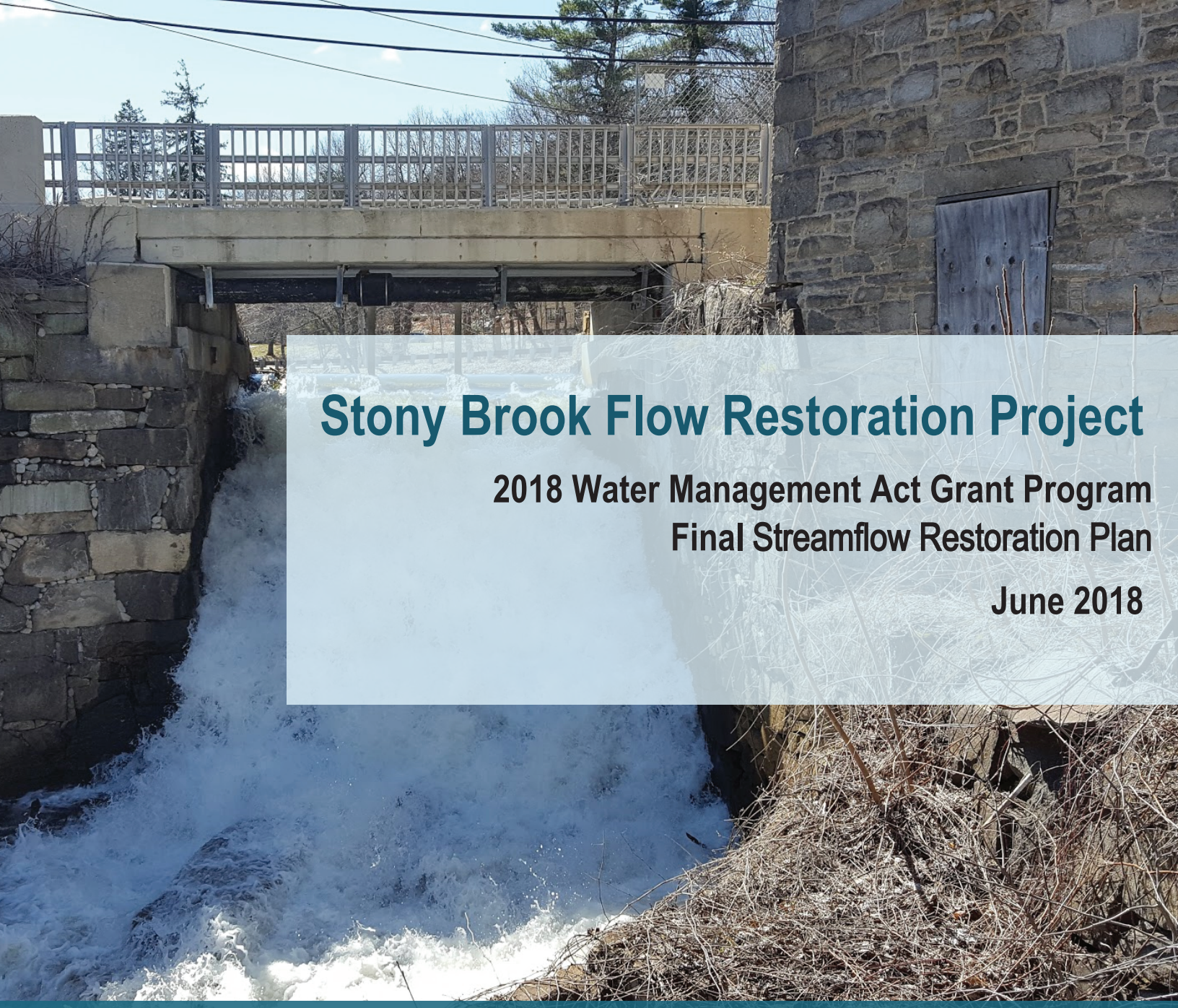


Stony Brook Flow Restoration Project

2018 Water Management Act Grant Program
Final Streamflow Restoration Plan

June 2018

Prepared for:

Executive Office of Energy & Environmental Affairs (EEA) and Department of Environmental Protection (DEP)

Submitted by:

Westford Water Department
Littleton Water Department
Geosyntec Consultants

Contents

CONTENTS I
ACKNOWLEDGEMENTS II
EXECUTIVE SUMMARY III
1. INTRODUCTION 1
1.1. Background 1
1.2. Purpose and Outcomes 1
1.3. Stakeholders 1
1.4. Literature Review 1
1.5. Stakeholder Interviews 2
1.6. Impoundment Information 3
2. GOAL SETTING 8
2.1. Initial Evaluation Indicators 8
2.2. Simplified Evaluation Indicators 9
2.3. Operational Strategy Development 11
3. MODEL DEVELOPMENT 12
3.1. Hydrologic Inputs 12
3.2. Hydraulic Inputs 14
3.3. Calibration 17
4. MODEL EVALUATION 20
4.1. Scenario Development 20
4.2. Results 22
4.3. Discussion 23
4.4. Limitations 27
5. MONITORING AND DECISION SUPPORT 28
5.1. Streamflow Monitoring Stations 28
5.2. Decision Support Dashboard 28
5.3. Decision Support Alerts 28
6. TAKEAWAYS AND RECOMMENDATIONS 75
6.1. Analysis Takeaways 75
6.2. Recommendations 75
7. REFERENCES 79

Appendices

Appendix A: Report Figures
Appendix B: Supporting Model Input Data
Appendix C: Raw Model Time-Series Output for Study Impoundments
Appendix D: Data Collection Plans for Streamflow Monitoring Stations
Appendix E: Backup Data and Lookup Tables for Decision Support Dashboards

List of Tables

Table 1.1: List of Study Data Sources
Table 1.2: Summary of Stakeholder Interviews
Table 1.3: Mill Pond Reference Values
Table 1.4: Spectacle Pond Reference Values
Table 1.5: Forge Pond Reference Values
Table 1.6: Stony Brook Reference Values
Table 1.7: Depot Dam Reference Values
Table 1.8: Brookside Mills Dam Reference Values
Table 2.1: Categorical Goal Definitions
Table 2.2: Goal Evaluation Thresholds and Criteria
Table 2.3 Summary of Evaluation Thresholds for Each Study Impoundment
Table 3.1: Precipitation Station Attributes
Table 3.2: Impoundment Baseflow Inputs
Table 4.1: Baseline Conditions Logic Summary
Table 4.2: Basic (Iteration 1) Controls Logic Summary
Table 4.3: Forecast Based (Iteration 2) Controls Logic Summary
Table 4.4: Forecast Based Sequenced (Iteration 3) Controls Logic Summary (Recommended)
Table 4.5: Summary of Simulated Streamflow Exceedance Results
Table 4.6: Summary of Impoundment Water Level Exceedance Results
Table 4.7: Impoundment Water Level Relative to Spillway
Table 4.8: Low Flow Release Summary
Table 5.1: Summary of Recommended Alerts for Mill Pond
Table 5.2: Summary of Recommended Alerts for Spectacle Pond
Table 5.3: Summary of Recommended Alerts for Forge Pond
Table 5.4: Summary of Recommended Alerts for Stony Brook Impoundment

List of Figures (Appendix A)

Figure 1.1: Study area vicinity map
Figure 1.2: Mill Pond spillway and outlet control structure
Figure 1.3: Spectacle Pond outlet control structure
Figure 1.4a: Forge Pond spillway and secondary outlet structure (downstream)
Figure 1.4b: Forge Pond spillway and secondary outlet structure (upstream)
Figure 1.5a: Stony Brook spillway and outlet control structure (downstream)
Figure 1.5b: Stony Brook spillway and outlet control structure (upstream)
Figure 1.6: Depot Dam culverts and decommissioned spillway
Figure 1.7: Brookside Mills Dam
Figure 2.1: Mill Pond summary of evaluation indicators and thresholds
Figure 2.2: Spectacle Pond summary of evaluation indicators and thresholds
Figure 2.3: Forge Pond summary of evaluation indicators and thresholds
Figure 2.4: Stony Brook Dam summary of evaluation indicators and thresholds
Figure 2.5: Depot Dam summary of evaluation indicators and thresholds
Figure 2.6: Brookside Mills Dam summary of evaluation indicators and thresholds
Figure 3.1: Overview of Hydrologic and Hydraulic Model Components
Figure 3.2a: Bathymetric representation of floodplain storage at Mill Pond
Figure 3.2b: Bathymetric representation of floodplain storage at Spectacle Pond
Figure 3.2c: Bathymetric representation of floodplain storage at Forge Pond
Figure 3.2d: Bathymetric representation of floodplain storage at Stony Brook Impoundment
Figure 3.3: Spectacle Pond water elevation, 10/1/2017 through 5/1/2018
Figure 3.4: Forge Pond water elevation, 10/1/2017 through 5/1/2018
Figure 4.1: Spectacle Pond baseline conditions logic (2016 drought year)
Figure 4.2: Spectacle Pond proposed conditions logic, Iteration 1 (2016 drought year)
Figure 4.3: Spectacle Pond proposed conditions logic, Iteration 2 (2016 drought year)
Figure 4.4: Spectacle Pond proposed conditions logic, Iteration 3 (2016 drought year)
Figure 4.5: Summary of streamflow exceedance results by scenario (2016 – drought conditions)
Figure 4.6: Summary of streamflow exceedance results by scenario (2017 – typical conditions)
Figure 4.7: Mill Pond Dam downstream streamflow exceedance curve
Figure 4.8: Spectacle Pond Outlet downstream streamflow exceedance curve
Figure 4.9: Forge Pond Outlet downstream streamflow exceedance curve
Figure 4.10: Stony Brook Dam d/s streamflow exceedance curve
Figure 4.11: Depot Dam downstream streamflow exceedance curve
Figure 4.12: Brookside Mills Dam d/s streamflow exceedance curve
Figure 4.13: Mill Pond Dam impoundment water level exceedance curve

List of Acronyms

3DEP	3D Elevation Program
ABF	Aquatic Base Flow
ANGD	August Net Groundwater Depletion
BC	Biological Category
CMAC	Continuous Monitoring and Adaptive Control
CN	Curve Number
FEMA	Federal Emergency Management Agency
FIS	Flood Information Study
FOFP	Friends of Forge Pond
GIS	Geographic Information Systems
GSOD	Global Surface Summary of the Day
GWC	Groundwater Withdrawal Category
HSG	Hydrologic soil group
ISE	Integral Square Error
LCLC	Littleton Clean Lakes Committee
LWD	Littleton Water Department
LiDAR	Light Detection and Ranging
MA DCR	Massachusetts Department of Conservation and Recreation
MA DEP	Massachusetts Department of Environmental Protection
MDFW	Massachusetts Department of Fish and Wildlife
MA DOT	Massachusetts Department of Transportation
MA DER	Massachusetts Division of Ecological Restoration
MAODS	Massachusetts Office of Dam Safety
MB	Merrimack Basin
NHD	National Hydrography Dataset
NOAA	National Oceanic and Atmospheric Administration
NOI	Notice of Intent
RDA	Request for Determination of Applicability
SCS	Soil Conservation Service
SPA	Spectacle Pond Association
SWMM	Stormwater Management Model
SRP	Streamflow Restoration Plan
SYE	Sustainable Yield Estimator
UMMS	Unimpacted median monthly streamflow
USDA	United States Department of Agriculture
US EPA	United States Environmental Protection Agency
US FWS	United States Fish and Wildlife Service
USGS	United States Geological Survey
WMA	Water Management Act
WBP	Watershed Boundary Dataset
WHLPC	Westford Healthy Lakes and Ponds Collaborative
WPA	Wetlands Protection Act
WWD	Westford Water Department

Acknowledgements

This study involved collaboration and coordination amongst many project team members, stakeholders, and collaborators. The Geosyntec / CEI project team thanks Westford Water Department and Littleton Water Department for their guidance, input, and enthusiasm throughout the duration of the project and for providing in-kind support to perform culvert assessments, monitoring station site visits, technical review of deliverables, and many other tasks. The project team also thanks OptiRTC, Inc. for developing decision support dashboards and for providing in-kind support to configure the dashboards and alerts.

Most importantly, the project team also thanks all stakeholders and collaborators for providing invaluable input and guidance throughout the process, including attendance at stakeholder meetings and review of project deliverables. Project stakeholders and collaborators included: Littleton Clean Lakes Committee (LCLC), Friends of Forge Pond (FOFP), Mr. Chris Yule (owner and operator of the dam at Forge Pond/Abbot Mill), Westford Healthy Lakes and Ponds Collaborative (WHLPC), Spectacle Pond Association (SPA), the Massachusetts Department of Transportation (MA DOT), and the Massachusetts Division of Ecological Restoration (MA DER).

Finally, the project team would like to thank the Massachusetts Department of Environmental Protection for providing funding for this effort through the Water Management Act (WMA) Grant Program. We are excited about the results of this unique study and hope to continue working with project stakeholders and collaborators to implement recommendations from the Stony Brook Streamflow Restoration Plan.

Executive Summary

Introduction

The purpose of this study was to assess opportunities for improvement of instream flow in the 38-square mile Stony Brook Watershed downstream of a series of surface water impoundments located in the Towns of Littleton and Westford through a coordinated Streamflow Restoration Plan (SRP). Specifically, this SRP evaluates if coordinated releases can be made to improve the timing, magnitude, and duration of downstream flows to better mimic natural conditions without compromising other in-lake uses (e.g., significant impacts to recreation, ecology, or other uses). It is expected that recommendations from this SRP will be incorporated into WWD's and LWD's minimization plans.

The existing study area impoundments are controlled by a series of six control structures located in Littleton and Westford including the Spectacle Pond Outlet, the Mill Pond Dam, the Forge Pond Dam (or Abbot Mill Dam), the Stony Brook Dam, the Depot Dam, and the Brookside Mills Dam. The primary activities and outcomes of this study were to:

- Engage stakeholders in a quantitative goal setting process;
- Develop a calibrated regional surface water model;
- Expand the existing streamflow monitoring network;
- Iteratively evaluate potential operational strategies for impoundments within the study area;
- Develop a SRP with recommended operational strategies to improve streamflow; and
- Create a web-based decision support dashboard with alerts to implement and track recommendations.

Based on a literature review and interviews with project stakeholders, it was determined that four of the six impoundments are controllable (excluding Depot Dam and Brookside Mills) and two of the six impoundments (Spectacle Pond Outlet and Forge Pond Dam) are regularly operated. Additional notable information was gathered as follows: channels downstream of most impoundments are anecdotally known to run low in select years, upstream flooding is typically not a known issue at most of the study impoundments except for Spectacle Pond, and four of the six impoundments (excluding Depot Dam and Brookside Mills) are used for some form of recreation (e.g., powerboats, cartop boat access, etc.).

Goal Setting

Once relevant study area data were reviewed and tabulated, stakeholders were engaged in a goal setting process to define and refine operational goals for the study area impoundments. The overarching goal of the SRP is to mimic natural streamflow conditions without compromising other in-lake uses such as recreation. To evaluate this goal, a series of quantitative indicators, thresholds, and criteria were developed based on downstream streamflow and impoundment water level at all impoundments and their downstream channels. Indicators were then simplified into a low to high range to enable straightforward evaluations based on exceedance frequency analysis (e.g., percent of time that a streamflow threshold or impoundment water level is exceeded).

Once evaluation indicators were developed, it was determined that three (3) potential operational strategies would be evaluated at the four controllable impoundments:

- *Streamflow Enhancement:* Hold water during high flow periods for later release during low flow periods.
- *Winter Drawdown:* Release water to accommodate winter drawdown (Forge and Spectacle Pond only).
- *Spring Refill:* Hold water to accommodate spring refill (Forge and Spectacle Pond only).

The overall goal was to make proposed adjustments simple and at a reasonable frequency (for example, one modification per month).

Modeling

To enable testing of operational strategies and evaluation of streamflow and impoundment water level criteria, a regional hydrologic and hydraulic (H&H) model of the study area was developed using the United States Environmental Protection agency's (US EPA) Stormwater Management Model (SWMM), version 5.1. The model was then coarsely calibrated based

on continuous water level data collected at two previously installed monitoring stations at Forge Pond and Spectacle Pond for the period 10/1/2017 through 5/1/2018. Once calibration was complete, iterative model scenarios were developed to test proposed operational strategies. A two-year simulation period from 1/1/2016 through 12/31/2017 was selected to represent a drought year (2016) and a typical year (2017).

The following model scenarios were performed during the simulation period:

- *Baseline Conditions*: Included representative annual winter drawdown and spring refill logic at applicable impoundments to enable comparison across multiple proposed conditions scenarios.
- *Proposed Conditions (Iteration 1)*: Identical to baseline conditions but focused on streamflow enhancement by configuring the control structures of the four controllable impoundments to release water when downstream streamflow approaches the previously defined low threshold. An iterative exercise was performed to determine the optimal opening for each control structure to maintain adequate downstream streamflow while releasing. Logic was then configured to halt releases once each impoundment's minimum allowable water level was reached.
- *Proposed Conditions (Iteration 2)*: Identical to Iteration 2 but included an additional condition to perform low releases contingent on the precipitation forecast to limit the amount of required adjustments at each impoundment. Low flow releases configured to be initiated if there is less than 0.10 inch of precipitation in the 7-day forecast.
- *Proposed Conditions (Iteration 3)*: Identical to Iteration 2 but was configured to improve upon the first two iterations by testing various forecasting thresholds and experimenting with sequenced releases. The following modifications were included in this scenario: 1) increased the 7-day forecast threshold from 0.10-inches to 0.25-inches to trigger low flow releases based on a more notable precipitation event; and 2) changed sequencing such that Stony Brook Dam will only release water if Forge Pond Dam is releasing water to decrease the rate of drawdown at Stony Brook Dam.

