 (d/s)
18 (Elev 185 ft)		0-1 (d/s)	0-2	d/s (eddies)	d/s	0-2 (d/s)
25 (Elev 176 ft)	15,700 (25%)	0-5 (d/s)	0-4	d/s	d/s	0-9 (d/s)
53 (Elev 181.3 ft)		0-3 (d/s)	0-3	d/s	d/s	0-5 (d/s)
26 (Elev 185 ft)		0-2 (d/s)	0-2	d/s	d/s	0-3 (d/s)
33 (Elev 176 ft)	40,100 (5%)	0-6 (d/s)	0-5	d/s	d/s	0->10 (d/s)
57 (Elev 181.3 ft)		0-5 (d/s)	0-5	d/s	d/s	0->10 (d/s)
34 (Elev 185 ft)		0-4 (d/s)	0-4	d/s	d/s	0-7 (d/s)

Table 7.1.2-2: Range of Velocities at Key Locations when Northfield is Generating at 20,000 cfs (4 units)

Scenario	Flow through TFI (cfs)	Site 1: Velocity Range near Kidds Island- magnitude and velocity direction (ft/sec)	Site 2: Velocity Range near Northfield Tailrace/Intake (ft/sec)			Site 3: Velocity Range near French King Gorge- magnitude and direction (ft/sec)
			Magnitude range (ft/sec)	Velocity Direction above tailrace/intake	Velocity Direction below tailrace/intake	
3 (Elev 176 ft)	1,760 (95%)	0-1 (u/s & d/s)	0-5	u/s	d/s	0-4 (d/s)
42 (Elev 181.3 ft)		0-2 (u/s)	0-7	u/s	d/s	0-5 (d/s)
4 (Elev 185 ft)		0-2 (u/s)	0-5	u/s (eddies)	d/s	0-3 (d/s)
11 (Elev 176 ft)	4,900 (75%)	0-2 (u/s & d/s)	0-6	u/s	d/s	0-7 (d/s)
46 (Elev 181.3 ft)		0-2 (u/s)	0-6	u/s	d/s	0-4 (d/s)
12 (Elev 185 ft)		0-2 (u/s)	0-5	u/s	d/s	0-3 (d/s)
19 (Elev 176 ft)	8,440 (50%)	0-2 (d/s)	0-6	u/s	d/s	0-7 (d/s)
50 (Elev 181.3 ft)		0-1 (u/s)	0-6	u/s	d/s	0-4 (d/s)
20 (Elev 185 ft)		0-1 (u/s)	0-4	u/s (eddies)	d/s	0-3 (d/s)
27 (Elev 176 ft)	15,700 (25%)	0-4 (d/s)	0-7	d/s	d/s	0-10 (d/s)
54 (Elev 181.3 ft)		0-2 (d/s)	0-6	d/s (eddies)	d/s	0-6 (d/s)
28 (Elev 185 ft)		0-1 (d/s)	0-4	d/s (eddies)	d/s	0-4 (d/s)
35 (Elev 176 ft)	40,100 (5%)	0-5 (d/s)	0-6	d/s	d/s	0->10 (d/s)
58 (Elev 181.3 ft)		0-4 (d/s)	0-6	d/s	d/s	0->10 (d/s)
36 (Elev 185 ft)		0-4 (d/s)	0-5	d/s	d/s	0-7 (d/s)

Table 7.1.2-3: Range of Velocities at Key Locations when Northfield is Pumping at 7,600 cfs (2 pumps)

Scenario	Flow through TFI (cfs)	Site 1: Velocity Range near Kidds Island- magnitude and velocity direction (ft/sec)	Site 2: Velocity Range near Northfield Tailrace/Intake (ft/sec)			Site 3: Velocity Range near French King Gorge- magnitude and direction (ft/sec)
			Magnitude range (ft/sec)	Velocity Direction above tailrace/intake	Velocity Direction below tailrace/intake	
5 (Elev 176 ft)	1,760 (95%)	0-3 (d/s)	0-3	d/s	u/s	0-1 (u/s)
43 (Elev 181.3 ft)		0-2 (d/s)	0-2	d/s	u/s	0-1 (u/s)
6 (Elev 185 ft)		0-1 (d/s)	0-2	d/s	u/s	0-1 (u/s)
13 (Elev 176 ft)	4,900 (75%)	0-4 (d/s)	0-3	d/s	d/s (eddies)	0-2 (d/s)
47 (Elev 181.3 ft)		0-2 (d/s)	0-2	d/s	d/s (eddies)	0-1 (d/s)
14 (Elev 185 ft)		0-2 (d/s)	0-2	d/s	d/s	0-1 (d/s)
21 (Elev 176 ft)	8,440 (50%)	0-5 (d/s)	0-4	d/s	d/s (eddies)	0-4 (d/s)
51 (Elev 181.3 ft)		0-3 (d/s)	0-3	d/s	d/s (eddies)	0-2 (d/s)
22 (Elev 185 ft)		0-2 (d/s)	0-2	d/s	d/s	0-1 (d/s)
29 (Elev 176 ft)	15,700 (25%)	0-6 (d/s)	0-4	d/s	d/s	0-6 (d/s)
55 (Elev 181.3 ft)		0-4 (d/s)	0-3	d/s	d/s	0-4 (d/s)
30 (Elev 185 ft)		0-3 (d/s)	0-3	d/s	d/s	0-3 (d/s)
37 (Elev 176 ft)	40,100 (5%)	0-6 (d/s)	0-5	d/s	d/s	0-10 (d/s)
59 (Elev 181.3 ft)		0-6 (d/s)	0-5	d/s	d/s	0-9 (d/s)
38 (Elev 185 ft)		0-5 (d/s)	0-4	d/s	d/s	0-7 (d/s)