Results

Primary takeaways are summarized below:

- Model results indicate that implementation of low flow releases have great potential to improve downstream streamflow throughout the study area while balancing competing goals (e.g., maintaining adequate upstream impoundment water levels).
- It is recommended that Iteration 3 be implemented for future empirical testing. Iteration 3 provides significant streamflow improvements relative to baseline conditions, provides stable impoundment water levels, and limits the overall number of required low flow releases. Iteration 3 provides a compromise between Iteration 1 (largest streamflow improvements) and Iteration 2 (highest impoundment water levels and least amount of required low flow releases).
- Simulated streamflow improvements were typically more pronounced at headwater locations (e.g., Spectacle Pond Outlet and Mill Pond Dam) and were typically more dramatic in 2016 (drought year) than in 2017 (typical year). Results indicate that all impoundments (and their downstream channels) are susceptible to low downstream streamflow resulting from prolonged dry periods.
- Impoundment water level was effectively managed relative to the defined critical minimum water level for all simulated model runs and at all impoundments. Implementation of low flow releases increases the frequency that simulated impoundment water levels are below the spillway which could potentially have an impact on recreation, aesthetics, or other factors. Simulation results also indicate a higher frequency of extremely low streamflow (i.e., ranging from 1 to 10 cfs) due to times when the impoundment is refilling after reaching the minimum water level trigger upstream of the impoundment (or the maximum allowable release level). Empirical testing is required to test assumptions, to confirm that critical minimum water levels were properly defined, and to investigate potential strategies to mitigate critically low downstream flows.

- The number and duration of simulated low flow releases varied widely based on the impoundment and model iteration. With the inclusion of forecast based logic (Iterations 2 and 3), the number and duration of simulated releases is greatly reduced. Results indicate that it is reasonable to assume that on any given year, low flow releases may realistically be required on a monthly to bi-monthly (i.e., once every two months) basis at the various impoundments. Results are also indicative that automation could be beneficial at locations to maximize responsiveness of low flow release adjustments and to allow for more frequent adjustments, which could result in improved downstream flow.
- Model simulations are sensitive to modification of various inputs such as the release opening (e.g., fraction that a sluice gate is opened) and indicate that empirical evaluations will be beneficial to test and validate results.

Monitoring and Decision Support

As part of this study and a previous study, four (4) continuous streamflow monitoring stations were installed throughout the study area (Mill Pond, Spectacle Pond, Forge Pond, Stony Brook Impoundment). Data from each monitoring station is continuously streamed to an online dashboard at a two-minute logging interval. The online dashboard is accessible to all project stakeholders via secure, user-specific login at www.optirtc.com configured to provide email-based alerts and precipitation forecast-based decision support based on recommended operational strategies. An example email-based alert would be to inform the user to perform a low flow release if downstream flow is low, if there is minimal rain in the forecast, and if the upstream impoundment water level is above the minimum threshold. The decision support dashboard can also be used to empirically track and improve upon recommendations.

Recommendations

Based on analysis of model results, it is recommended that Iteration 3 logic be implemented, as feasible, at each study impoundment. To implement Iteration 3, the following steps are recommended:

- *Model Validation, Additional Calibration, and Baseline Sampling:* Perform streamflow gaging downstream of study impoundment monitoring stations under a range of streamflow conditions to validate modeled discharge rates. Couple gaging results with new data from monitoring stations to perform additional calibration and validation of the regional H&H model. Evaluate monitoring data and alerts from the data decision support dashboard to determine if baseline model predictions are reasonable – e.g., frequency of various alerts such as low flow conditions. Perform baseline and periodic post-implementation sampling of stream biota at downstream channels of all study impoundments to track success of recommendations.
- *Low Flow Release Feasibility Evaluation*: Obtain permission from owners and operators of all dams to perform empirical testing of low flow release strategies outlined by this report. Perform evaluation of Stony Brook Dam to determine if the sluice gate is in adequate condition for safe operation. Evaluate if installation of low flow orifices at Spectacle Pond Outlet and Mill Pond Dam are feasible. Implementation will require permitting under the Massachusetts Office of Dam Safety for all impoundments that are performing low flow releases. Depending on the proposed modifications and construction methods, additional permitting is expected through the Massachusetts Wetland Protection Act and Chapter 91 regulations for Spectacle Pond and Mill Pond if low flow orifices are installed.
- *Empirical Testing and Implementation*: If and when low flow controls at particular impoundments become operable, implement the recommended streamflow restoration tasks outlined by the decision support dashboard (i.e., model Iteration 3). Relative to modeled conditions, evaluate the effectiveness of release openings size, duration, and the resulting impacts to upstream impoundment water level and downstream flow. Based on testing results, the SRP can be modified and adjusted to better meet empirical conditions – i.e., release opening size, release thresholds, precipitation forecast thresholds, control rules, sequencing order, etc.
- *Automated Controls*: Modeling results suggest that automation could result in improved overall streamflow performance. Automation would make response time instantaneous and would take the burden from various stakeholders and managers of each impoundment. It is recommended that an evaluation be performed to determine if implementation of automated controls is feasible. Such an evaluation would consider availability of

power and internet at each location and physical condition and operability.

- *Study Area*: Finally, there is one additional documented downstream impoundment in the Stony Brook Watershed in Chelmsford near School Street that was not included in the initial study. It is recommended that future steps seek to include the owner of this dam and other stakeholders from Chelmsford to truly turn this into a complete watershed-wide restoration project that includes all impoundments along the mainstem of Stony Brook prior to discharging into the Merrimack River.

1. Introduction

1.1. Background

As part of the revised Water Management Act (WMA) regulations (the Regulations), the Massachusetts Department of Environmental Protection (MA DEP) has identified Westford Water Department (WWD) and Littleton Water Department (LWD) water supply source sub-basins in the Merrimack Basin (MB) as highly impacted by groundwater withdrawals; specifically, as groundwater withdrawal category (GWC) 5, Biological Category (BC) 5, and August Net Groundwater Depletion (ANGD) greater than 25 percent. As such, WWD and LWD will need to minimize the impact of existing withdrawals to "the greatest extent feasible" to meet the Regulations through development of a minimization plan (MA DEP, 2014).

1.2. Purpose and Outcomes

The purpose of this study was to assess opportunities for improvement of instream flow in the 38-square mile Stony Brook Watershed downstream of a series of surface water impoundments located in the Towns of Littleton and Westford through a coordinated Streamflow Restoration Plan (SRP). Specifically, this SRP evaluates if coordinated releases can be made to improve the timing, magnitude, and duration of downstream flows to mimic natural conditions without compromising other in-lake uses (e.g., significant impacts to recreation, ecology, or other uses) (MA DEP, 2014). It is expected that recommendations from this SRP will be incorporated into WWD's and LWD's minimization plans.

The existing study area impoundments are controlled by a series of six control structures located in Littleton and Westford including the Spectacle Pond Outlet, the Mill Pond Dam, the Forge Pond Dam (or Abbot Mill Dam), the Stony Brook Dam, the Depot Dam, and the Brookside Mills Dam (see **Figure 1.1** for vicinity map). The primary activities and outcomes of this study were to:

- Engage stakeholders in a quantitative goal setting process;
- Develop a calibrated regional surface water model;
- Expand the existing streamflow monitoring network;
- Iteratively evaluate potential operational strategies for impoundments within the study area;
- Develop a SRP with recommended operational strategies to improve streamflow; and
- Create a web-based decision support dashboard with alerts to implement and track recommendations.

1.3. Stakeholders

This study was performed by the WWD, the LWD, Geosyntec Consultants, and Comprehensive Environmental (the Project Team) with funding from MA DEP through the WMA Grant Program (BWR-2018-01). This study builds upon a previous pilot project ("DAM Dashboard") performed by LWD and Geosyntec Consultants where continuous streamflow monitoring equipment was installed at Forge Pond and Spectacle Pond (Geosyntec Consultants, 2017).

Project collaborators and stakeholders included Littleton Clean Lakes Committee (LCLC), Friends of Forge Pond (FOFP), Mr. Chris Yule (owner and operator of the dam at Forge Pond/Abbot Mill), Westford Healthy Lakes and Ponds Collaborative (WHLPC), Spectacle Pond Association (SPA), the Massachusetts Department of Transportation (MA DOT), and the Massachusetts Division of Ecological Restoration (MA DER).

1.4. Literature Review

The Project Team gathered existing information relevant to the study area to inform goal setting, model development, and other activities. The following data sources were evaluated as part of this study (**Table 1.1**) as provided by stakeholders and other publicly available sources.

Table 1.1: List of Study Data Sources

Title / Description	Primary Data Use	Source	Date
Federal Emergency Management Agency (FEMA) Flood Information Study (FIS) for Middlesex County, FIS Number 25017CV003C. The FIS was last revised on July 6, 2016; however, FIS data for the study area were last revised in 1982. Supporting FIS data were also requested and obtained from the FEMA Engineering Library for the study area.	Development of model cross sections and culvert geometry	FEMA	2016
United States Geological Survey (USGS) StreamStats Application	Delineation of subwatersheds, calculation of hydrologic statistics	USGS	2018
The Massachusetts Sustainable Yield Estimator	Calculation of unaffected median monthly streamflow (UMMS)	USGS	2010
United States Fish and Wildlife Service (USFWS) Questions and Answers on the New England Flow Policy	Goal setting and calculation of acceptable streamflow limits	USFWS	1999
WMA Permit Guidance Document	Goal setting and proposed condition guidance	MA DEP	2014
The Practical Guide to Lake Management in Massachusetts (Jointly released by MA DEP and Massachusetts Department of Conservation and Recreation (MA DCR)	Goal setting as it relates to drawdown and refill	MA DEP / MA DCR)	2004
Design Report: Mill Pond Restoration Project, Extended Detention	Geometry of Mill Pond, including spillway elevation	ESS Group	2002
Notice of Inspection by the Massachusetts Office of Dam Safety (MA ODS) for Mill Pond Dam	Geometry of Mill Pond, including spillway length and dam height	MA ODS	2003
A Diagnostic and Feasibility Investigation of Mill Pond	Stage-Storage relationship for Mill Pond	ESS Group	1999
Spectacle Pond Stop Log Configuration History 2010-2018	Development of model logic for Spectacle Pond	L. Weaver	2018b
Diagnostic Feasibility Study of Spectacle Pond	Stage-Storage relationship for Spectacle Pond	ESS Group	2001
Engineering Plans: Proposed Culvert Rehabilitation, Great Road over Gilson Brook	Geometry of Spectacle Pond outlet control structure and downstream culvert	MA DOT	2010
Engineering Plans for the Forge Pond Water Level Control Structure	Development of model geometry and logic for Forge Pond	Baystate Environmental Consultants	1991
Diagnostic Feasibility Study for the Management of Forge Pond	Initial Stage-Storage Relationship for Forge Pond	Baystate Environmental Consultants	1987
DAM Dashboard: Desktop Analysis and Modeling Summary for Forge Pond and Spectacle Pond	Development of model geometry for Forge and Spectacle Ponds, updated Stage-Storage relationships for both Ponds.	Geosyntec Consultants	2017
2015 Lakes and Ponds Monitoring Report, Westford, MA	Stony Brook Dam stage-storage relationship	ESS Group	2016
Stony Brook Dam Phase I Inspection / Evaluation Report	Stony Brook Dam Geometry (spillway, sluice) and invert data	Weston and Sampson	2011

1.5. Stakeholder Interviews

The Project Team performed a series of interviews with stakeholders to gain an understanding of each impoundments characteristics. Interview findings are summarized by **Table 1.2**. Items of interested are listed below.

- Four of the six impoundments are controllable; Depot Dam and Brookside Mills Dam do not have existing control mechanisms (i.e., they are configured with double barrel culverts that directly pass flow). The Depot Dam was apparently previously controllable by inserting stop logs across the existing spillway and potentially through other control mechanisms to block/restrict flow through the existing culverts. Brookside Mills Dam was previously configured with sluice gates at the location of the existing culverts that are currently broken and inoperable.

- Two of the six impoundments, Spectacle Pond Outlet and Forge Pond Dam, are regularly operated. Mill Pond Dam and Stony Brook Dam are configured with sluice gates, but neither have been operated in recent years (last operation unknown). Additionally, the Mill Pond Dam sluice gate is heavily impacted by sedimentation.
- Channels downstream of most impoundments are anecdotally known to run low in select years. For instance, the flow over the spillway at Stony Brook Dam is frequently reduced to a "trickle" in the late summer months resulting in seasonal low downstream flows.
- Flooding is typically not a known issue at most of the study impoundments. Spectacle Pond does have a history of flooding, particularly when greater than four concrete stop logs are installed in the outlet control structure.
- Four of the six impoundments are used for some form of recreation (e.g., powerboats, cartop boat access, etc.). Spectacle Pond and Forge Pond both support powerboat recreation and have known approximate thresholds where the low water levels impair powerboat recreation in shallow areas (e.g., unnavigable areas, propellers scraping bottom, etc.).

Table 1.2: Summary of Stakeholder Interviews

Input Item	Mill Pond Dam	Spectacle Pond Outlet	Forge Pond Dam	Stony Brook Dam	Depot Dam	Brookside Mills Dam
Owner / Operator	MA DOT	LWD	Abbot Mill	Town of Westford	Town of Westford	Brookside Mills
Existing Operational Information	Operable Sluice Gate (Not Operated)	Concrete Stop Logs (Seasonally Adjusted)	Triple Sluice Gates / Stop Logs (Seasonally Adjusted)	Dual Sluice Gate (Not Operated)	Double Barrel Culvert (No Controls)	Double Barrel Culvert (No Controls, Previous Sluice Gates)
Downstream Channel Low Flow Data	Unknown	Gilson Brook can run very low in select years	Stony Brook can run very low in select years	Stony Brook almost always low in August	Stony Brook almost always low in August	Stony Brook almost always low in August
Upstream Flooding Data	Unknown	Low lying properties may flood with > 4 stop logs	No known issues	No known issues	No known issues	Previous nuisance flooding when sluice gates were operable
Upstream Recreation Observations	Recreation with car top access - no known issues	Powerboats - channel unnavigable with < 3 stop logs	Powerboats - Boat access at Beaver Brook Road boat launch becomes difficult in late summer. Issues occur appx. 1 to 2 ft below spillway (prop. scraping)	Recreation with car top access - no known issues	No known recreation	No known recreation
Other Observations	Algae blooms prevalent in summer, pond severely impacted by sedimentation – dredging needed	Frequent beaver blockages	-	-	-	Outflow in poor condition

Interview Sources: Mill Pond (J. Clyde, 2018); Spectacle Pond (L. Weaver, 2018); Forge Pond (R. Hartzel, 2018); Stony, Depot, and Brookside Mills Dams (C. Barret, 2018).

1.6. Impoundment Information

The following relevant information was gathered for each impoundment and control structure from the literature review (**Table 1.2**), stakeholder interviews, and site visits performed by the project team in April 2018.

Mill Pond

Mill Pond is a 25-acre pond (Mass DEP, 2018) located in Littleton, Massachusetts with an approximate watershed area of 5,504 acres (USGS, 2018). Mill Pond's primary tributaries are Beaver Brook and Reedy Meadow Brook. Mill Pond is impounded by a dam to the east with an ogee style, horseshoe shaped spillway. In addition, there is a concrete headwall with one (1) embedded rectangular sluice gate that appears to be operable via hand wheel (**Figure 1.2**). As previously indicated, the sluice gate has not been operated in recent years. Discharge from Mill Pond flows via Beaver Brook to Forge Pond, approximately three miles to the northeast. Refer to **Table 1.3** for reference values, elevations, and dimensions for the impoundment.

Table 1.3: Mill Pond Reference Values

Description	Value	Source / Comments
Spillway Crest Elevation	215 (ft, NAVD88)	ESS Group (2002)
Spillway Length	60 (ft)	MA ODS (2003)
Dam Structure Height	6 (ft)	MA ODS (2003)
Sluice Gate Dimensions	2' W x 3' H	Geosyntec Field Measurements (4/4/2018)
Sluice Invert Elevation (Downstream of Dam)	209 (ft, NAVD88)	Spillway minus dam height
Pond Invert Elevation[1]	207 (ft, NAVD88)	ESS Group (1999)
Pond Depth at Spillway	8 (ft, NAVD88)	Spillway minus Invert

1. Invert elevation does not account for sedimentation. Based on discussions with project stakeholders, sedimentation currently limits average depth of Mill Pond to approximately 1 to 3 feet.