Table 7.1.2-4: Range of Velocities at Key Locations when Northfield is Pumping at 15,200 cfs (4 pumps)

Scenario	Flow through TFI (cfs)	Site 1: Velocity Range near Kidds Island- magnitude and velocity direction (ft/sec)	Site 2: Velocity Range near Northfield Tailrace/Intake (ft/sec)			Site 3: Velocity Range near French King Gorge- magnitude and direction (ft/sec)
			Magnitude range (ft/sec)	Velocity Direction above tailrace/intake	Velocity Direction below tailrace/intake	
7 (Elev 176 ft)	1,760 (95%)	0-3 (d/s)	0-4	d/s	u/s	0-5 (u/s)
44 (Elev 181.3 ft)		0-3 (d/s)	0-4	d/s	u/s	0-1 (u/s)
8 (Elev 185 ft)		0-1 (d/s)	0-4	d/s	u/s	0-1 (u/s)
15 (Elev 176 ft)	4,900 (75%)	0-4 (d/s)	0-5	d/s	u/s	0-4 (u/s)
48 (Elev 181.3 ft)		0-3 (d/s)	0-5	d/s	u/s	0-2 (u/s)
16 (Elev 185 ft)		0-2 (d/s)	0-4	d/s	u/s	0-2 (u/s)
23 (Elev 176 ft)	8,440 (50%)	0-5 (d/s)	0-5	d/s	d/s (eddies)	0-2 (d/s)
52 (Elev 181.3 ft)		0-3 (d/s)	0-4	d/s	d/s (eddies)	0-2 (d/s)
24 (Elev 185 ft)		0-2 (d/s)	0-4	d/s	u/s	0-1 (u/s)
31 (Elev 176 ft)	15,700 (25%)	0-6 (d/s)	0-6	d/s	d/s (eddies)	0-5 (d/s)
56 (Elev 181.3 ft)		0-4 (d/s)	0-4	d/s	d/s	0-3 (d/s)
32 (Elev 185 ft)		0-3 (d/s)	0-4	d/s	d/s	0-2 (d/s)
39 (Elev 176 ft)	40,100 (5%)	0-7 (d/s)	0-7	d/s	d/s	0-9 (d/s)
60 (Elev 181.3 ft)		0-6 (d/s)	0-6	d/s	d/s	0-8 (d/s)
40 (Elev 185 ft)		0-5 (d/s)	0-5	d/s	d/s	0-6 (d/s)

7.2 Velocities within the Northfield Tailrace Boat Barrier Line

As described earlier, per the RSP, water column velocity data were collected at three (3) transects within the Northfield Mountain Project tailrace under four different operating scenarios. Velocity profiles and channel bed data were collected for two (2) units generating (~ 10,000 cfs) and pumping (~7,600 cfs) on April 6, 2014 and April 7, 2014 respectively. Likewise the same data for four (4) units generating (~20,000 cfs) and pumping (~15,200 cfs) were collected on July 12, 2014.

An ADCP linked to a GPS unit was used for collecting velocity and depth data at three transects located between the tailrace exit and boat barrier line. The observed velocity data collected under the four operating scenarios are summarized in the following figures:

Figure 7.2-1: Depth-Averaged Channel Velocities at Transects below Northfield tailrace (4 units at full hydraulic generating capacity ~20,000 cfs)

Figure 7.2-2: Depth-Averaged Channel Velocities at Transects below Northfield tailrace (2 units at full hydraulic generating capacity ~ 10,000 cfs)

Figure 7.2-3: Depth-Averaged Channel Velocities at Transects below Northfield tailrace (4 units at full hydraulic pumping capacity ~ 15,200 cfs)

Figure 7.2-4: Depth-Averaged Channel Velocities at Transects below Northfield tailrace (2 units at full hydraulic pumping capacity ~ 7,600 cfs)

Figure 7.2-5: RiverSurveyor Velocity output at Transects below Northfield tailrace (4 units at full hydraulic generating capacity ~20,000 cfs)

Figure 7.2-6: RiverSurveyor Velocity output at Transects below Northfield tailrace (2 units at full hydraulic generating capacity ~ 10,000 cfs)

Figure 7.2-7: RiverSurveyor Velocity output at Transects below Northfield tailrace (4 units at full hydraulic pumping capacity ~ 15,200 cfs)

Figure 7.2-8: RiverSurveyor Velocity output at Transects below Northfield tailrace (2 units at full hydraulic pumping capacity ~ 7,600 cfs)

Relatively high velocities (max velocity ~ 16 ft/s) were measured during 4 units generating, with the greatest velocities occurring at depths greater than 20 feet. A similar pattern was observed during 2 units generating, though the measured velocities were lower (max velocity ~ 9 ft/s). During both generation scenarios, eddies were present near the shorelines and lower water velocities (velocity < 2 ft/s) were measured near the surface.