Spectacle Pond

Spectacle Pond is a 79-acre pond located in Littleton, Massachusetts (Mass DEP, 2018) with an approximate watershed area of 4,416 acres (USGS, 2018). Spectacle Pond's primary tributary is Bennett's Brook. Spectacle Pond is impounded by a concrete outlet control structure that consists of two stop log-type weirs that discharge to a dual 48-inch culvert under Great Road (**Figure 1.3**). The pictured primary stop log weir is typically seasonally adjusted to allow for winter drawdown and spring refill while the secondary weir is typically configured to pass large flows. The weir can accept up to five (5) concrete stop logs. Discharge from Spectacle Pond flows via Gilson Brook to Forge Pond, approximately 0.5 miles to the northeast. Refer to **Table 1.4** for reference values, elevations, and dimensions for the impoundment.

Table 1.4: Spectacle Pond Reference Values

Description	Value	Source / Comments
Width of Each Weir	6.42 (ft)	Geosyntec Consultants (2017)
Top Elevation of Weir	212.36 (ft, NAVD88)	Geosyntec Consultants (2017)
Top Elevation of 5 Stop Logs	211.21 (ft, NAVD88)	Geosyntec Consultants (2017)
Top Elevation of 4 Stop Logs	210.46 (ft, NAVD88)	Geosyntec Consultants (2017)
Top Elevation of 3 Stop Logs (Typical Summer Configuration)	209.71 (ft, NAVD88)	Geosyntec Consultants (2017)
Top Elevation of 2 Stop Logs	208.96 (ft, NAVD88)	Geosyntec Consultants (2017)
Top Elevation of 1 Stop Log (Typical Winter Configuration)	208.21 (ft, NAVD88)	Geosyntec Consultants (2017)
Bottom Elevation of Weir	207.7 (ft, NAVD88)	Geosyntec Consultants (2017)
Bottom Elevation of Pond	170.38 (ft, NAVD88)	ESS Group (2001)
Maximum Depth of Pond	41.98 (ft)	Top of weir minus pond invert
Pond Depth at 3 Stop Logs	39.33 (ft)	Top of 3 stop logs minus pond invert
Pond Depth at 1 Stop Log	37.83 (ft)	Top of 1 stop log minus pond invert
Depth of Pond at Bottom of Weir	37.32 (ft)	Bottom of weir minus pond invert

1. Elevations are approximate and were obtained by referencing field measurements performed in June 2017 to engineering plans for the outlet control structure (MA DOT, 2010)

Forge Pond

Forge Pond is a 202-acre pond (Mass DEP, 2018) located in Littleton and Westford, Massachusetts with an approximate watershed area of 14,976-acres (USGS, 2018). Forge Pond's primary tributaries are Gilson Brook (from Spectacle Pond) and Beaver Brook (from Mill Pond). The pond is impounded to the north by a dam constructed of stone blocks, with a primary spillway weir constructed of wooden planks on its northern side and three timber sluice gates on its southern side (**Figure 1.4a**). A secondary outlet control structure was constructed in the 1990's, downstream of the sluice gates, which consists of a concrete weir with adjustable aluminum stop logs (Baystate Environmental Consultants, 1991). In addition, an approximate 6-inch diameter penstock pipe is installed downstream of the sluice gates which runs through the Abbott Mill Building. The penstock pipe was previously used to power the mill's turbine (Yule, C., 2018).

The timber sluice gates and secondary outlet control structure are seasonally adjusted to allow for winter drawdown and spring refill. The penstock pipe is operated, sporadically, but may be operated on a more frequent basis in the future (Yule. C., 2018). Discharge from the dam flows into Stony Brook via a rectangular channel that passes through the Abbot Mill property (**Figure 1b**). Refer to **Table 1.5** for reference values, elevations, and dimensions for the impoundment.

Table 1.5: Forge Pond Reference Values

Description	Value	Source / Comments
Spillway crest elevation	203.68 (ft, NAVD88)	Baystate Environmental Consultants (1991)
Spillway length	40 (ft)	Baystate Environmental Consultants (1991)
Forge Pond Invert Elevation	173.68 (ft, NAVD88)	FOFP (2016); Geosyntec Consultants (2017)
Sluice Gate Dimensions (3)	3' W x 3' H	Baystate Environmental Consultants (1991)
Sluice Gate Invert Elevation	199.22 (ft, NAVD88)	Baystate Environmental Consultants (1991)
Penstock Pipe Diameter	6 (inches)	Yule (2018); invert elevation unknown, assumed to be at invert of "canal" (See Section 3, "*Storage Units*"
Forge Pond Maximum Elevation	207.5 (ft, NAVD88)	Based on top elevation of secondary outlet control structure; Baystate Environmental Consultants (1991)
Maximum Pond Depth	33.82 (ft)	Maximum depth minus invert
Pond Depth at Spillway	30 (ft)	Spillway minus invert
Secondary Outlet Control Dimensions:		
Top Elevation	207.5 (ft, NAVD88)	Baystate Environmental Consultants (1991)
Invert Elevation	199 (ft, NAVD88)	Baystate Environmental Consultants (1991)
Overall Height of Stop Log Structure	8.5 (ft)	Baystate Environmental Consultants (1991)
Stop Log Width	4 (ft)	Baystate Environmental Consultants (1991)
Top El. of 1st Stop Log (12" Height, perforated with weep holes)	200 (ft, NAVD88)	Baystate Environmental Consultants (1991)
Top El. of 2nd Stop Log (18" Height)	201.5 (ft, NAVD88)	Baystate Environmental Consultants (1991)
Top El. of 3rd Stop Log (12" Height)	202.5 (ft, NAVD88)	Baystate Environmental Consultants (1991)
Top El. of 4th Stop Log (12" Height)	203.5 (ft, NAVD88)	Baystate Environmental Consultants (1991)
Top El. of 5th Stop Log (12" Height)	204.5 (ft, NAVD88)	Baystate Environmental Consultants (1991)
Top El. of 6th Stop Log (12" Height)	205.5 (ft, NAVD88)	Baystate Environmental Consultants (1991)
Top El. of 7th Stop Log (12" Height)	206.5 (ft, NAVD88)	Baystate Environmental Consultants (1991)
Top El. of 8th Stop Log (12" Height)	207.5 (ft, NAVD88)	Baystate Environmental Consultants (1991)

Stony Brook Dam

The Stony Brook Dam impounds an approximate 15-acre waterbody in Westford, Massachusetts with an approximate watershed area of 16,768 acres (USGS, 2018). The impoundment consists of two primary sub-basins, divided by Bridge Street and connected by a culvert (ESS Group, 2016). The Stony Brook Impoundment's primary tributaries are Stony Brook (from Forge Pond) and Boutwell Brook. The impoundment is comprised of an earthen dam with a stone masonry outlet structure with a primary spillway and low-level outlet with two (2) sluice gates. The sluice gates have not been operated in recent years (**Figure 1.5a and 1.5b**). Discharge from the impoundment flows to Depot Street Dam,

approximately two miles to the northeast. Refer to **Table 1.6** for reference values, elevations, and dimensions for the impoundment.

Table 1.6: Stony Brook Reference Values

Description	Value	Source / Comments
Spillway Crest Elevation	182.36 (ft, NAVD88)	Weston and Sampson (2001)
Spillway Length	20 (ft)	Weston and Sampson (2001)
Sluice Gate Dimensions (2)	3' W x 3.3' H	Weston and Sampson (2001)
Sluice Gates Invert Elevation	170.7 (ft, NAVD88)	Weston and Sampson (2001)
Normal Pool Elevation	182.4 (ft, NAVD88)	Weston and Sampson (2001)
Maximum Pool Elevation	187.7 (ft, NAVD88)	Weston and Sampson (2001)
Impoundment Invert Elevation	167.36 (ft, NAVD88)	ESS Group (2016); calculated from 15-foot bathymetry contour from spillway crest elevation
Maximum Impoundment Depth	18.64 (ft)	Maximum elevation minus invert
Impoundment Depth at Spillway	15 (ft)	Spillway elevation minus invert

Depot Dam

The Depot Dam is located at Depot Street in Westford, Massachusetts and has an approximate watershed area of 22,080 acres (USGS, 2018). Depot Dam's primary tributaries are Stony Brook (from the Stony Brook Impoundment), Keyes Brook, and Coldspring Brook. At this location, Stony Brook was formerly impounded by a concrete structure with configurable wooden stop logs that could extend across the entire structure. Based on a site visit by the Project Team on 4/5/2018, the stop logs have been decommissioned and two circular steel culverts are installed at either end to allow continuous flow through the structure (**Figure 1.6**). If the culverts surcharge, discharge will flow over the decommissioned spillway. Discharge from Depot Dam flows via Stony Brook to Brookside Mills Dam, approximately 1.5 miles to the northeast. Refer to **Table 1.7** for reference values, elevations, and dimensions for the impoundment.

Table 1.7: Depot Dam Reference Values

Description	Value	Source / Comments
Culvert Diameter (2)	3 to 5 (ft)	Approximate Geosyntec Field Measurements (4/5/2018); inlet of culvert on northern side of structure was partially crushed and had an approximate diameter of 3 feet.
Culvert and Spillway Invert Elevation	156 (ft, NAVD88)	FEMA (2016)
Spillway Crest Elevation	160 (ft, NAVD88)	Geosyntec Field Measurements (4/5/2018); approximate 4-foot-tall structure.
Spillway Length	30 (ft)	Approximate Geosyntec Field Measurements (4/5/2018)

Brookside Mills Dam

Brookside Mills Dam (formerly known as Commodore Foods Dam) is located at Brookside Road in Westford, Massachusetts and has an approximate watershed area of 24,192 acres (USGS, 2018). The primary tributaries of the Brookside Mills Dam are Stony Brook (from the Depot Dam) and Tadmuck Brook. At this location, Stony Brook was formerly impounded by a stone block structure with low level sluice gates; however, the sluice gates are no longer operable. Based on a site visit by the Project Team on 4/5/2018, the sluice gates have been decommissioned and two arched shaped stone culverts are installed at the bottom of the stone block structure which allow for continuous flow through the structure (**Figure 1.7**). If the culverts surcharge, discharge will flow over the spillway. Discharge from

Brookside Mills Dam flows via Stony Brook to the Town of Chelmsford, and eventually to the Merrimack River, approximately 2.5 miles to the northeast. Refer to **Table 1.8** for reference values, elevations, and dimensions for the impoundment.

Table 1.8: Brookside Mills Dam Reference Values

Description	Value	Source / Comments
Culvert Diameter (2)	6 (ft)	Approximate Geosyntec Field Measurements (4/5/2018)
Culvert and Spillway Invert Elevation	141.6 (ft, NAVD88)	FEMA (2016)
Spillway Crest Elevation	151.6 (ft, NAVD88)	Based on Geosyntec Field Measurements (4/5/2018). Could not access spillway to measure; however, total height of structure over culvert was 15.5 ft. Assume spillway was approximately 10 ft tall based on field photos.
Spillway Length	40 (ft)	GIS measurement from aerial photography

2. Goal Setting

Once relevant study area data were reviewed and tabulated, the Project Team engaged stakeholders in a goal setting process to define and refine operational goals for the study area impoundments. A stakeholder meeting was held at WWD on March 27, 2018 to solicit input and obtain consensus from stakeholders on operational goals. The overarching goal of the SRP is to mimic natural streamflow conditions without compromising other in-lake uses. To inform this overall goal, the following categorical goals were defined (**Table 2.1**).

Table 2.1: Categorical Goal Definitions

Goal	Goal Description
Natural Conditions	Mimic natural conditions without compromising other uses (listed as below goals)
Streamflow / Water Supply	Maintain streamflow during times of low flow
Storm Event Resiliency	Reduce the potential for property flooding and scour associated with high magnitude, low frequency storm events
Fish Protection	Maintain adequate downstream flow to support fish habitat
Vegetation Control	Allow for seasonal (winter) pond level drawdown for control of non-native species
Recreation	Maintain recreational uses of the ponds for lakeshore residents and visitors

2.1. Initial Evaluation Indicators

To evaluate these goals, a series of initial quantitative indicators, thresholds, and criteria were developed based on downstream streamflow and impoundment water level as summarized by **Table 2.2**.

Table 2.2: Goal Evaluation Thresholds and Criteria

Goal	Evaluation Indicator	Critical Indicator Threshold(s)[1]	Evaluation Period(s)	Evaluation Criteria
Natural Conditions	Streamflow	Unimpacted Monthly Median Streamflow[2]	All Year	Exceedance Frequency (%)
Streamflow / Water Supply	Streamflow	Aquatic Baseflow (Streamflow > 0.5 cfsm)[3]	Operational Year – May through November	Exceedance Frequency (%)
Storm Event Resiliency	Streamflow	2-yr Peak Discharge[4]	All Year	Number of Exceedances
	Water Level	Determine on case-by-case basis	All Year	Number of Exceedances
Fish Protection	Streamflow	Streamflow between 1 cfsm and 4 cfsm[5,6]	All Year	Exceedance Frequency (%)
Vegetation Control	Streamflow	Drawdown streamflow < 4 cfsm[7] Refill streamflow > 0.5 cfsm[8]	Drawdown - November; Refill - March / April	Exceedance Frequency (%)
	Water Level	Limit overall drawdown to 3 feet[7] (varies); Limit drawdown to 3 in/day[7] (varies)	Drawdown - November; Refill - March / April	Number of Exceedances
Recreation	Water Level	Determine on case-by-case basis	May - October	Number of Exceedances

Explanation of Indicators (Table 2.2 Notes):

1. cfsm refers to cubic feet per second of streamflow per upstream square mile of drainage area.

2. Unimpacted median monthly streamflow (UMMS) means the estimated near natural median monthly streamflow over a simulated 44-year period generated by The Massachusetts Sustainable Yield Estimator (SYE) (Archfield et al, 2010).
3. Aquatic Base Flow (ABF) is a set of chemical, physical, and biological conditions that represent limiting conditions for aquatic life and wildlife in stream environments. In hydrological terms, it means median August streamflow (USFWS, 1999).
4. Statistic obtained from USGS Stream Stats (2018).
5. The USFWS recommends that the ABF release be 0.5 cfsm at all times of the year, unless superseded by spawning and incubation flow recommendations. The USFWS recommends flow releases of 1.0 cfsm in the fall/winter (Oct-Feb) and 4.0 cfsm in the spring (March-May) for the entire applicable spawning and incubation periods (per appendix B sample hydrograph, >2 cfsm is acceptable in March, April, May) (USFWS, 1999).
6. Optimal streamflow conditions frequently range from 1 to 1.5 cfsm based on species with an affinity to moderate velocities such as trout salmon, dace, and macroinvertebrates such as stoneflies (USFWS, 1999).
7. Based on general guidelines, drawdown should be limited to three (3) feet, should be performed November through the beginning of December, should be limited to less than three (3) inches per day, with outflows no greater than 4 cfsm (MA DEP / MA DCR, 2004). However, drawdown is permitted under the Wetlands Protection Act (WPA) on a case-by-case basis for a wide range of depths base as described by MA DEP (2004). For example, Forge Pond drawdown has been permitted for 1.5 meters (4.9 feet) and 2.0 meters (6.5 feet) on alternating years.
8. Lake full status should be achieved by beginning of April with outflows of at least 0.5 cfsm (MA DEP / MA DCR, 2004).

2.2. Simplified Evaluation Indicators

Goal indicators were then simplified to enable straightforward evaluations based on exceedance frequency curves (i.e., the amount of time per year that a certain threshold is exceeded). Specifically, “low”, “normal”, and “high” ranges were assigned to each impoundment’s depth and downstream channel flow as defined below.

Streamflow:

- *Low Range*: Less than Aquatic Base Flow (0.5 cfsm)
- *Normal Range*: Between Aquatic Base Flow (0.5 cfsm) and 4 cfsm (USFWS and MA DCR maximum recommended release)
- *High Flow Range*: Greater than 4 cfsm

Water Level:

- *Low Range*: Below critical recreational range (defined on case-by-case basis)
- *Normal Range*: Between critical recreational range and approximate elevation associated with 2-year peak discharge
- *High Range*: Above the approximated 2-year peak discharge (as an indicator of potential flooding issues)

Refer to **Table 2.3** for a summary of evaluation indicators for each impoundment. The table is useful to gain an understanding of general streamflow ranges for a variety of conditions. For example, expected streamflow at Mill Pond ranges from 0.6 cfs (7-day, 10-year low flow) to 187 cfs (2-year storm) with an expected ABF of 4.3 cfs and an expected fish protection and drawdown limit (4 cfsm) of 34.3 cfs. Therefore, Mill Pond’s ABF can be approximated by October UMMS while Mill Pond’s fish protection and drawdown limit can be approximated by March and April UMMS. Finally, refer to **Figures 2.1 through 2.6** for a visual depiction of evaluation indicators as they relate to each impoundment.