Velocities were more consistent with depth during the pumping scenarios. Measured velocities during pumping were lower than those measured during generation (max velocity during both pumping scenarios ~ 4.5 ft/s). During two units pumping, the highest velocities were measured toward the south side of the channel, whereas during four units pumping, velocities were more consistent across the channel with a relatively large area where velocities were 3-4 ft/s.

7.3 Potential Implications for Migratory Fish Passage

FirstLight is undertaking multiple studies in 2015 that will provide data regarding fish movement in the vicinity of the Northfield Mountain Project. However, this modeling will inform those studies on the physical conditions that could be encountered by migrating diadromous species.

7.3.1 Velocities

In some cases, the maximum velocity could be as high as 10 ft/sec at Site 3 in the narrow section of the French King Gorge (worst case - Scenario 35). However, even for Scenario 35, the maximum velocity does not extend across the entire width of the river. Velocity is high in many areas across the channel, but there are areas along the river margins with lower velocities that migrating fish can utilize.

Adult American Shad

Based on the available flow data and modeling simulation runs, velocity barriers to upstream migration of adult American Shad may be present in localized areas. However, the small size of these areas, coupled with the facultative swimming ability and avoidance behavior of adult shad, should enable them to ascend the river through the French King Gorge and past Northfield Mountain under the highest modeled flow scenario (40,000 cfs) and assuming Northfield Mountain was generating at full capacity (20,000 cfs).

The maximum velocities near Site 2 (Northfield tailrace/intake) under all 10,000 cfs generation scenarios was no higher than 5 ft/sec, which does not create a velocity barrier for American Shad passage (shad prolonged speed is approximately 7 ft/sec, and burst speeds up to 13 ft/sec). Velocities along the river margins are less than 5 ft/sec. Under full generation (20,000 cfs), velocities can be up to 2-3 ft/s higher downstream of Northfield tailrace relative to the 10,000 cfs generation scenarios. However, spatial patterns of high velocities areas are similar, with velocity refuges available along the edges of the river channel.

Juvenile American Eel

Since juvenile eels utilize shoreline areas and bottom substrates to pass through areas of swift current, this migration strategy is likely used by young eels in the TFI to pass high velocity areas associated with the French King Gorge and the Northfield Mountain discharge. Eels are likely to avoid the high velocities by using available cover objects along the shorelines or other low velocity areas to bypass the higher velocity areas. Given the breadth of river available near the Northfield Project discharge, and lower velocity shoreline areas, the potential for a velocity barrier to upstream migration of juvenile American eel should be considered low.

Relative to hydroelectric plant operations, overnight hours generally correspond to times of reduced generation or increased pumping, when current velocities in tailwaters and downstream would be less than during daylight hours.

Adult Sea Lamprey

With a sustained speed of 3.3 ft/s, burst speeds of up to 13 ft/s, and the tendency to traverse swift areas by using shoreline structure and eddies, Sea Lamprey should be able to traverse swift sections of the TFI such as the French King Gorge.

7.3.2 Flow Reversals and Eddies

The effects of flow reversals on upstream and downstream migrating fish are poorly understood in upriver freshwater areas. Fish that encounter flow reversals may change direction, similar to how migratory fish sometimes respond to tidal water (i.e. Grote *et al.,* 2014), resulting in migration delay. However, tide-related swimming direction reversals encountered in various species in previous studies were hypothesized as attempts to adjust to salinity or take advantage of additional feeding areas in upper estuaries (*Grote et* *al.*, 2014; Stich *et al.*, 2015). Eddies in the vicinity of the Northfield tailrace may also confuse fish and delay their migration.

Migrating fish that move during the daytime may encounter flow reversals upstream of the tailrace due to generation and low incoming flow, in the event that these conditions actually occur during migration periods. Alternatively, migrating fish that move considerably at night may encounter flow reversals downstream of the tailrace due to pumping and low incoming flow from upstream.

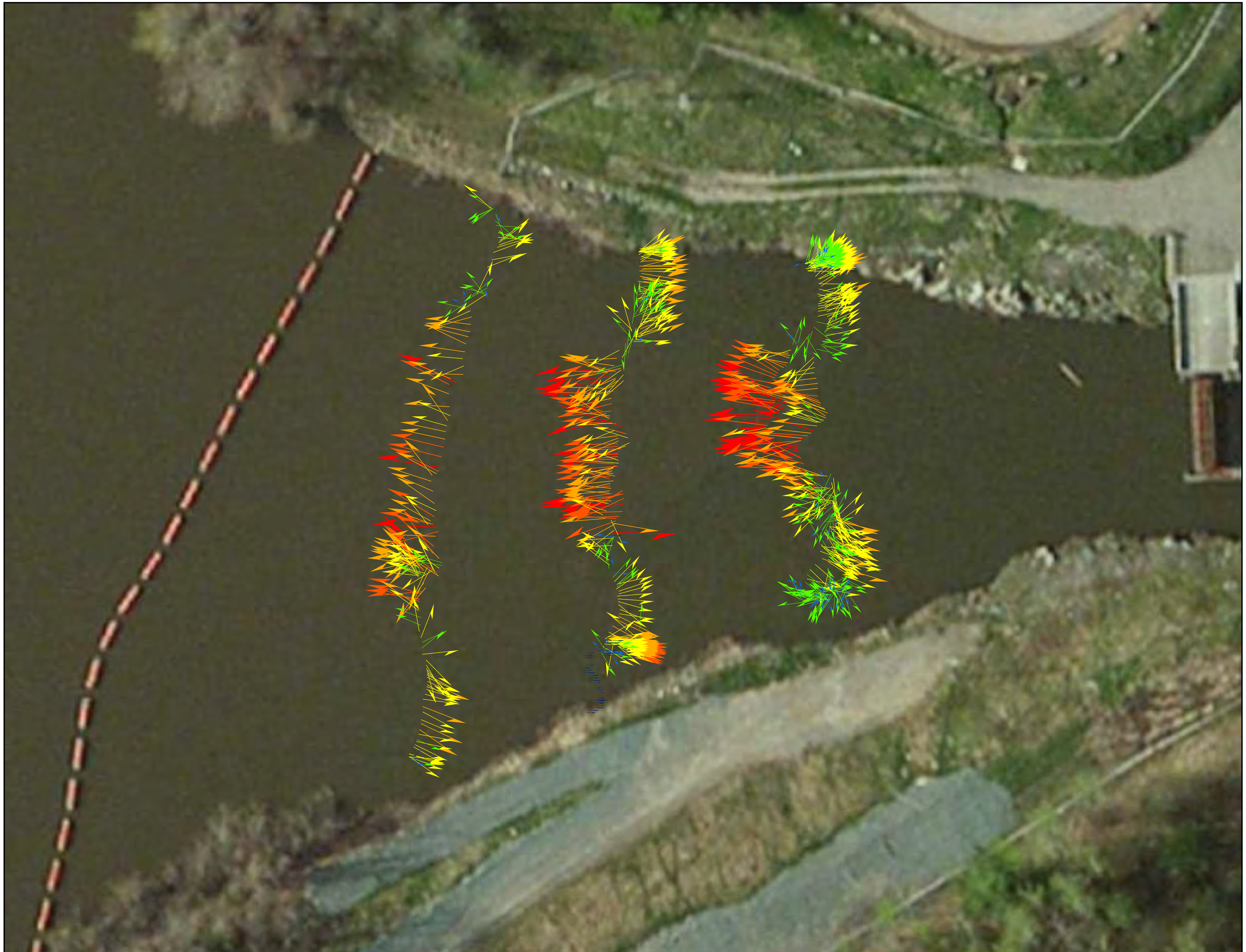
7.3.3 Attraction

Similar to the attraction of downstream migrating fish that could result in entrainment during pumping, upstream migrating fish such as adult American Shad, Sea Lamprey, and juvenile American Eel could be attracted to the flow from Northfield Mountain during generation. These fish could be delayed in their upstream migration if they are attracted to the tailrace area and stay there for extended periods; however, it should be noted that generation at Northfield Mountain is typically followed by idle and pumping cycles, during which fish should be able to pass upstream of Northfield in a relatively short amount of time and resume their course upstream. Given that American Eel and Sea Lamprey typically move at night, many individuals would not be exposed to long durations of generation while they are migrating. Adult American Shad may orient into generation currents, and could become delayed due to attraction during long generating periods.

7.3.4 Potential for Entrainment

Because pumping operations at Northfield Mountain primarily occur during the night, species that move through the area at night such as American Eel, Sea Lamprey, and out-migrating juvenile shad may be susceptible to entrainment. Additionally, drifting eggs or larval/juvenile fish residing in the area could also become entrained.

Adult shad possess sufficient swimming speed to avoid entrainment. Out-migrating adult eel and juvenile shad could be attracted to and potentially follow the flow into the intake. Given a relatively low burst speed of 2.5 ft/s, it is unlikely that a juvenile shad that was attracted to the intake structure would be able to escape if it traveled too close to the structure, particularly during pumping at full capacity. Juvenile American Eel within the tailrace area could also potentially become entrained if pumping is initiated. Sea Lamprey, while nocturnal, likely have sufficient swim speeds and a tendency to find resting areas where they will latch onto substrate, such that they will avoid becoming entrained.