Table 2.3 Summary of Evaluation Thresholds for Each Study Impoundment

Goal	Indicator Threshold	Mill Pond Dam	Spectacle Pond Outlet	Forge Pond Dam	Stony Brook Dam	Depot Dam	Brookside Mills Dam	Source
N/A	Upstream Drainage Area (sq. mi.)	8.6	6.9	23.4	26.2	34.5	37.8	USGS (2018)
Natural Conditions	UMMS, Jan - (cfs)	13.7	10.7	36.9	41.5	54.5	59.9	Archfield et al (2010)
	UMMS, Feb - (cfs)	15.4	12.2	41.5	46.6	61.1	67.0	Archfield et al (2010)
	UMMS, Mar - (cfs)	33.3	27.2	88.4	98.9	128.7	140.4	Archfield et al (2010)
	UMMS, Apr - (cfs)	33.4	27.3	88.4	98.9	128.5	140.3	Archfield et al (2010)
	UMMS, May - (cfs)	15.9	12.5	42.7	48.0	62.9	69.0	Archfield et al (2010)
	UMMS, Jun - (cfs)	7.9	6.1	21.5	24.3	32.0	35.2	Archfield et al (2010)
	UMMS, Jul - (cfs)	3.4	2.7	9.7	10.9	14.4	15.9	Archfield et al (2010)
	UMMS, Aug - (cfs)	2.5	1.9	7.1	8.0	10.7	11.8	Archfield et al (2010)
	UMMS, Sep - (cfs)	2.2	1.8	6.5	7.3	9.7	10.7	Archfield et al (2010)
	UMMS, Oct - (cfs)	4.4	3.4	12.3	13.9	18.4	20.3	Archfield et al (2010)
	UMMS, Nov - (cfs)	11.5	9.0	31.0	34.8	45.7	50.2	Archfield et al (2010)
	UMMS, Dec - (cfs)	12.5	9.8	33.8	38.0	49.9	54.9	Archfield et al (2010)
Streamflow / Water Supply	ABF (0.5 cfsm)	4.3	3.5	11.7	13.1	17.3	18.9	USFWS (1999)
	Aug. Median Flow (cfs)	2.5	2.3	7.5	8.2	10.8	11.7	USGS (2018)
	$Q_{7,2}$ (7-day, 2-year low flow)	1.2	1.1	3.6	4.0	5.3	5.7	USGS (2018)
	$Q_{7,10}$ (7-day, 10-year low flow)	0.6	0.5	1.8	2.0	2.6	2.8	USGS (2018)
Storm Event Resiliency	2-yr Peak Flow (cfs)	187	168	427	472	586	633	USGS (2018)
	2-yr Peak Water Level (ft, NAVD88)	216	212.1	205.85	186.1	N/A	N/A	Note 2
Fish Protection	Q > 1 cfsm	8.6	6.9	23.4	26.2	34.5	37.8	USFWS (1999)
	Q < 4 cfsm	34.3	27.7	93.6	104.8	138	151.2	USFWS (1999)
	Q < 4 cfsm (drawdown)	34.3	27.7	93.6	104.8	138	151.2	MA DEP / MA DCR (2004)
Vegetation Control	Q > 0.5 cfsm (refill)	4.3	3.5	11.7	13.1	17.25	18.9	MA DEP / MA DCR (2004)
	Max. Drawdown (ft)	3	3	5	3	3	3	MA DEP / MA DCR (2004), Note 3
	Max. Daily Drawdown (in/day)	3	3	3	3	3	3	MA DEP / MA DCR (2004)
Recreation	Min. Water Level (ft, NAVD88)	214	208.96	202.5	180.36	N/A	N/A	Note 4

Notes:

1. Highlighted values represent break points for simplified "low", "normal", and "high" streamflow and water level ranges.
2. 2-year peak water level was approximated by inputting 2-year peak flow into a simplified weir equation for each applicable impoundment, solving for head (i.e., depth) over the weir, then converting to elevation. The weir equation is as follows: $Q = C_s b H^{1.5}$ (Lindeburg, 2012); Q is streamflow over the weir (cfs), C_s is a spillway coefficient which was approximated as 3.3 $ft^{0.5}$/sec, b is the width of the weir (ft), and H is the depth of water over the weir (ft). For Spectacle Pond, this evaluation was performed assuming an initial configuration of three (3) stop logs (typical summer configuration, El. 209.71'). All other impoundments were evaluated using the spillway as a basis to convert head over the weir to an elevation.
3. Forge Pond drawdown threshold based on previously permitted values where drawdown was permitted for 1.5 meters (4.9 feet) and 2.0 meters (6.5 feet) on alternating years.
4. Minimum Water Level values were determined as follows:
    a. Mill Pond: Verbal communication with C. Godfrey of LWD on 4/2/2018. Elevation of 214 ft., NAVD88 = 1-ft below the spillway.
    b. Spectacle Pond: Verbal communication with L. Weaver of SPA on 3/15/2018. Elevation of 208.96 ft., NAVD88 corresponds to approximate two (2) stop log configuration.
    c. Forge Pond: Verbal comm. with FOFP at 3/28/2018 project kickoff meeting. Elevation of 202.5 ft., NAVD88 = 1.2 ft below spillway.
5. Stony Brook Dam: Verbal comm. with M. Warren of WWD on 4/5/2018. Elevation of 180.36 ft., NAVD88 = 2-ft below spillway.

2.3. Operational Strategy Development

Once evaluation indicators were developed, it was determined that three (3) potential operational strategies would be evaluated:

1. *Streamflow Enhancement:* Hold water during high flow periods for later release during low flow periods.
2. *Winter Drawdown:* Release water to accommodate winter drawdown (Forge and Spectacle Pond only).
3. *Spring Refill:* Hold water to accommodate spring refill (Forge and Spectacle Pond only).

Note: *Flood control was initially a fourth potential evaluation strategy (i.e., perform controlled release of stored water prior to forecasted precipitation event.); however, this strategy has been omitted from the SRP since the overall focus of this study is to improve streamflow.*

Potential operational adjustments were discussed during the stakeholder meeting as summarized below:

- *Mill Pond Dam*: Evaluate adjustments to existing sluice gate. Mill Pond is significantly impacted by sedimentation and the existing sluice gate is completely buried. The Town of Littleton and the Army Corps of Engineers are currently conducting a dredging feasibility study. Operational adjustments assume that the sluice gate is fully operational and that the pond and sluice gate are not impacted by sedimentation.
- *Spectacle Pond Outlet*: Evaluate implementation of control valve or sluice gate. Given the rapid rate at which the pond level decreases when a single concrete stop log is removed, it was determined at the stakeholder meeting that this would be the best option to evaluate potential low flow releases which require the ability to perform fine adjustments.
- *Forge Pond Dam*: Evaluate adjustments to existing sluice gates and stop logs at secondary overflow structure.
- *Stony Brook*: Evaluate adjustments to existing sluice gates. Note that it is unclear if WWD can currently operate this structure. Model simulations assumes that operation is feasible.
- *Depot Dam*: No adjustments proposed, no control mechanisms in place.
- *Brookside Mills Dam*: No adjustments proposed, no control mechanisms in place.

The overall goal of the operational adjustments is to make proposed adjustments simple and at a reasonable frequency. For example, one modification per month. Proposed adjustments will require approval from owners and stakeholders prior to implementation.

3. Model Development

Once operational strategies, project goals, and evaluation criteria were developed, a regional hydrologic and hydraulic (H&H) model of the 38-square mile study area was developed. The hydrologic basis of the model included development of subcatchments on a regional scale for all major inputs to the study area impoundments – for example, Bennet's Brook forms a subcatchment draining to Spectacle Pond. Cross-sectional information including culvert and channel geometry were developed for the mainstem of the Stony Brook watershed between each of the study impoundments. Refer to **Figure 3.1** for a depiction of components comprising the regional model, including delineated subcatchments and modeled reaches.

The regional H&H model was developed using the United States Environmental Protection Agency's (US EPA) Stormwater Management Model (SWMM), version 5.1. SWMM is a dynamic rainfall-runoff simulation model used for single event or long-term (continuous) simulation of runoff quantity. The runoff component of SWMM operates on a collection of subcatchment areas that receive precipitation and generate runoff. The routing component of SWMM transports this runoff through a system of pipes, channels, storage units, weirs, and other features. SWMM tracks the quantity of runoff generated within each subcatchment, and the corresponding flow rate and flow depth in each pipe and channel during a simulation period comprised of user selected time steps (USEPA, 2015). SWMM was primarily chosen for use in this study for its ability to run continuous multi-year simulations and to implement operational logic and rules.

Refer to **Appendix B** for supporting information used to develop model inputs.

3.1. Hydrologic Inputs

Precipitation

Historical precipitation records from nearby USGS atmospheric monitoring stations were input into the model as summarized by **Table 3.1**. While much closer, the Groton station only has an available period of record of approximately 6 months. Therefore, precipitation records were used from the Groton station for various simulations where feasible and supplemented with records from the Barre station.

Table 3.1: Precipitation Station Attributes

Station ID	Location	Proximity to Study Area	Period of Record	Logging Interval
USGS 423701071344800	Groton, MA	Appx. 5 miles	11/6/2017 through 5/2/2018	15 minutes
USGS 422328072035300	Barre, MA	Appx. 40 miles	10/1/2014 through 5/2/2018	15 minutes

Evaporation

Under natural conditions, a fraction of surface water may circulate back to the atmosphere via evaporation. Lacking regional empirically-based estimates, a handful of generalized models of varying complexity are available to simulate these processes. The Brutsaert model (Brutsaert, 1982), a simple empirical model that calculates a daily evaporation rate, was used for this analysis:

Where, E = evaporation (m/day)
Va = wind speed (m/s)
Es = vapor pressure of evaporating surface (kPa)
Ea = vapor pressure of overlying air (kPa)

Data for wind speed and vapor pressure were obtained from the National Oceanic and Atmospheric Administration's (NOAA) Global Surface Summary of the Day (GSOD) dataset for Manchester, New Hampshire (Station Number: 743945)

and input into the above equation to obtain daily estimates of evaporation. These estimates were then input into model storage units (i.e., impoundments) as a time series. The average calculated evaporation for 2016 and 2017 was 0.015 inches per day with a maximum of 0.45 inches per day (summer) and a minimum of 0.00 inches per day (winter).

Subcatchments

Each regional subcatchment was delineated based on the USGS StreamStats application. StreamStats determines drainage-basin boundaries by use of digital elevation data obtained from the USGS 3D Elevation Program (3DEP). Elevation data are processed within StreamStats so that the elevation data conforms to the digital stream channels depicted in the high-resolution version of the National Hydrography Dataset (NHD) and to the drainage-basin boundaries of the Watershed Boundary Dataset (WBD) (USGS, 2018).

Initial subcatchment delineations were then reviewed based on existing available Geographic Information Systems (GIS) information from the Massachusetts Bureau of Geographic Information (MassGIS) including: 2012 Light Detection and Ranging (LiDAR) terrain data with 1 m horizontal resolution and 15 cm vertical resolution for the Merrimack Watershed, aerial orthophotography, the 2017 state-wide MA DEP wetlands layer, and the 2017 state-wide MA DEP hydrography layer.

The Stony Brook Watershed was divided into 15 subwatersheds ranging in size from approximately 800 to 4,000 acres (See **Table B-1** for inputs). Relevant physical subcatchment input parameters used for this study are as follows:

- *Area*: The area of each subcatchment was calculated from the USGS StreamStats delineations.
- *Width*: According to the SWMM 5.1 Manual, the width of the watershed is the physical width of overland flow. The width can be approximated by dividing the area of the subcatchment by the maximum length of overland flow, which was approximated based on the site topography as shown in the GIS coverages.
- *Slope*: The subcatchment slope should reflect the average slope along the pathway of overland flow to the inlet location (USEPA, 2015). The slope for each subcatchment was calculated using Spatial Analysis, an extension of ArcGIS. The average slope algorithm assigns each cell within the subcatchment a maximum rate of change relative to its neighbors. The value of each cell is then averaged across the subcatchment to calculate an average percent slope.
- *Percent Impervious Area*: Impervious area was calculated for the existing conditions of each subcatchment by summing impervious areas calculated from the 2005 MassGIS impervious surface layer.
- *Manning's n for overland flow*: Manning's n values were assigned for overland flow for pervious and impervious areas based on the SWMM 5.1 Manual, Table A.6 (USEPA, 2015). Impervious areas were assigned a value of n= 0.13 (default). An area weighted approach was then performed for pervious areas based on the 2005 MassGIS land use layer by assigning a value of n = 0.6 to forested area and a value of n = 0.24 to all other pervious areas (representative of dense grass). Resulting n values for pervious areas ranged from 0.44 to 0.59 which is indicative of the forested nature of many subcatchments within the study area which can result in flow attenuation and smooth (prolonged) runoff hydrographs.

Infiltration

Infiltration was then estimated for each subcatchment based on the SCS Curve Number method. The SCS Runoff Curve Number method was developed by the United States Department of Agriculture (USDA) Soil Conservation Service (SCS) and is a method of estimating the resultant runoff from rainfall. EPA SWMM 5.1 performs these calculations with two input parameters:

- *Curve Number (CN)*: Area weighted CNs were calculated for the pervious areas of each subcatchment. The individual areas of each land use, Hydrologic soil group (HSG) combination were calculated for each subcatchment using the 2005 MassGIS land use layer, and the Web Soils Survey (USDA, 1993). There were a total of 80 land use/HSG combinations for the pervious areas of each subcatchments. Each land use/HSG

combination was assigned a CN based on TR-55 (USDA 1986). Once these data were obtained, weighted CNs were calculated with the following equation:

Where =area of land use/HSG combination divided by subcatchment total area and = Curve Number of the land use/HSG combination. The resulting weighted curve numbers for the pervious areas of each of the subcatchments generally ranged from 60 to 70. See **Table B-1** for tabulated CNs for each subcatchment.

- *Drying Time*: Drying time is the time for a fully saturated soil to completely dry. Drying time was initially set to the SWMM default of 7 days.

Baseflow

USGS StreamStats was used to calculate and input a constant baseflow (i.e., median August streamflow) at each study impoundment. Baseflow computations are listed by **Table 3.2**. A net baseflow was input into each impoundment rather than a total baseflow to maintain the integrity of the mass balance. For example, Spectacle Pond and Mill Pond drain to Forge Pond; since the total estimated baseflow at Forge Pond is 7.5 cfs, the contributions from Mill Pond and Spectacle Pond are subtracted to arrive at a net contribution of 2.7 cfs at Forge Pond.

Table 3.2: Impoundment Baseflow Inputs

Impoundment	Net Baseflow (cfs)	Total Baseflow (cfs)
Mill Pond	2.5	2.5
Spectacle Pond	2.3	2.3
Forge Pond	2.7	7.5
Stony Brook Dam	0.7	8.2
Depot Dam	2.6	10.8
Brookside Mills Dam	0.9	11.7

3.2. Hydraulic Inputs

In addition to hydrologic modeling capabilities, SWMM contains a component for hydraulic modeling, used to route runoff and other inflows through the drainage system network. The model translates the runoff generated from each subcatchment into flow directed to a junction in the drainage system network. For this project, junctions represent nodes on the conveyance system (i.e., culvert/channel inlets and outlets, and outfalls). The junctions are connected by links (i.e., weirs), conduits, (i.e., culverts, channels), or storage units (i.e., ponds).

Hydraulic inputs for this study were primarily developed based on available data from the effective FEMA FIS study for this study as referenced in **Table 1.1** of this report. These data were supplemented by additional available studies such as diagnostic feasibility studies to develop stage-storage curves, GIS data (i.e., LiDAR), and limited field observations. Given that the FEMA FIS study was performed in 1982, culvert data is potentially outdated. To supplement and verify this data, WWD and LWD performed field reconnaissance in April 2018 of select culverts throughout the study area. Culvert assessments entailed a visual inspection to verify culvert shape, dimensions, and other characteristics (e.g., material).

Junctions

For this model, junctions were used to represent the confluence of natural surface water channels and pipe connections (i.e., culverts). Relevant junction input parameters used for this project are as follows:

- *Invert Elevation*: The invert elevation for each junction was determined from FEMA FIS Data. If FEMA FIS data was not available for a given junction, LiDAR data were used in combination with field observations from WWD and LWD, or the invert was interpolated based on nearby locations.

- *Ponded Area*: Ponded area is the area occupied by ponded water atop the junction (node) in the event of flooding. During simulations, ponded water is stored and subsequently returned to the conveyance system when capacity is regained. Flooding was not simulated in any junctions during model runs; therefore, the default ponded area of zero (0) was input for all junctions.

Conduits

Conduits are linear features, such as culverts or channels that convey water from one junction to another in the drainage system network. SWMM uses the Manning equation to express the relationship between flow rate, cross-sectional area, hydraulic radius, and slope in open channels and partially full closed conduits (USEPA, 2015). Relevant conduit input parameters used for this project are as follows:

- *Cross-sectional Geometry Shape*: Cross-sectional geometry was primarily obtained from the FEMA FIS study data for conveyance channels and culverts. Culvert geometry varied widely throughout the study area, but typically included circular culverts, box culverts, and arched culverts. FEMA FIS cross-sections for the natural channel sections were entered into the SWMM model as transects. Transects refer to the geometric data that describe how bottom elevation varies with horizontal distance over the cross section of a natural channel or irregular-shaped conduit. SWMM internally converts these data into tables of area, top width, and hydraulic radius versus channel depth (USEPA, 2015).

  Based on review of FEMA FIS data, cross sections and culverts along Beaver Brook (between Forge Pond and Mill Pond) appeared to be mislabeled. Channel transects at these locations were therefore approximated based on MassGIS LiDAR data at representative locations while culvert data were input based on aforementioned WWD and LWD culvert assessments. Finally, some culverts and bridge crossings with limited supporting data were omitted from the model that did not appear to be constricting flow (i.e., based on significant cross-sectional areas). WWD and LWD collected data on all culverts that did appear to have the potential to cause restrictions and influence model results. Similarly, FEMA FIS data were unavailable for the Gilson Brook channel (between Spectacle Pond and Forge Pond); therefore, channel geometry was approximated based on MassGIS LiDAR data.

- *Conduit Length*: The SWMM model was geospatially referenced to a GIS base map which was used to calculate the length of each conduit in plan view.

- *Conduit Depth*: The depth of each conduit was entered as the diameter of the conduit as obtained from FEMA FIS data or supplemental field observations. Depth is internally calculated by SWMM for transects.

- *Manning's Roughness*: A Manning's roughness coefficient was assigned to each conduit based on FEMA FIS data.

- *Entrance and Exit Losses*: Entrance (0.5) and exit (1.0) pipe loss coefficients were assigned to each culvert for sharp-edged pipe entrances/exits (Munson, 1994).

See **Table B-6** and **B-7** for specific inputs.

Storage Units

Storage units are drainage system nodes that provide storage volume. Physically they represent storage facilities as small as a catch basin or as large as a lake. The volumetric properties of a storage unit are described by a function or table of surface area versus height (i.e., stage-storage curve). The principal input parameters for storage units include: (1) invert elevation, (2) maximum depth, (3) initial depth, (4) stage-area relationship.

Storage unit characteristics were obtained from a variety of sources for each impoundment as described below.

- *Mill Pond*: Stage-storage relationship obtained from a diagnostic feasibility study (ESS Group, 1999). This relationship only included information up to the spillway of the pond (El. 215 ft NAVD88); therefore, MassGIS LiDAR data were used to calculate additional storage up to 217 ft NAVD88. As previously discussed in **Section**

1.6, Mill Pond is currently significantly impacted by sedimentation; however, the model does not account for sedimentation. Note that this will not have a significant impact on model results since model simulations will only draw down Mill Pond by one (1) foot below the spillway, which mimics potential sedimentation limitations.

- *Spectacle Pond*: Stage-storage relationship obtained from a diagnostic feasibility study (ESS Group, 2000). This relationship only included information up to the approximate normal surface water elevation of the pond (El. 208.3 ft NAVD88 as referenced by MassGIS LiDAR data); therefore, MassGIS LiDAR data were used to calculate additional storage, up to 212.36 ft NAVD88).
- *Forge Pond*: Stage-storage relationship obtained from existing data collected by Friends of Forge Pond (FOFP, 2016) and compiled by Geosyntec Consultants (2017). This information only included information up to the approximate spillway crest elevation (El. 203.68 ft NAVD88); however, the channels leading into Forge Pond from Spectacle Pond (Gilson Brook) and Mill Pond (Beaver Brook) account for the additional floodplain storage above the spillway. Therefore, additional LiDAR computations were not required.
- *Forge Pond Canal*: The small canal downstream of the Forge Pond sluice gates was modeled as a storage unit based on dimensions from engineering plans (Baystate Environmental Consultants, 1991).
- *Stony Brook*: Stage-storage relationship obtained from a vegetation monitoring report (ESS Group, 2015). Information from this report was supplemented by calculating the available storage up to the spillway elevation (El. 182.36 ft NAVD88) based on MassGIS LiDAR data. Additional storage above the spillway is accounted for in the floodplain of the Stony Brook channel entering the reservoir.
- *Depot Dam and Commodore Foods Dam:* Stage-storage data was not calculated for Depot Dam or Brookside Mills Dam as these locations no longer significantly impound water. These areas were instead modeled as natural channels using FEMA FIS data.

See **Tables A.1** through **A.5** for input values.

Flow Control Structures

Like conduits, flow control structures (i.e., weirs and orifices) are configured in the model to convey water from storage units to downstream junctions. Refer to **Tables 1.3 through 1.8** for a detailed description, dimensions, and elevations of flow control structures included in the model. The features were input into SWMM as follows:

- *Spillways and Stop Log Structures*: Transverse weir with default discharge coefficient of 3.33.
- *Sluice Gates*: Side orifice with default discharge coefficient of 0.65.

Dynamic Routing

Flow routing within a conduit link in SWMM is governed by the conservation of mass and momentum equations for gradually varied, unsteady flow. The three routing options are: (i) Steady Flow Routing, (ii) Kinematic Wave Routing, and (iii) Dynamic Wave Routing. For this project, Dynamic Wave Routing was chosen as the routing methodology. Dynamic Wave Routing solves the complete one-dimensional Saint Venant flow equations and therefore produces the most theoretically accurate results. These equations consist of continuity and momentum in conduits and volume continuity at nodes. With this form of routing, it is also possible to represent pressurized flow (i.e., when a closed conduit becomes full) in which the actual flow in the conduit can exceed the full-flow Manning's equation value.

In addition to pressurized flow, Dynamic Wave Routing can account for channel storage, backwater effects, entrance/exit losses, and flow reversal. Because it combines the solution for water levels in nodes and flows in conduits, it can be applied to any general network layout (USEPA, 2015).

3.3. Calibration

Data Used for Calibration

As previously discussed, Geosyntec Consultants and LWD previously installed monitoring stations at Forge Pond and Spectacle Pond during the DAM Dashboard Pilot Project. The monitoring stations were installed on the week ending August 25, 2017 and are configured to continuously record water level at a 5-minute interval. These water level measurements are then converted into estimates of downstream streamflow and transmitted to a live web-based dashboard (Geosyntec Consultants, 2017).

Calibration Workflow

Once inputs to the existing conditions model were developed, the following workflow was performed to perform rough calibration of the model:

- *Calibration Period:* The secondary outlet control structure was releasing water at Forge Pond from approximately August 30, 2017 through September 13, 2017, potentially because of vandalism or other unknown reason (personal communication with members of FOFP). The release settings during the release were not documented (i.e., penstock pipe, number of stop logs, sluice configuration); therefore, model calibration was initiated after this release. The selected calibration period was 10/1/2017 through 5/1/2018.
- *Calibration Locations and Parameters:* Impoundment water level (i.e., elevation) of Forge Pond and Spectacle Pond was evaluated during the calibration period. As previously discussed, downstream streamflow from the DAM Dashboard Pilot Project was estimated from measured water levels and was not field verified during a stream gauging program. Therefore, discharge was not included as a calibration parameter given uncertainty and the potential to compound errors during the calibration process (i.e., estimated monitoring station discharge error versus estimated model error).
- *Logic Setup*: To initiate the calibration process, model logic was configured to match operations of the outlet control structure at Forge Pond and Spectacle Pond during the calibration period. For Spectacle Pond, this entailed setting the weir opening elevation from three (3) stop logs to one (1) stop log on 10/18/2017, setting the weir opening elevation from one (1) stop log to two (2) stop logs on 1/4/2018, and setting the weir elevation opening from two (2) stop logs to three (3) stop logs on 4/17/2018. These settings were based on documented modifications obtained from Weaver (2018) and observations from the continuous DAM Dashboard data. Since drawdown was not performed at Forge Pond, the sluice gate was left closed all winter and no further operational logic was required.
- *Subcatchment Calibration*: Subcatchment parameters were iteratively modified to obtain the most reasonable runoff results during the simulation period. Although many parameters were tested, the subcatchment "Width" parameter had the greatest impact on model results. Watershed width was decreased by approximately half for all subcatchments which generally resulted in smoother hydrograph peaks and slower response rates.
- *Channel Roughness Calibration*: Next, attenuation of transects was tested. As previously discussed, manning's "n" values were initially obtained for all model transects (i.e., natural stream channel sections) from the FEMA FIS study (FEMA, 2012). After review, the overbank (i.e., the portion of the transect outside of the main low flow conveyance channel) value for manning's "n" was changed to 0.2 (US EPA, 2015) for all channels to increase roughness and simulate additional attenuation of flows associated with heavily vegetated wetland banks. This additional attenuation is important given the role that the floodplains play in the study area. The Forge Pond floodplain extends most of the way to Mill Pond and Spectacle Pond while the Stony Brook Dam floodplain extends most of the way Abbott Mill. Therefore, these systems have an enormous storage capacity and associated attenuation. See **Figures 3.2a-d** for a depiction of floodplain storage associated with each impoundment.
- *Channel / Culvert Conveyance Calibration*: Once transect attenuation was addressed, a review of hydraulic conveyances was performed. It was determined that the FEMA FIS transect for the Abbott Mill channel (downstream

of Forge Pond) was overly complex. This transect was simplified based on field observations performed during the DAM Dashboard Pilot Project (Geosyntec, 2017) into a rectangular stone channel with a 25-ft width and 8-ft height.

In addition, it was observed that the culvert located downstream of the Stony Brook Dam was surcharging and causing simulated backup into the Stony Brook Dam during a large storm event in October 2017. The culvert was originally modeled as 4.3-foot-tall culvert with a 32-foot width based on FEMA FIS data (FEMA, 2012). While the culvert may be undersized, the extreme simulated backup appeared to be unrealistic (i.e., the entire surrounding area would have been flooded and there was no anecdotal evidence of this occurrence during the calibration period). Based on review of available photographs at the road crossing courtesy of Google Street View, the bridge appeared to have been reconstructed since information was originally collected for the FEMA FIS study in 1982. Based on review of the photographs, the bridge deck was raised significantly above the water surface elevation and did not visibly appear to be a significant constriction. Therefore, the geometry of the modeled culvert was increased from a height of 4.3 feet to 8 feet to more closely mimic current conditions.

- *Spillway Conveyance Calibration*: Impoundment drawdown rates were evaluated and spillway characteristics were adjusted accordingly. Specifically, it appeared that the 40-ft wide spillway at Forge Pond was causing more rapid drawdown of the pond than what the observed DAM Dashboard water level data suggested. While 40-ft wide in plan view, the spillway is comprised of many segmented sections which likely result in greater head loss and less overall flow capacity and width than a continuous spillway. In addition, there is a sand berm in the outlet channel of Forge Pond that may be limiting drawdown rates and capacity of Forge Pond. Evaluation of potential drawdown restrictions at Forge Pond is outside the scope of this study, but is being addressed in a concurrent study with FOFP. The spillway width at Forge Pond was therefore reduced to a 20-ft width to better match observed water level drawdown rates.

  Similarly, the horseshoe shaped Mill Pond spillway with an overall length of 60-ft appeared to be causing exceptionally rapid drawdown. Based on field observations performed in April 2018 and May 2018, discharge from the spillway did not appear to be uniformly consistent throughout the entire length of the spillway (i.e., it appeared that there were variations in elevation potentially caused by obstructions causing lower head at some sections of the spillway). To address the rapid, potentially unrealistic observed drawdown, the discharge coefficient was first decreased to account for the ogee style spillway from 3.33 (SWMM Default) to 2.63 (Lindeburg, 2012). Next, the overall weir length was reduced to 30-feet to account for the observed irregularities in head across the length of the spillway and to account for additional overall attenuation from slower drawdown.

  Note: It is not typical to modify physical parameters of structures such as spillway length when calibrating a hydrologic and hydraulic model. These assumptions were therefore re-visited at the end of the model evaluation process (See **Section 4**) to assess if they had a notable overall impact on results and study findings. When evaluating results with the full length (unmodified) physical spillways, results indicate that overall peak water levels decreased at Mill Pond, while peak discharge values increased. However, the frequency and duration of low flow releases remained unchanged. Since the focus of model evaluations for this study is on low flow, particularly making low flow releases when impoundment water level is below the spillway, these observations indicate that comparison of relative results amongst model scenarios remains unchanged. **Section 6** provides recommendations for potential future work, including additional calibration of the model from additional streamflow monitoring data currently being collected, as well as empirical validation through stream gauging and testing of operational strategies.

- *Downstream Discharge Testing*: Finally, downstream discharge values at all impoundments were checked with criteria developed in **Section 2.2** (**Table 2.4**) to confirm that model results were generally in line with these estimated values.

Calibration Results

Calibration results for Forge Pond and Spectacle Pond are depicted by **Figure 3.3** and **Figure 3.4**.

- *Spectacle Pond:* On average, the difference between modeled and observed data for Spectacle Pond is 2.4 inches (i.e., modeled depth is typically greater than observed depth) with an average absolute difference of 3 inches. For

Spectacle Pond, modeled inflow into the pond is typically more responsive to precipitation than observed data suggests, potentially from extensive beaver activity upstream of the pond; however, this effect is mitigated by the generally slow drawdown times. For example, the model peaks approximately 1.6 feet higher than observed data on 10/27/2017 after a significant storm, then generally follows the observed drawdown trend of the pond, closely matching observed data through December 2017.

- *Forge Pond:* On average, the difference between modeled and observed data for Forge Pond is -1.2 inches (i.e., modeled depth is typically less than observed depth) with an average absolute difference of 4.3 inches (i.e., modeled depth is typically more than observed depth). This apparent contradiction is because the model is consistently overpredicting in October through November, closely matching observed data through December, then consistently underpredicting in the winter of 2018. Like Spectacle Pond, the model overpredicts the significant storm that occurred on 10/27/2017 then generally follows the observed drawdown trend of the pond, closely matching observed data through December 2017. The model then diverges in January through April and consistently under-predicts observed data by an average of 4.4 inches during these months.

These results were evaluated using the Integral Square Error (ISE), a commonly used quantitative evaluation metric which integrates the square of the error over time. ISE penalizes large errors more than smaller ones since the square of a large error is much larger. The ISE for both calibration locations (i.e., Forge Pond and Spectacle Pond) was evaluated to be zero (0) which is indicative that the regional watershed model at the Forge Pond and Spectacle Pond calibration points is suitable for planning level purposes (Shamsi and Koran, 2017).

While suitable for planning level purposes, caution should be exercised when interpreting and acting on model results beyond this coarse planning level. Results are indicative that the model is unable to fully capture the significant assimilative capacity of the Stony Brook Watershed, particularly during wetter months when significant flows are continuously generated long after precipitation. Additional effort beyond the scope of this study would be required to further improve the model by performing additional field assessments and modeling of upstream reaches, with emphasis on wetland complexes and pockets of standing water (e.g., beaver dams, small natural upstream impoundments, etc.). Additional calibration points at new monitoring stations (Mill Pond and Stony Brook – see **Section 5**) and a longer record length would also provide added confidence in the model.

4. Model Evaluation

4.1. Scenario Development

Once calibration was complete, iterative model scenarios were developed to test proposed operational strategies. A two-year simulation period from 1/1/2016 through 12/31/2017 was selected to represent a drought year (2016) and a typical year (2017). For reference, the USGS Barre Rain Gauge summarized by **Table 3.1** recorded precipitation of just 31 inches in 2016 compared to 48 inches in 2017. Average annual precipitation in the Merrimack River Basin from 1971 through 2000 was 44.2 inches (NRCC, 2018).

Baseline Conditions Scenario

To enable comparison of results across multiple scenarios, a baseline scenario was first developed for the simulation period. The baseline scenario included representative annual winter drawdown and spring refill logic for Forge Pond and Spectacle Pond as summarized by **Table 4.1**. The logic is sequenced such that drawdown and refill at Spectacle Pond is performed before Forge Pond to avoid potential conflicts. Refer to **Figure 4.1** for an example timeseries of Spectacle Pond depth illustrating baseline conditions logic.

Table 4.1: Baseline Conditions Logic Summary

Description:	Representative of a typical year with standard drawdown and refill logic for Forge and Spectacle Ponds.
Simulation Period:	2016 – 2017
Streamflow Enhancement Logic: *(Hold water during high flow periods for later release during low flow periods.)*	None.
Winter Drawdown Logic: *(Release water to accommodate winter drawdown)*	▪ Spectacle Pond: Keep one (1) stop log in outlet control structure from 10/15 through 2/28 ▪ Forge Pond[1]: Open sluice gates by 12-in., allow flow through penstock pipe underneath Abbott Mill, and remove all but two (2), 12in. tall stop logs from secondary overflow structure from 11/1 through 11/30 (top elevation = 201.5ft NAVD88) – Leave sluice gates and stop logs in place until 3/14, disallow flow through penstock pipe underneath Abbott Mill on 11/30.
Spring Refill Logic: *(Hold water to accommodate spring refill)*	▪ Spectacle Pond: Keep three (3) stop logs in outlet control structure from 3/1 through 10/14 ▪ Forge Pond: Close sluice gates and place all stop logs into secondary overflow structure, 3/15 through 10/31

1. The Forge Pond secondary overflow structure is configured with multiple stop logs. The first stop log is a 12-inch-tall perforated stop log with weep holes. For the purposes of model simulations, it was assumed that this stop log was solid.

Proposed Conditions Scenario (Iteration 1) – Basic Controls

The first proposed conditions iteration focused on streamflow enhancement by configuring various control structures of applicable impoundments to release water when downstream streamflow approaches ABF. An iterative exercise was performed to determine the optimal opening setting for each control structure to maintain ABF during release as summarized below:

- *Spectacle Pond*: Fully opened 12-inch diameter orifice installed at the invert of the existing outlet control weir structure.
- *Mill Pond*: Open the existing sluice gate by approximately 4 inches.
- *Forge Pond*: Open the three (3) existing sluice gates by approximately 12 inches and remove all but three (3) stop logs from the secondary overflow structure. The model assumes that the first stop log with the weep holes is replaced with a solid stop log. Therefore, the stop log configuration is two (2), 12 inch stop logs and one (1), 18 inch stop log with a top elevation of 202.5 ft.
- *Stony Brook Dam*: Open one (1) existing sluice gate by approximately 4 inches. Since Depot Dam and Brookside Mills Dam cannot be controlled, it is important to set the Stony Brook sluice gate such that it passes the required ABF for the channels downstream of Depot Dam and Brookside Mills Dam.