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

STUDY REPORT
RELICENSING STUDY 3.3.9

Figure 7.2-1
Depth-Averaged Channel Velocities at Transects below Northfield Tailrace (4 units at full hydraulic generating capacity ~20,000 cfs)

Legend

Depth-Averaged Velocity (ft/sec)

- 0.0 - 0.1
- 0.1 - 0.5
- 0.5 - 1.5
- 1.5 - 3.0
- 3.0 - 4.5
- 4.5 - 6.0
- 6.0 - 8.5

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
Sources: Esri, HERE, DeLorme, USGS, Intermap, increment P Corp.,

0 3,250 6,500 13,000 Feet

1 inch = 6,500 feet

FirstLight™
GDF SUEZ

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

STUDY REPORT
RELICENSING STUDY 3.3.9

Figure 7.2-2
Depth-Averaged Channel Velocities at Transects below Northfield Tailrace (2 units at full hydraulic generating capacity ~10,000 cfs)

Legend

Depth-Averaged Velocity (ft/sec)

- 0.0 - 0.1
- 0.1 - 0.5
- 0.5 - 1.5
- 1.5 - 3.0
- 3.0 - 4.5
- 4.5 - 6.0
- 6.0 - 8.5

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
Sources: Esri, HERE, DeLorme, USGS, Intermap, increment P Corp.,

0 3,250 6,500 13,000 Feet

1 inch = 6,500 feet

FirstLight GDF SUEZ

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

STUDY REPORT
RELICENSING STUDY 3.3.9

Figure 7.2-3
Depth-Averaged Channel Velocities at Transects below Northfield Tailrace (4 units at full hydraulic pumping capacity ~15,200 cfs)

Legend

Depth-Averaged Velocity (ft/sec)

0.0 - 0.1
0.1 - 0.5
0.5 - 1.5
1.5 - 3.0
3.0 - 4.5
4.5 - 6.0
6.0 - 8.5

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
Sources: Esri, HERE, DeLorme, USGS, Intermap, increment P Corp.,

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1 inch = 6,500 feet

FirstLight GDF SUEZ

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

STUDY REPORT
RELICENSING STUDY 3.3.9

Figure 7.2-4
Depth-Averaged Channel Velocities
at Transects below Northfield Tailrace
(2 units at full hydraulic pumping
capacity ~7,600 cfs)

Legend

Depth-Averaged Velocity (ft/sec)

- 0.0 - 0.1
- 0.1 - 0.5
- 0.5 - 1.5
- 1.5 - 3.0
- 3.0 - 4.5
- 4.5 - 6.0
- 6.0 - 8.5

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
Sources: Esri, HERE, DeLorme, USGS, Intermap, increment P Corp.,

0 3,250 6,500 13,000 Feet

1 inch = 6,500 feet

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GDF SUEZ

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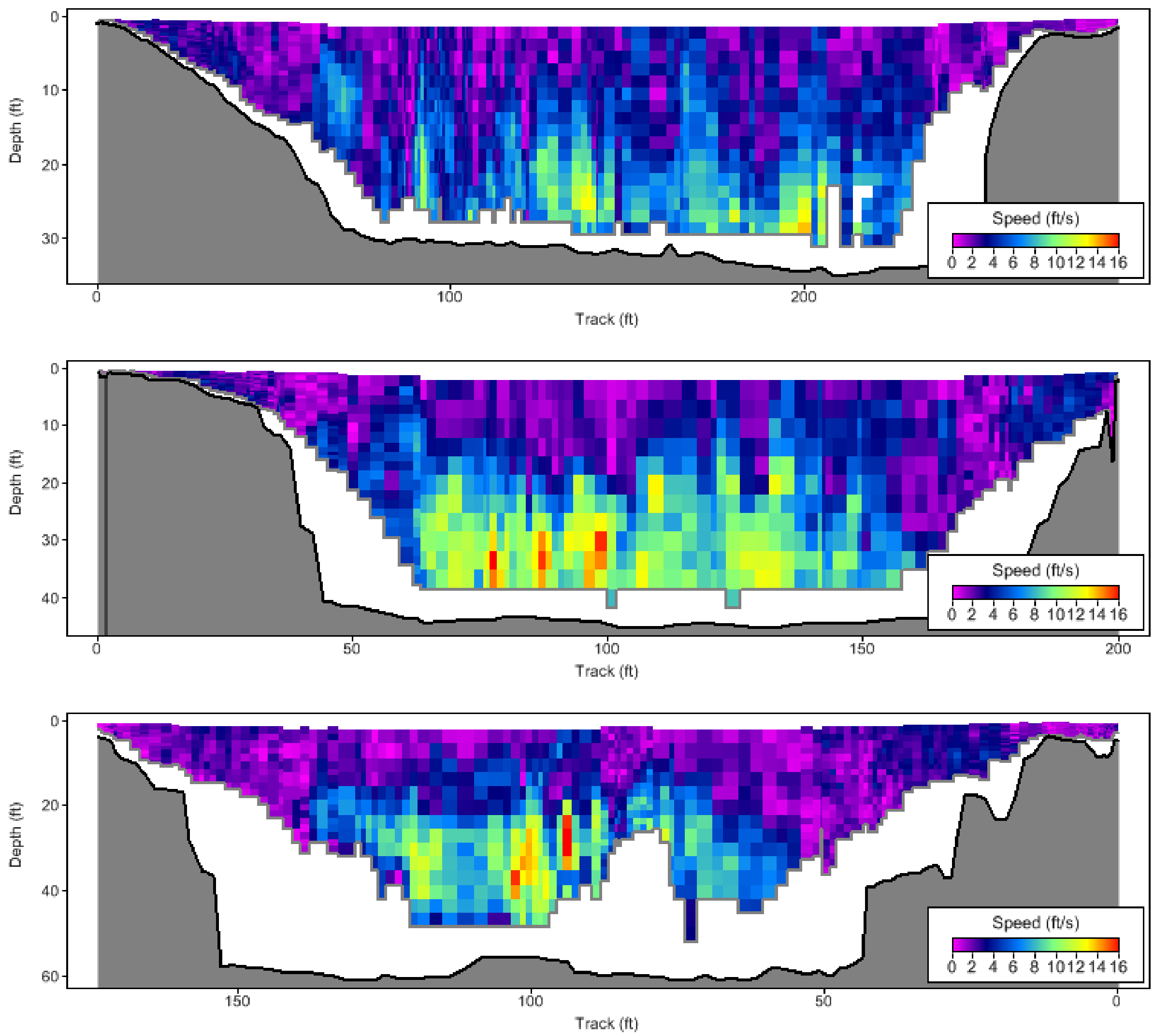

Figure 7.2-5: Raw RiverSurveyor output during 4 units generating at Northfield Tailrace. The top panel was collected at the transect furthest from the face of the intake structure, the bottom panel was collected nearest to the face of the intake structure, and the middle panel was collected in between.

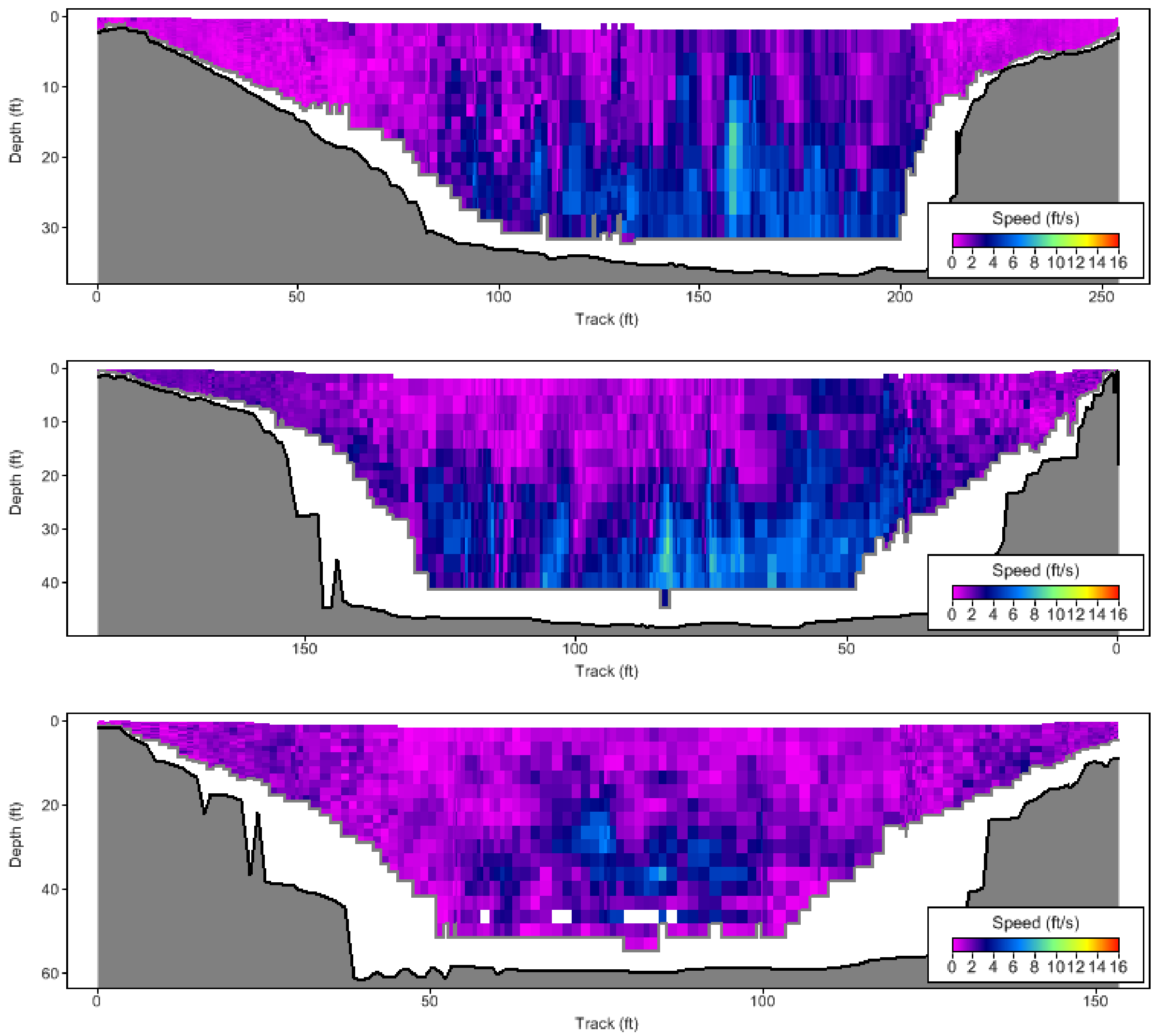

Figure 7.2-6: Raw RiverSurveyor output during 2 units generating at Northfield Tailrace. The top panel was collected at the transect furthest from the face of the intake structure, the bottom panel was collected nearest to the face of the intake structure, and the middle panel was collected in between.