Logic was then configured to halt releases once each impoundment's minimum water level was reached as summarized by **Table 2.4**. Refer to **Table 4.2** for a summary of logic for this scenario. Refer to **Figure 4.2** for an example timeseries of Spectacle Pond depth illustrating proposed conditions logic for this iteration.

Table 4.2: Basic (Iteration 1) Controls Logic Summary

Description:	Includes standard drawdown and refill logic that is representative of a typical year for Forge and Spectacle Ponds. Also includes basic control logic to release water, as feasible, in times of low downstream flow.
Simulation Period:	2016 – 2017
Streamflow Enhancement Logic: *(Hold water during high flow periods for later release during low flow periods.)*	The following rules are effective from 4/1 through 10/31: ▪ Mill Pond: Open sluice gate 4-in if downstream flow < 4.3 cfs (ABF) and Mill Pond Water Level ≤ 214.5 ft; close sluice gate if Mill Pond Water Level ≤ 214 ft ▪ Spectacle Pond: Open 12-inch orifice if downstream flow < 3.5 cfs (ABF) and Spectacle Pond Water Level ≤ 209.5 ft; Close 12-inch orifice if Spectacle Pond Water Level ≤ 208.96 ft ▪ Forge Pond: Open three (3) sluice gates 12-in and remove all but three (3) stop logs (top elevation = 202.5 ft); if downstream flow < 11.7 cfs (ABF) and Forge Pond Water Level ≤ 203.0 ft; close sluice gate and replace stop logs if Forge Pond Water Level ≤ 202.5 ft ▪ Stony Brook: Open one (1) sluice gate 4-in if downstream flow < 13.1 cfs (ABF) and Stony Brook Water Level ≤ 181.4 ft; close sluice gate if Stony Brook Water Level ≤ 180.36 ft
Winter Drawdown Logic: *(Release water to accommodate winter drawdown)*	Same as baseline condition.
Spring Refill Logic: *(Hold water to accommodate spring refill)*	Same as baseline condition.

Proposed Conditions Scenario (Iteration 2) – Forecast Based Controls

The next iteration adds an additional condition to make low flow streamflow enhancements contingent on the precipitation forecast. Low flow releases were configured to be initiated if there is less than 0.10 inch of precipitation in the 7-day forecast. The purpose of this rule is to limit the amount of required adjustments to each impoundment. Refer to **Table 4.3** for a summary of logic for this scenario. Refer to **Figure 4.3** for an example timeseries of Spectacle Pond depth illustrating proposed conditions logic for this iteration.

Table 4.3: Forecast Based (Iteration 2) Controls Logic Summary

Description:	Includes standard drawdown and refill logic that is representative of a typical year for Forge and Spectacle Ponds. Also includes basic control logic to release water as feasible in times of low downstream flow if there is less than 0.10-inches of precipitation in the 7-day forecast.
Simulation Period:	2016 – 2017
Streamflow Enhancement Logic: *(Hold water during high flow periods for later release during low flow periods.)*	The following rules are effective from 4/1 through 10/31: ▪ Forecast: If there is < 0.10-in of rain in the 7-day forecast, then implement the below rules. ▪ Mill Pond: Same as Iteration 1. ▪ Spectacle Pond: Same as Iteration 1. ▪ Forge Pond: Same as Iteration 1. ▪ Stony Brook Impoundment: Same as Iteration 1.
Winter Drawdown Logic: *(Release water to accommodate winter drawdown)*	Same as baseline condition.
Spring Refill Logic: *(Hold water to accommodate spring refill)*	Same as baseline condition.

Proposed Conditions Scenario (Iteration 3) – Forecast Based Sequenced Controls (Recommended)

The final iteration is the recommended scenario and was configured to improve upon the first two iterations by testing various forecasting thresholds and experimenting with sequenced releases. The following improvements are included in this scenario: 1) increased the 7-day forecast threshold from 0.10-inches to 0.25-inches to trigger low flow releases based on a more notable precipitation event; and 2) changed sequencing such that Stony Brook will only release water if Forge Pond is releasing water. This adjustment decreases the simulated drawdown rate of the Stony Brook impoundment when low flow releases are performed. Refer to **Table 4.4** for a summary of logic for this scenario. Refer to **Figure 4.4** for an example timeseries of Spectacle Pond depth illustrating proposed conditions logic for this iteration

Table 4.4: Forecast Based Sequenced (Iteration 3) Controls Logic Summary (Recommended)

Description:	Includes standard drawdown and refill logic that is representative of a typical year for Forge and Spectacle Ponds. Also includes basic control logic to release water, as feasible, in times of low downstream flow if there is less than 0.25-inches of precipitation in the 7-day forecast. Finally, includes sequencing to only initiate a release at Stony Brook Impoundment if Forge Pond is actively releasing.
Simulation Period:	2016 – 2017
Streamflow Enhancement Logic: *(Hold water during high flow periods for later release during low flow periods.)*	The following rules are effective from 4/1 through 10/31: ▪ Forecast: If there is < 0.25" of rain in the 7-day forecast, then implement the below rules. ▪ Mill Pond: Same as Iteration 1. ▪ Spectacle Pond: Same as Iteration 1. ▪ Forge Pond: Same as Iteration 1. ▪ Stony Brook: Open one (1) sluice gate 4" if downstream flow < 13.1 cfs (ABF) and if Forge Pond is actively releasing; close sluice gate if Stony Brook Water Level ≤ 180.36'.
Winter Drawdown Logic: *(Release water to accommodate winter drawdown)*	Same as baseline condition.
Spring Refill Logic: *(Hold water to accommodate spring refill)*	Same as baseline condition.

4.2. Results

Once scenarios were configured and simulated, results were tabulated into a series of exceedance curves for streamflow and impoundment depth for each location. Exceedance curves indicate the percentage of time that a certain threshold is exceeded and allow for direct comparison and evaluation of changes that occur between the baseline simulation and subsequent simulations (i.e., simulation iterations 1, 2, and 3).

- **Table 4.5** and **Table 4.6** summarize the percent of time that streamflow and impoundment water level are in the "normal" range for each model iteration, respectively.
- **Table 4.7** summarizes the number and duration of simulated low flow releases in 2016 and 2017.
- **Figure 4.4** and **Figure 4.5** provide a visual summary of streamflow exceedance results for 2016 (drought year) and 2017 (typical year) along the full range of exceedance (i.e., "low", "normal", "high") for each model iteration, respectively.
- **Figures 4.7** through **Figure 4.12** include compiled streamflow exceedance curves (i.e., flow duration curves) for each impoundment in 2016 and 2017.
- **Figure 4.13** through **Figure 4.16** include compiled depth exceedance curves for each applicable impoundment for 2016 and 2017.
- Finally, **Appendix C** provides timeseries plots for all model iterations of each impoundment's depth (elevation), downstream streamflow, and discharge from control structures as applicable (e.g., sluice gates, stop logs).

4.3. Discussion

As discussed in more detail below, it is recommended that Iteration 3 be implemented for future testing. Iteration 3 provides significant streamflow improvements at all impoundments, provides stable impoundment water levels between the maximum allowable release level and spillway, and limits the overall number of required releases by incorporating forecast into the logic to initiate releases.

The below sections provide detailed discussion of each iteration as it relates to downstream streamflow, management of impoundment water levels, low flow releases, and seasonal drawdown and refill activities.

Downstream Streamflow

Improvements in downstream streamflow relative to baseline conditions were simulated at all impoundments for Iterations 1, 2 and 3 (**Table 4.5**). Iteration 1 (basic controls) provided the largest simulated downstream streamflow improvements relative to the baseline scenario, with simulated improvements ranging from 5% at Stony Book Dam in 2017 (typical year) to 25% at the Spectacle Pond Outlet in 2016 (drought year). Iterations 2 and 3, which incorporate forecast logic, provided slightly less improvement to simulated streamflow.

As would be expected, improvements were more dramatic in 2016 (drought year) than in 2017 (typical year). For example, the expected improvement in "normal" downstream streamflow at Mill Pond Dam relative to baseline conditions for Iteration 3 was simulated to be 18% in 2016 as compared to 9% in 2017 (**Table 4.5**). Based on model simulations, all impoundments are susceptible to drought conditions as evidence by the simulated frequency that streamflow was below ABF in 2016; Mill Pond Dam (62%), Spectacle Pond Outlet (52%), Forge Pond Dam (46%), Stony Brook Dam (44%), Depot Dam (50%) and Brookside Mills Dam (53%) (**Figure 4.5**).

Table 4.5: Summary of Simulated Streamflow Exceedance Results

Year	Impoundment	Percent of Time Simulated Downstream Streamflow is "Normal"				Percent Improvement from Baseline		
		Baseline	Iteration 1	Iteration 2	Iteration 3 (Recommended)	Iteration 1	Iteration 2	Iteration 3 (Recommended)
2016	Mill Pond Dam	37%	60%	54%	55%	23%	17%	18%
	Spectacle Pond Outlet	48%	73%	63%	71%	25%	15%	23%
	Forge Pond Dam	54%	62%	60%	63%	8%	6%	9%
	Stony Brook Dam	56%	76%	68%	74%	20%	12%	18%
	Depot Dam	50%	70%	59%	59%	20%	9%	9%
	Brookside Mills Dam	47%	67%	53%	53%	20%	6%	6%
2017	Mill Pond Dam	64%	74%	67%	73%	10%	3%	9%
	Spectacle Pond Outlet	61%	75%	65%	69%	14%	4%	8%
	Forge Pond Dam	75%	83%	78%	82%	8%	3%	7%
	Stony Brook Dam	72%	77%	76%	74%	5%	4%	2%
	Depot Dam	74%	80%	78%	78%	6%	4%	4%
	Brookside Mills Dam	77%	84%	80%	83%	7%	3%	6%

Simulated streamflow improvements are typically more pronounced at headwater locations (e.g., Spectacle Pond Outlet and Mill Pond Dam) than at Forge Pond Dam which is indicative of Forge Pond Dam's slower response time, presumably from excess storage associated with previously discussed extensive upstream wetland areas. Surprisingly, simulated streamflow improvements at Stony Brook Dam were higher than Forge Pond Dam during 2016 drought conditions (e.g., 18% improvement for Iteration 3). This improvement may be caused by Forge Pond Dam continuously releasing in 2016 which supplements Stony Brook Impoundment (See "*Low Flow Releases*" for further discussion).

While improvements in overall ABF were simulated downstream of all impoundments, the exceedance curves (**Figures**

4.7 through 4.12) indicate that low flow releases may result in a higher frequency of extremely low streamflow (i.e., ranging from 1 to 10 cfs), particularly during periods of drought (e.g., 2016). This phenomenon is likely a result of times of no or extremely low flow when the impoundment is frequently refilling after reaching the maximum allowable release level (i.e., the minimum water level trigger upstream of the impoundment). For example, these periods of low flow propagate from Stony Brook Dam downstream at Depot Dam and Brookside Dam (**Figure 4.11** and **Figure 4.12**) and are indicative that streamflow at these locations is sensitive to the Stony Brook Impoundment. This phenomenon was not observed at Forge Pond or in any of the impoundments during the 2017 simulation year.

It was also surprising to note that all impoundments are expected to frequently experience streamflow below ABF, even during a typical year (i.e., 2017). Baseline simulations of streamflow below ABF in 2017 ranged from 36% at Spectacle Pond Outlet to 18% at Brookside Mills Dam. These results corroborate the vulnerability of this interconnected system to prolonged dry periods. Conversely, **Figure 4.5** and **Figure 4.6** illustrate that streamflow in excess of the 4 cfsm threshold is exceeded infrequently at all impoundments. Mill Pond is the most susceptible to elevated streamflows and exceeded 4 cfsm approximately 10% of the time during the 2017 typical year.

Impoundment Water Level

For all model simulations and for all impoundments, the impoundment water level never fell below the minimum depth (i.e., maximum allowable release level / critical recreation level) (**Table 4.6**). Thus, impoundment water level is effectively managed between the spillway and maximum allowable release level for all simulated model runs. However, differences were noted amongst scenarios in the overall management of impoundment water levels as evidenced by the percentage of time that simulated water level was below the spillway.

Table 4.6: Summary of Impoundment Water Level Exceedance Results

Year	Impoundment	Percent of Time Simulated Impoundment Water Level is "Normal"[1]
2016	Mill Pond Dam	100%
	Spectacle Pond Outlet	100%
	Forge Pond Dam	100%
	Stony Brook Dam	100%
2017	Mill Pond Dam	93%
	Spectacle Pond Outlet	99%
	Forge Pond Dam	99%
	Stony Brook Dam	100%

Notes:
1. Results summarized for 4/1 to 10/31 except for Spectacle Pond Outlet which are from 4/1 to 10/15 (when drawdown begins)
2. Results are the same for all iterations.
3. Maximum allowable release level was exceeded 100% of the time for all simulations.
4. Percent of time that simulated water level exceeded 2-year peak storm level can be calculated as 100% minus "normal" – e.g., Mill Pond Dam baseline results = 1% exceedance.

Iteration 1 typically results in the lowest impoundment water levels (**Table 4.7)**, presumably because it is simulated to be releasing the most and therefore resulting in the greatest simulated streamflow improvements. Iterations 2 and 3 resulted in higher impoundment water levels relative to the spillway, presumably due to implementation of forecasting logic and less frequent releases. Iteration 2 results in the highest impoundment levels relative to the spillway because the forecast threshold is so low (i.e., only release if there is less than 0.10 inches of precipitation in the 7-day forecast). This observation is visually evident when reviewing comparisons in water level amongst model scenarios for each impoundment provided in **Appendix C** (e.g., for Mill Pond, **Figure C.2** vs. **Figure C.3**) or individual water level exceedance

curves (**Figures 4.13** through **4.16**).

Low flow releases are frequently required at all impoundments to maintain downstream ABF which results in simulated water levels below the spillway. For Iteration 1, the water level of Mill Pond was below the spillway 91% of the time in 2016 (drought year) as compared to 33% of the time in 2017 (typical year). By incorporating forecasting into the simulations (i.e., Iteration 1 and 2), water level stability is dramatically improved. For Iteration 3, the water level was below the spillway 67% of the time in 2016 and just 23% of the time in 2017 (**Table 4.7**, **Figure 4.13**). These results are echoed for Spectacle Pond and the Stony Brook Impoundment and are indicative that inclusion of forecast based logic is important to effectively manage impoundment water levels and reduce the overall number of adjustments required at each impoundment (see "*Low Flow Releases*" for further discussion). The response of Forge Pond to releases is more muted than its upstream and downstream counterparts; however, similar behavior was simulated where releases were more frequent in the drought year, resulting in water levels slightly below the spillway approximately 30% of the time (**Table 4.7**, **Figure 4.15**). Based on these observations, it is apparent that all impoundments are susceptible to drought conditions.

Table 4.7: Impoundment Water Level Relative to Spillway

Year	Impoundment	Percent of Time Simulated Impoundment Water Level is Below the Spillway[1]			
		Baseline	Iteration 1	Iteration 2	Iteration 3 (Recommended)
2016	Mill Pond Dam	0%	91%	55%	67%
	Spectacle Pond Outlet	0%	82%	42%	82%
	Forge Pond Dam	0%	32%	17%	26%
	Stony Brook Dam	0%	71%	12%	16%
2017	Mill Pond Dam	0%	33%	7%	23%
	Spectacle Pond Outlet	0%	35%	6%	16%
	Forge Pond Dam	0%	0%	0%	0%
	Stony Brook Dam	0%	0%	6%	0%

Notes:
1. Water level results summarized for 4/1 to 10/31.

Conversely, results from **Table 4.6** indicate that water level infrequently approaches potential flood levels associated with 2-year peak discharge. Spectacle Pond and Forge Pond reach the 2-year peak water level approximately 1% of the time in 2017 (attributed to a large series of storms in late October 2017), while Mill Pond exceeds the 2-year peak water level approximately 7% of the time. Mill Pond does not have any known evidence of flooding based on stakeholder interviews (**Section 1.5**). It is possible that the model is overestimating peak inflows into Mill Pond and not accounting for potential upstream attenuation. The newly installed streamflow monitoring network (discussed by **Section 5** of this report) may be used to validate these results in a future phase of work.

Low Flow Releases

The number and duration of simulated low flow releases varies widely based on impoundment and model iteration (**Table 4.8**). Because releases were made solely based on current water level and downstream streamflow, Iteration 1 generally resulted in the most number of releases which occurred for the greatest amount of time of all model scenarios. With the inclusion of forecasting, Iteration 2 generally resulted in the least number of releases for the least amount of time of all model scenarios. Iteration 3 resulted in slightly more releases as a result of increasing the 7-day forecasting release threshold from 0.10 to 0.25 inches.

As evidenced by **Table 4.8**, releases generally occur frequently for shorter durations at Mill Pond Dam and Stony Brook Dam and infrequently for longer durations at Forge Pond Dam and Spectacle Pond. Forge Pond Dam and Spectacle Pond Outlet typically release for a month or greater, while Mill Pond Dam and Stony Brook Dam typically release for one week to a month, or greater (see **Appendix C** Figures). Thus, all impoundments spend a significant amount of time releasing,

particularly in the 2016 drought year. For example, all impoundments were simulated to be releasing at least 67% of the time between 4/1/2016 and 10/31/2016 for Iteration 1.

Table 4.8: Low Flow Release Summary

Year	Impoundment	Number of Releases[1]			Percent of Time Releasing[1]		
		Iteration 1	Iteration 2	Iteration 3 (Recommended)	Iteration 1	Iteration 2	Iteration 3 (Recommended)
2016	Mill Pond Dam	11	5	8	75%	52%	51%
	Spectacle Pond Outlet	4	2	4	79%	39%	77%
	Forge Pond Dam	1	1	1	88%	51%	62%
	Stony Brook Dam	16	2	5	67%	10%	11%
2017	Mill Pond Dam	2	1	2	94%	15%	31%
	Spectacle Pond Outlet	1	1	1	85%	8%	25%
	Forge Pond Dam	1	0	0	94%	15%	31%
	Stony Brook Dam	0	1	0	0%	14%	0%

Notes:
1. Results summarized for 4/1 to 10/31, when simulated low releases occur.

Releases are so lengthy because the water level is typically below the spillway once the release begins. Logic is then configured to maintain baseflow and only halt the release if the maximum release threshold is reached. Therefore, if a significant storm arrives when an active release is occurring, it will supplement the impoundment water level, potentially above the spillway, and enable continuation of the release. Thus, Forge Pond Dam and Spectacle Pond Outlet can maintain a continuous balance between inflow and outflow due to slower drawdown times and therefore take a longer time to reach the maximum release level than Mill Pond Dam and Stony Brook Outlet.

Inclusion of forecasting logic has a significant positive impact on the number and duration of low flow releases at each impoundment. For example, Stony Brook Dam was simulated to require 16 releases for Iteration 1, five (5) releases for Iteration 3, and just two (2) releases for Iteration 2 in 2016. Results for Iteration 3 indicate that releases may be required during drought conditions ranging from one (1) adjustment at Forge Pond Outlet to eight (8) adjustments at Mill Pond Dam. Conversely, results for Iteration 3 in 2017 indicate that releases may be required during typical conditions ranging from no adjustments at the Forge Pond Outlet to two (2) adjustments at the Mill Pond Dam. Therefore, it is reasonable to assume that on any given year, adjustments may realistically be required on a monthly to bi-monthly (i.e., every two months) basis at the various impoundments. Results are also indicative that automation could be beneficial at locations to maximize responsiveness of adjustments and to allow for more frequent adjustments which could result in improved downstream streamflow.

It should also be noted that model simulations are sensitive to modification of various inputs including release opening (e.g., fraction that a sluice gate is opened) and evaporation. For example, removing evaporative processes from the model results in significantly less low flow releases for Iteration 3 in 2016 – Mill Pond Dam (three compared to eight), Spectacle Pond Outlet (two compared to four), Forge Pond (unchanged), and Stony Brook Dam (four compared to five). Similarly, slight modifications to low flow release openings (which were previously optimized to enable passage of ABF, see **Section 4**) can have significant impacts on simulated results. For example, decreasing the sluice gate opening at Stony Brook Dam from 4-inches to 3-inches and increasing the sluice gate opening at Mill Pond Dam from 3-inches to 4-inches results in significantly slower drawdown times such that both impoundments are only simulated to require one (1) prolonged release in the 2016 drought year (**See Figure 4.17a and 4.17b** for a depiction of results at the Stony Brook Impoundment). Therefore, it is possible that fewer modifications will be required in practice than those simulated by the model depending on empirical testing and the level of precision that can reasonably be achieved in practice.

Drawdown and Refill Operations

Based on simulation results, it does not appear that seasonal drawdown and refill at Forge Pond and Spectacle Pond have a notable impact on simulated summer streamflow. The maximum simulated drawdown release from Forge Pond's secondary outlet stop log structure during baseline and subsequent model simulations was approximately 45 cfs (well below the 4 cfsm threshold of 93.6 cfs presented by **Table 2.4**) (**Figures B.10** through **B.12**). Similarly, the maximum simulated drawdown release from Spectacle Pond's stop log structure during baseline and subsequent model simulations was approximately 40 cfs (**Figures B.6** through **B.8**). This value is above the 4 cfsm threshold of 27.7 cfs presented by **Table 2.4**; however, representative logic implemented by model simulations assumes that all stop logs are removed at once. In reality, just one stop log is removed at a time, resulting in lower flow.

As indicated in **Section 3** of this report, model logic is sequenced such that drawdown and refill at Spectacle Pond is performed before Forge Pond to avoid potential conflicts. Based on model simulations, if drawdown commences on 10/15 at Spectacle Pond, winter drawdown levels are reasonably achieved within less than 1 week. Therefore, drawdown can commence at Forge Pond with little to no impact of inflows from Spectacle Pond. Similarly, by commencing refill at Spectacle Pond in early March and commencing refill at Forge Pond in mid-March, both impoundments are simulated to achieve typical summer conditions by early April.

Future ongoing work will provide a more in-depth evaluation of drawdown and refill capacity of Forge Pond with a focus on potential siltation of the outlet channel which may be limiting overall drawdown capacity.

4.4. Limitations

- This model is deterministic – this means that the results are based on two years of data, but rainfall can come in varying sizes and sequences in the future. The purpose of these model results is to gauge potential relative performance of low flow releases. The results do not consider other possible precipitation sequences.
- The "forecast" in this model is the actual historical precipitation record, not a forecast of anticipated precipitation. Actual wet weather performance will deviate from the values provided due to the fluctuations in forecast reliability and accuracy.
- Because of the assumptions embedded in the model, the results described herein are meant to provide an estimation of relative performance between model scenarios (i.e., baseline vs. proposed conditions iterations)
- The model was developed on a regional scale using the best available information with limited field activities to verify data. The model does not account for all potential features within the Stony Brook watershed (i.e., beaver dams, sedimentation, culverts, upstream channel characteristics, etc.).
- Findings are intended to be used to help improve understanding and management of surface impoundments within the Stony Brook watershed at the planning level. Findings are not intended to be used for engineering design or other related analysis.

5. Monitoring and Decision Support

5.1. Streamflow Monitoring Stations

Two (2) continuous streamflow monitoring stations were installed at the outlets of Spectacle Pond and Forge Pond in August 2017 (See **Figure 1.1** for locations). Data from these stations were used to perform coarse calibration of the existing conditions model (See **Section 3**) and inform operational release scenarios developed as part of this SRP (See **Section 4**).

As part of this study, the existing streamflow monitoring network was expanded through installation of two (2) additional streamflow monitoring stations. Prior to installation, an evaluation was performed to select the best locations for installation of these additional monitoring stations. It was determined that the most suitable locations were Mill Pond Dam and Stony Brook Dam (See **Figure 5.1** for locations). These locations were primarily selected because they can both be potentially controlled for low flow releases and have suitable locations for installation of monitoring equipment; both locations have abundant sunlight, have locations where monitoring equipment can physically be mounted and easily maintained, and have relatively "still" water to enable effective measurement of water level and subsequent conversion into estimates of discharge.

Each streamflow monitoring station is comprised of a solar powered monitoring probe with water level and temperature functions and cellular telemetry. Refer to **Appendix D** for data collection plans developed for each monitoring station outlining instrumentation configuration and operation and maintenance requirements.

5.2. Decision Support Dashboard

All data from the streamflow monitoring stations is continuously streamed to an online dashboard with a two-minute logging interval. The online dashboard is accessible to all Project Stakeholders via secure, user-specific login at www.opti.com. The online dashboard includes the following data streams:

- Real-Time Data Streams
  - Measured Water Level (Upstream of Impoundment)
  - Measured Water Temperature (Upstream of Impoundment)
  - Calculated Outflow (Based on Rating Curve and Stage-Discharge Curve)
  - Existing Impoundment Storage Capacity (Based on Stage-Storage Curve)
  - Precipitation from USGS Groton Rain Gauge
- Forecasts, Predictions, and Alerts
  - National Weather Service and DarkSky Precipitation Forecasts
  - Predicted Impoundment Inflow (Based on modified rational method)
  - Email-based alerts and suggested management actions (see "Decision Support Alerts" below)

Data streams were developed based on input data and simulations results from the regional H&H model (**Section 3**). Measured water levels were related to elevation based on reference values provided by **Table 1.3** and **Table 1.6**. Stage-discharge curves were developed based on model simulations while stage-storage curves were developed from model input data presented by **Appendix B**. Refer to **Appendix E** for the tables used to develop the dashboard data streams.

5.3. Decision Support Alerts

Recommended operational strategies for applicable impoundments were developed and evaluated based on Iteration 3 of the modeling results, and stakeholder input (see **Section 4**). These recommended strategies were incorporated into the dashboard infrastructure as part of an alert system. Alerts were then configured to be sent to stakeholders on an elective basis to inform interested parties on recommended actions based on the data collected by the dashboard. Available alerts are summarized by **Table 5.1** through **Table 5.4** for each applicable impoundment.

Table 5.1: Summary of Recommended Alerts for Mill Pond

Alert	Alert Description	Variable(s)	Condition(s)	Alert Text
1	System Offline	Connection Status, Status	Status = Offline	**System Offline!** The Mill Pond monitoring station is offline. This may be a result of poor internet connection or discharged battery. Troubleshooting may be required to regain connectivity.
2	Low Battery	Battery Voltage, V	V < 12 V	**Low Battery!** Mill Pond battery voltage is currently **VALUE** V. The monitoring station may go offline when battery voltage approaches 11.5 V.
3	Approaching Critical Low Flow	Downstream Streamflow, Q	Q ≤ 5.1 cfs Q > 4.3 cfs	**Low Flow!** The measured streamflow downstream of Mill Pond Dam is approximately **VALUE** cfs and is approaching **4.3 cfs** (Aquatic Baseflow).
4	Start Release, Critical Low Flow Reached	▪ 7-Day Precipitation Forecast, P ▪ Downstream Streamflow, Q ▪ Upstream Water Level, L	▪ P ≤ 0.25-in ▪ Q ≤ 4.3 cfs ▪ L ≥ 214.5 ft	**Low Flow, Initiate Release!** There is minimal rain in the forecast and the measured streamflow downstream of Mill Pond Dam is less than **4.3 cfs** (Aquatic Baseflow). Measured water level in the Mill Pond impoundment is **VALUE** ft and appears to be adequate to support a low flow release. It is recommended that the sluice gate be opened approximately **4 inches** to supplement downstream streamflow.
5	Approaching Critical Low Water Level	Upstream Water Level, L	L ≤ 214.25 ft L > 214 ft	**Low Water Level!** The measured water level of Mill Pond is approximately **VALUE** ft and is approaching the critical low level of **214 ft** (i.e., one foot below the spillway). If a low flow release is currently occurring, plan to mobilize in near future to halt the release.
6	Stop Release, Critical Low Level Reached	Upstream Water level, L	L ≤ 214 ft	**Low Water Level, Halt Release!** The measured water level of Mill Pond is approximately **VALUE** ft and is below the critical low level of 214 ft. If a low flow release is currently occurring, mobilize immediately to halt the release.
7	2-year Streamflow	Downstream Streamflow, Q	Q ≥ 187 cfs	**High Flow!** The measured streamflow downstream of Mill Pond Dam is approximately **VALUE** cfs. This is greater than the approximate 2-year peak discharge (**187 cfs**) and is indicative of potential flooding conditions.
8	2-year Water Level	Upstream Water Level, L	L ≥ 216.10 ft	**High Water Level!** The measured water level of the Mill Pond Impoundment is approximately **VALUE** ft. This is greater than the approximate level associated with 2-year peak discharge (**216.10** ft) and is indicative of potential flooding conditions.

Notes:
1. All conditions must be effective for at least 12 continuous hours before an alert is sent.
2. Alerts will be sent once every 24 hours when condition thresholds are met.
3. Alert 3 threshold computed as 0.6*cfsm.
4. Alert 4 forecast based on at least 20% probability of precipitation.

Table 5.2: Summary of Recommended Alerts for Spectacle Pond

Alert	Alert Description	Variable(s)	Condition(s)	Alert Text
1	System Offline	Connection Status, Status	Status = Offline	**System Offline!** The Spectacle Pond monitoring station is offline. This may be a result of poor internet connection or discharged battery. Troubleshooting may be required to regain connectivity.
2	Low Battery	Battery Voltage, V	V < 12 V	**Low Battery!** Spectacle Pond battery voltage is currently **VALUE** V. The monitoring station may go offline when battery voltage approaches 11.5 V.
3	Approaching Critical Low Flow	Downstream Streamflow, Q	Q ≤ 4.2 cfs Q > 3.5 cfs	**Low Flow!** The measured streamflow downstream of Spectacle Pond is approximately **VALUE** cfs and is approaching **3.5 cfs** (Aquatic Baseflow).
4	Start Release, Critical Low Flow Reached	▪ 7-Day Precipitation Forecast, P ▪ Downstream Streamflow, Q ▪ Upstream Water Level, L	▪ P ≤ 0.25 in ▪ Q ≤ 3.5 cfs ▪ L ≥ 209.5 ft	**Low Flow, Initiate Release!** There is minimal rain in the forecast and the measured streamflow downstream of Spectacle Pond is less than **3.5 cfs** (Aquatic Baseflow). Measured water level in Spectacle Pond is **VALUE** ft and appears to be adequate to support a low flow release. It is recommended that the gate valve be fully opened by approximately **12 inches** to supplement downstream streamflow.
5	Approaching Critical Low Water Level	Upstream Water Level, L	L ≤ 209.25 ft L > 209 ft	**Low Water Level!** The measured water level of Spectacle Pond is approximately **VALUE** ft and is approaching the critical low level of **209 ft** (i.e., top elevation of approximately two stop logs). If a low flow release is currently occurring, plan to mobilize in near future to halt the release.
6	Stop Release, Critical Low Level Reached	Upstream Water level, L	L ≤ 209 ft	**Low Water Level, Halt Release!** The measured water level of Spectacle Pond is approximately **VALUE** ft and is below the critical low level of **209 ft**. If a low flow release is currently occurring, mobilize immediately to halt the release.
7	2-year Streamflow	Downstream Streamflow, Q	Q ≥ 168 cfs	**High Flow!** The measured streamflow downstream of Spectacle Pond is approximately **VALUE** cfs. This is greater than the approximate 2-year peak discharge (**168 cfs**) and is indicative of potential flooding conditions.
8	2-year Water Level	Upstream Water Level, L	L ≥ 212.10 ft	**High Water Level!** The measured water level of Spectacle Pond is approximately **VALUE** ft. This is greater than the approximate level associated with 2-year peak discharge (**212.10** ft) and is indicative of potential flooding conditions.

Notes:

1. All conditions must be effective for at least 12 continuous hours before an alert is sent
2. Alerts will be sent once every 24 hours when condition thresholds are met.
3. Alert 3 threshold computed as 0.6*cfsm.
4. Alert 4 forecast based on at least 20% probability of precipitation.

Table 5.3: Summary of Recommended Alerts for Forge Pond

Alert	Alert Description	Variable(s)	Condition(s)	Alert Text
1	System Offline	Connection Status, Status	Status = Offline	**System Offline!** The Forge Pond monitoring station is offline. This may be a result of poor internet connection or discharged battery. Troubleshooting may be required to regain connectivity.
2	Low Battery	Battery Voltage, V	V < 12 V	**Low Battery!** Forge Pond battery voltage is currently **VALUE** V. The monitoring station may go offline when battery voltage approaches 11.5 V.
3	Approaching Critical Low Flow	Downstream Streamflow, Q	Q ≤ 14.0 cfs Q > 12.0 cfs	**Low Flow!** The measured streamflow downstream of Forge Pond is approximately **VALUE** cfs and is approaching **14.0 cfs** (Aquatic Baseflow).
4	Start Release, Critical Low Flow Reached	▪ 7-Day Precipitation Forecast, P ▪ Downstream Streamflow, Q ▪ Upstream Water Level, L	▪ P ≤ 0.25 in ▪ Q ≤ 14.0 cfs ▪ L ≥ 203.0 ft	**Low Flow, Initiate Release!** There is minimal rain in the forecast and the measured streamflow downstream of Forge Pond is less than **12.0 cfs** (Aquatic Baseflow). Measured water level in Forge Pond is **VALUE** ft and appears to be adequate to support a low flow release. It is recommended that the three (3) sluice gates be opened by 12" and all but three (3) stop logs (top elevation = 202.5') be removed from the secondary outlet control structure to supplement downstream streamflow.
5	Approaching Critical Low Water Level	Upstream Water Level, L	L ≤ 202.75 ft L > 202.5 ft	**Low Water Level!** The measured water level of Forge Pond is approximately **VALUE** ft and is approaching the critical low level of **202.5 ft** (i.e., approximately 1.2 ft below the spillway). If a low flow release is currently occurring, plan to mobilize in near future to halt the release.
6	Stop Release, Critical Low Level Reached	Upstream Water level, L	L ≤ 202.5 ft	**Low Water Level, Halt Release!** The measured water level of Forge Pond is approximately **VALUE** ft and is below the critical low level of **202.5 ft**. If a low flow release is currently occurring, mobilize immediately to halt the release.
7	2-year Streamflow	Downstream Streamflow, Q	Q ≥ 427 cfs	**High Flow!** The measured streamflow downstream of Forge Pond is approximately **VALUE** cfs. This is greater than the approximate 2-year peak discharge (**427 cfs**) and is indicative of potential flooding conditions.
8	2-year Water Level	Upstream Water Level, L	L ≥ 204.98 ft	**High Water Level!** The measured water level of Forge Pond is approximately **VALUE** ft. This is greater than the approximate level associated with 2-year peak discharge (**204.98** ft) and is indicative of potential flooding conditions.