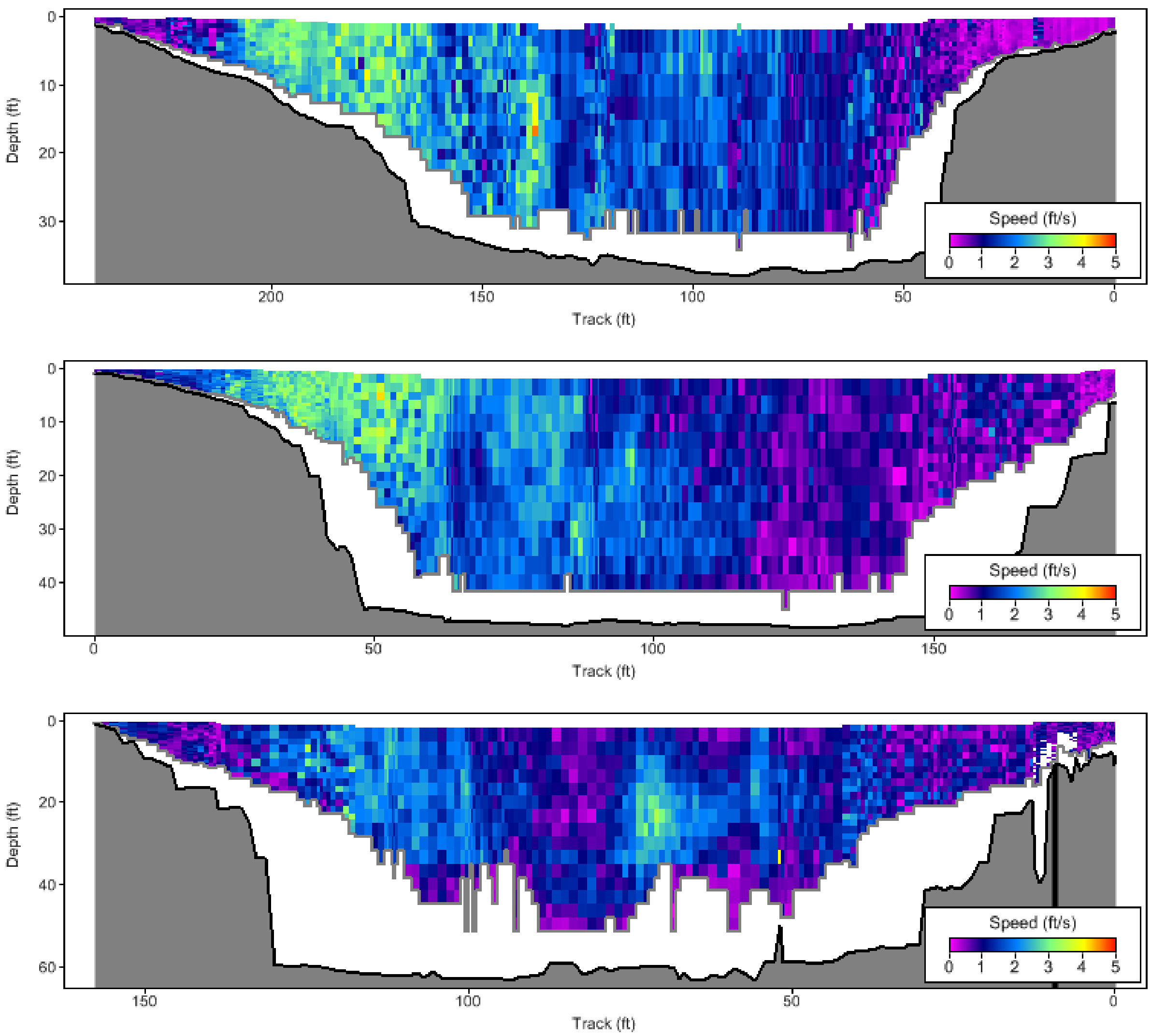

Figure 7.2-7: Raw RiverSurveyor output during 2 units pumping at Northfield Tailrace. The top panel was collected at the transect furthest from the face of the intake structure, the bottom panel was collected nearest to the face of the intake structure, and the middle panel was collected in between.

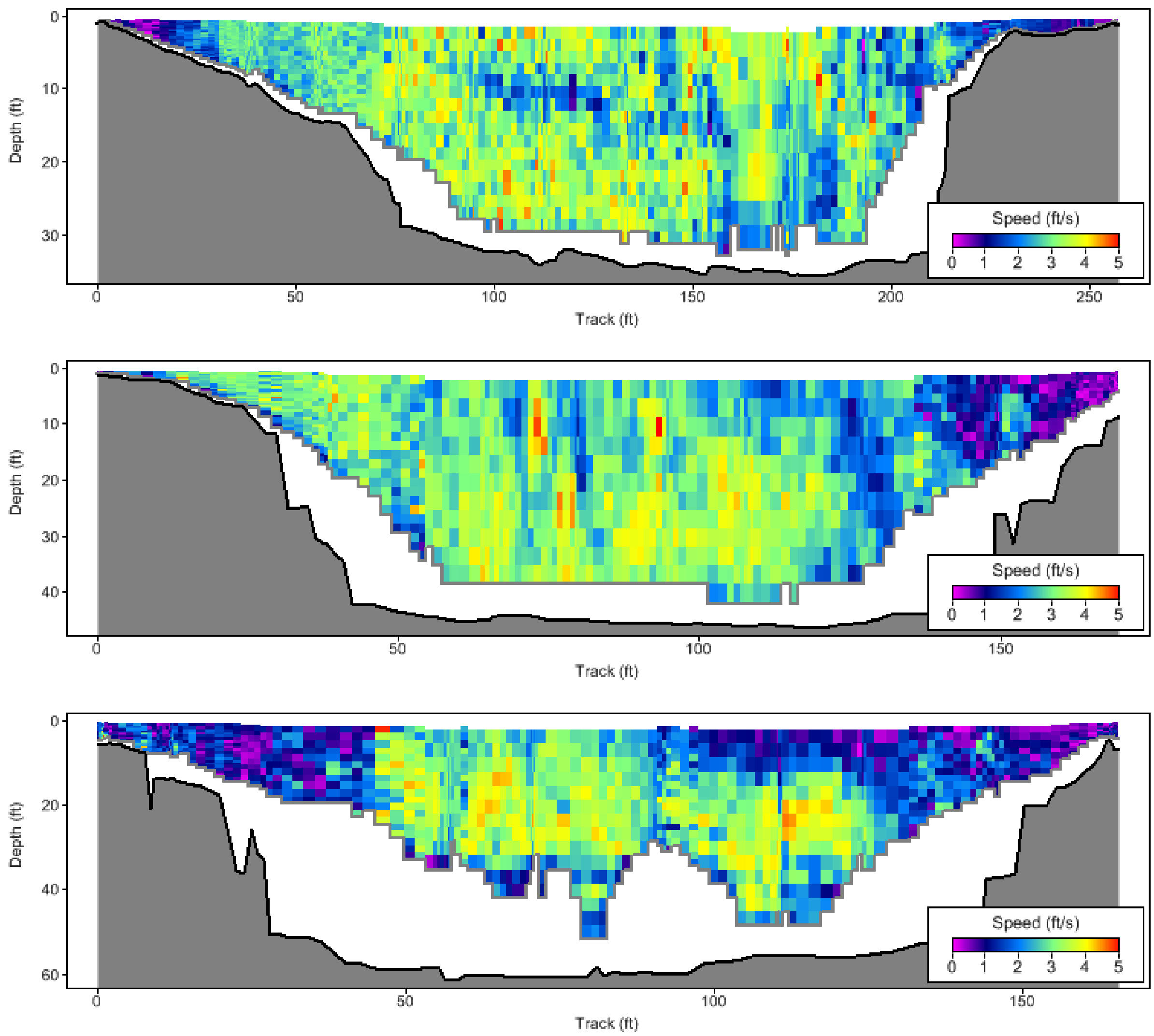

Figure 7.2-8: Raw RiverSurveyor output during 4 units pumping at Northfield Tailrace. The top panel was collected at the transect furthest from the face of the intake structure, the bottom panel was collected nearest to the face of the intake structure, and the middle panel was collected in between.

8 DISCUSSION

Based on model results, operations of the Northfield Mountain Pumped Storage Project has the potential to delay migratory fish that pass through the study area, primarily during low river flow conditions through the TFI when the physical effects of operations are most prevalent. However, the scenarios modeled in this study assume a constant set of variables (i.e. Northfield operating conditions; flow through the TFI; TFI water level). Many of the scenarios model conditions rarely occur, such as extremely low flow coupled with the highest or lowest TFI elevations allowed by the current license; thus, the probability of the most extreme scenarios occurring for extended periods during fish migration periods is also low. Additionally, during low flow periods, flow through the TFI can change often as a result of operations at Vernon Dam. Flow scenarios identified with the potential to delay fish migration would likely be reduced in duration and/or extent by rapid increases in river flow from upstream, given that increases in river flow during low flow events will reduce the extent and magnitude of flow reversals.

The effects of Northfield Mountain operations on migrating American Shad, American Eel, and Sea Lamprey are being evaluated with radio telemetry (Studies 3.3.2, 3.3.3, 3.3.5, and 3.3.15). These studies will also provide entrainment information for these species, along with Study 3.3.7. Hydraulic modeling and the associated literature reviewed for this study has revealed the potential for migration delay and entrainment, but definitive conclusions pertaining to actual effects on migratory fish are not possible until results from this study can be coupled with empirical fisheries data from other studies. This study has the potential to inform and strengthen the conclusions of the other studies by delineating the conditions encountered by migratory fish in the vicinity of the Northfield Mountain Pumped Storage Project.

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