Notes:

1. All conditions must be effective for at least 12 continuous hours before an alert is sent.
2. Alerts will be sent once every 24 hours when condition thresholds are met.
3. Alert 3 threshold computed as 0.6*cfsm.
4. Alert 4 forecast based on at least 20% probability of precipitation.

Table 5.4: Summary of Recommended Alerts for Stony Brook Impoundment

Alert	Alert Description	Variable(s)	Condition(s)	Alert Text
1	System Offline	Connection Status, Status	Status = Offline	**System Offline!** The Stony Brook Impoundment monitoring station is offline. This may be a result of poor internet connection or discharged battery. Troubleshooting may be required to regain connectivity.
2	Low Battery	Battery Voltage, V	V < 12 V	**Low Battery!** Stony Brook Impoundment battery voltage is currently **VALUE** V. The monitoring station may go offline when battery voltage approaches 11.5 V.
3	Approaching Critical Low Flow	Downstream Streamflow, Q	Q ≤ 15.7 cfs Q > 13.1 cfs	**Low Flow!** The measured streamflow downstream of the Stony Brook Impoundment is approximately **VALUE** cfs and is approaching **13.1 cfs** (Aquatic Baseflow).
4	Start Release, Critical Low Flow Reached	▪ 7-Day Precipitation Forecast, P ▪ Downstream Streamflow, Q ▪ Upstream Water Level, L	▪ P ≤ 0.25" in ▪ Q ≤ 13.1 cfs ▪ L ≥ 181.4 ft	**Low Flow, Initiate Release!** There is minimal rain in the forecast and the measured streamflow downstream of the Stony Brook Impoundment is less than **13.1 cfs** (Aquatic Baseflow). Measured water level in the Stony Brook Impoundment is **VALUE** ft and appears to be adequate to support a low flow release. It is recommended that the sluice gate be opened approximately **4 inches** to supplement downstream streamflow.
5	Approaching Critical Low Water Level	Upstream Water Level, L	L ≤ 180.75 ft L > 180.36 ft	**Low Water Level!** The measured water level of the Stony Brook Impoundment is approximately **VALUE** ft and is approaching the critical low level of **180.36 ft** (i.e., two feet below the spillway). If a low flow release is currently occurring, plan to mobilize in near future to halt the release.
6	Stop Release, Critical Low Level Reached	Upstream Water level, L	L ≤ 180.36 ft	**Low Water Level, Halt Release!** The measured water level of the Stony Brook Impoundment is approximately **VALUE** ft and is below the critical low level of **180.36 ft**. If a low flow release is currently occurring, mobilize immediately to halt the release.
7	2-year Streamflow	Downstream Streamflow, Q	Q ≥ 472 cfs	**High Flow!** The measured streamflow downstream of the Stony Brook Impoundment is approximately **VALUE** cfs. This is greater than the approximate 2-year peak discharge (**472 cfs**) and is indicative of potential flooding conditions.
8	2-year Water Level	Upstream Water Level, L	L ≥ 183.56 ft	**High Water Level!** The measured water level of the Stony Brook Impoundment is approximately **VALUE** ft. This is greater than the approximate level associated with 2-year peak discharge (**183.56** ft) and is indicative of potential flooding conditions.

Notes:

1. All conditions must be effective for at least 12 continuous hours before an alert is sent.
2. Alerts will be sent once every 24 hours when condition thresholds are met.
3. Alert 3 threshold computed as 0.6*cfsm.
4. Alert 4 forecast based on at least 20% probability of precipitation.

6. Takeaways and Recommendations

6.1. Analysis Takeaways

The following provides a summary of primary takeaways from the data analysis and discussion presented in **Section 4** of this report.

- Model results indicate that implementation of low flow releases have great potential to improve downstream streamflow throughout the study area while balancing competing goals (e.g., maintaining adequate upstream impoundment water levels).
- It is recommended that Iteration 3 be implemented for future empirical testing. Iteration 3 provides significant streamflow improvements relative to baseline conditions, provides stable impoundment water levels, and limits the overall number of required low flow releases. Iteration 3 provides a compromise between Iteration 1 (largest streamflow improvements) and Iteration 2 (highest impoundment water levels and least amount of required low flow releases).
- Simulated streamflow improvements were typically more pronounced at headwater locations (e.g., Spectacle Pond Outlet and Mill Pond Dam) and were typically more dramatic in 2016 (drought year) than in 2017 (typical year). Results indicate that all impoundments (and their downstream channels) are susceptible to low downstream streamflow resulting from prolonged dry periods.
- Impoundment water level was effectively managed relative to the defined critical minimum water level for all simulated model runs and at all impoundments. Implementation of low flow releases increases the frequency that simulated impoundment water levels are below the spillway which could potentially have an impact on recreation, aesthetics, or other factors. Simulation results also indicate a higher frequency of extremely low streamflow (i.e., ranging from 1 to 10 cfs) due to times when the impoundment is refilling after reaching the minimum water level trigger upstream of the impoundment (or the maximum allowable release level). Empirical testing is required to test assumptions, to confirm that critical minimum water levels were properly defined, and to investigate potential strategies to mitigate critically low downstream flows.
- The number and duration of simulated low flow releases varied widely based on the impoundment and model iteration. With the inclusion of forecast based logic (Iterations 2 and 3), the number and duration of simulated releases is greatly reduced. Results indicate that it is reasonable to assume that on any given year, adjustments for low flow releases may realistically be required on a monthly to bi-monthly (i.e., every two months) basis at the various impoundments. Results are also indicative that automation could be beneficial at locations to maximize responsiveness of low flow release adjustments and to allow for more frequent adjustments which could result in improved downstream streamflow.
- Model simulations are sensitive to modification of various inputs such as the release opening (e.g., fraction that a sluice gate is opened) and indicate that empirical evaluations will be beneficial to test and validate results.

6.2. Recommendations

Based on analysis of model results, it is recommended that Iteration 3 logic be implemented as feasible at each study impoundment. As previously discussed, dashboard alerts will be configured to support Iteration 3 logic. Alerts will be custom configured to be sent to Project Stakeholders based on individual preferences. To implement Iteration 3, the following steps are recommended (as feasible):

- **Model Validation, Additional Calibration, and Baseline Sampling**
  - Perform streamflow gaging downstream of study impoundment monitoring stations (i.e., Mill Pond Dam, Spectacle Pond Outlet, Forge Pond Dam, Stony Brook Dam) under a range of streamflow

conditions to evaluate and validate modeled discharge rates and the underlying stage-discharge relationships.

- Perform additional calibration and validation of the regional surface water model by including data collected at the new Mill Pond Dam and Stony Brook Dam monitoring locations.
- Evaluate data and alerts from the data decision support dashboard to determine if baseline model predictions are reasonable – e.g., frequency of various alerts such as low flow conditions.
- Biota sampling is a critical component to understand if low flow releases are having a positive impact. Baseline and post-release implementation biota sampling is recommended at downstream channels of all study impoundments to track success of recommendations. Sampling is recommended to specifically focus on fish but can be expanded to include additional parameters of interest. Based on review of records, fish sampling was previously performed between Depot Dam and Brookside Mills Dams in 2006 and 2015 by Massachusetts Department of Fish and Wildlife (MDFW), but not on other segments of Stony Brook or the Gilson Brook and Beaver Brook tributaries within the study area.

- **Low Flow Release Feasibility Evaluation**

  - Evaluate if installation of a low flow orifice at the Spectacle Pond Outlet is feasible. Model simulations indicate that a 12-inch diameter orifice installed at the invert of the existing outlet control weir structure will potentially provide an adequate opening to allow passage of ABF without drawing down Spectacle Pond too rapidly. The secondary western weir structure could be modified by replacing the lower two (2) stop logs with metal sheeting or poured concrete, boring a hole, and installing a hand operated full port sluice gate. There are many potential options such as the inexpensive Valterra Gate Valve offered by www.agridrain.com. Permitting for installation of a low flow orifice would be required under the Massachusetts Wetlands Protection Act (WPA), although no direct wetland impacts are anticipated because this project would be a retrofit of the existing outlet structure. Depending on the type of structural modification selected and the proposed construction methods, WPA permitting could potentially be achieved either through submittal of a Request for Determination of Applicability (RDA) or a Notice of Intent (NOI) to the Littleton Conservation Commission. A pre-permitting meeting with the Conservation Commission is recommended to reach agreement on the preferred permitting application. Authorization for a Chapter 91 Minor Project Modification per 310 CMR 9.22 (3)(a) will also be required. This authorization requires written notice to MA DEP describing the proposed work in sufficient detail, with reference to any relevant Chapter 91 license plans, for the Department to determine compliance with the conditions of 310 CMR 9.22 (3)(a). If the Department does not object within 30 days, the project may proceed without any further approval required from MA DEP.
  - The sluice gate at the Mill Pond Dam is currently severely impacted by sediment and inoperable. It is likely that Mill Pond will not be dredged for at least another three (3) to five (5) years (or longer). As an interim step, evaluate if installation of a low flow orifice at the outlet control structure (above the sediment depth) is feasible. Based on field measurements taken on April 4, 2018, there is approximately three (3) feet of freeboard at the outlet control structure below the spillway not impacted by sedimentation. Like Spectacle Pond, installation would require boring through the concrete outlet control structure and approval from MA DOT. WPA and Chapter 91 permitting required for a low flow orifice would be as discussed above for the Spectacle Pond outlet.
  - It is unclear if the existing sluice gate at Stony Brook Impoundment is operable. Visually inspect the spillway during extreme low streamflow conditions (i.e., when water is not spilling over the spillway)

when the sluice gate is exposed. Investigate if the sluice gate is in adequate condition for safe operation and perform a test to see if it is operational.

- **Empirical Testing and Implementation**
  - Prior to empirical testing, an application will be required for each impoundment where low flow releases are made with the Massachusetts Office of Dam Safety (MA ODS). Specifically, any person(s), who proposes to construct, repair, materially alter, breach or remove a dam, pursuant to M.G.L. Chapter 253, as amended by Chapter 330 of the Acts of 2002, must file with the Commissioner a notice for jurisdictional determination and/or file for a permit (if applicable). Further, any maintenance work or water level change(s) that affect safety conditions must file for a determination (MA ODS, 2018).
  - If and when low flow controls at particular impoundments become operable, implement the recommended streamflow restoration tasks outlined by the decision support dashboard (i.e., model Iteration 3). Relative to modeled conditions, evaluate the effectiveness of release openings, duration, and the resulting impacts to upstream impoundment water level and downstream streamflow. (Note that the Forge Pond Dam is currently fully operable and recommendations can be implemented per this SRP upon approval by Abbot Mill Dam ownership).
  - It is expected that empirical testing and modifications will likely be required to fine-tune operation given previously discussed model sensitivity. For example, the Spectacle Pond outlet may be most effective when opened by 10 inches rather than 12 inches.
  - In addition, empirical testing may be required to set thresholds such that critical low flows are not reached when impoundments are refilling after reaching their maximum allowable release level. Testing might include additional considerations such as inserting perforated stop logs or continuing to allow flow passage through decreased orifice openings until rainfall induced inflow adequately increases impoundment levels. An alternate strategy would be to never allow the impoundment to stop releasing, but to systematically decrease the opening size and corresponding release rate as a function of decreasing impoundment water level and precipitation forecasts. The decision support dashboard and alerting system is configured to enable flexible and adaptable testing of potential alternative strategies such as this.
  - Additional assumptions can also be tested such as maximum allowable release levels. Empirical testing can be performed to validate these levels (and to determine if they need to be stricter or if they can be relaxed). For example, the maximum allowable release at Mill Pond Dam was set to just one (1) foot below the spillway. It is likely that significant additional benefits could be realized if the maximum allowable release level was decreased to two (2) feet depending on aesthetics and potential exposure of pond sediments.
  - Based on testing results, the SRP can be modified and adjusted to best meet empirical conditions – i.e, release openings, release thresholds, forecast thresholds, control rules, sequencing order, etc.
- **Automated Controls**
  - Modeling results suggest that automation could result in improved overall streamflow performance. Automation would make response time instantaneous and would take the burden from various stakeholders and managers of each impoundment. It is recommended that an evaluation be performed to determine if implementation of automated controls is feasible. Such an evaluation would consider availability of power and internet at each location and physical condition and operability.

- Based on site visits and model results, Spectacle Pond Outlet and Mill Pond Outlet have the best likelihood of being modified with automated controls; however, Forge Pond and Stony Brook are also possible (though could be cost prohibitive). For example, the aforementioned Valterra gate valve can be relatively easily and inexpensively retrofit with a linear actuator and relay to enable automated control.
- The software and hardware vendor of the streamflow monitoring network, Opti, specializes in continuous monitoring and adaptive control (CMAC) of infrastructure. Therefore, the decision support dashboards could be seamlessly transitioned to enable automated controls.

- **Study Area**
  - Finally, there is one additional documented downstream impoundment in the Stony Brook Watershed in Chelmsford near School Street that was not included in the initial study. It is recommended that future steps seek to include the owner of this dam and other stakeholders from Chelmsford to truly turn this into a complete watershed-wide restoration project that includes all impoundments along the mainstem of Stony Brook prior to discharging into the Merrimack River.

7. References

Archfield, S.A., Vogel, R.M., Steeves, P.A., Brandt, S.L., Weiskel, P.K., and Garabedian, S.P., 2010, The Massachusetts Sustainable-Yield Estimator: A decision-support tool to assess water availability at ungaged stream locations in Massachusetts: U.S. Geological Survey Scientific Investigations Report 2009–5227, 41 p. plus CD-ROM.

Baystate Environmental Consultants (1987). Diagnostic Feasibility Study for the Management of Forge Pond, January 1987.

Baystate Environmental Consultants (1991). Forge Pond Water Level Control Structure Plans, Engineering Plans, last revised September 1991.

Barret, C. (2018). Personal communication (interview) with Chip Barret of Westford Department of Public Works to discuss Beaver Brook and Mill Pond (anecdotal flood information, anecdotal low flow information). Interview on 3/21/2018 with H. O'Grady of Geosyntec Consultants.

Brutsaert, W. (1982). Evaporation Into the Atmosphere: Theory, History, and Applications. 10.1007/978-94-017-1497-6_1.

Clyde, J. (2018). Personal communication (interview) with Jim Clyde of Littleton Department of Public Works to discuss Beaver Brook and Mill Pond (anecdotal flood information, anecdotal low flow information). Interview on 3/22/2018 with H. O'Grady of Geosyntec Consultants.

ESS (1999). A Diagnostic Feasibility Study Investigation of Mill Pond, Littleton Massachusetts. ESS Project No. L091, dated January 11, 1999.

ESS (2000). Mill Pond Restoration Project, Extended Detention Wetland, Littleton Massachusetts, Design Report, Dated December 29, 2000.

ESS (2001). Diagnostic Feasibility Study of Spectacle Pond, ESS Project No. S327-000, dated April 6, 2001.

ESS (2015). 2015 Lakes and Ponds Monitoring Report, Westford, Massachusetts, Project W314-001, February 8, 2016.

FEMA (2016). Flood Insurance Study for Middlesex County, Massachusetts. Flood Insurance Study Number: 25017CV003C, revised July 6, 2016.

FOFP (2016). "Friends of Forge Pond, reference file obtained from Mr. Steve Hadden, "Forge Pond Lat-Long-Depth-Spring 2016".

Geosyntec Consultants (2017). DAM Dashboard: Desktop Analysis and Modeling Summary for Forge Pond and Spectacle Pond, technical memorandum, last revised August 25, 2017.

Lindeburg, M. (2012). Civil Engineering Reference Manual, 2nd Edition.

MA DCR / MA DEP (2004). The Practical Guide to Lake Management in Massachusetts, 2004.

MA DEP (2004). Guidance for Aquatic Plant Management in Lakes and Ponds as it Relates to the Wetlands Protection Act. Document Number BRP/DWM/WW/G04-1, April 2004.

MA DEP (2014). Water Management Act Permit Guidance Document, Published November 2014.

MA DEP (2018). Massachusetts Watershed Based Planning Tool. <http://prj.geosyntec.com/MassDEPWBP> Accessed May,

2018.

MA DOT (2010). Proposed Culvert Rehabilitation, Great Road over Gilson Brook, engineering plans, revised April 3, 2010.

Mass GIS (2012). Light Detection and Ranging terrain and elevation data for Massachusetts, 2012 Merrimack Watershed. < https://docs.digital.mass.gov/dataset/massgis-data-lidar-terrain-data> Accessed April 2018.

MA ODS (2003). Notice of Inspection for Mill Pond Dam, MA01149, Littleton. Letter dated April 30, 2003.

MA ODS (2018). Chapter 253 Permit Applications. < https://www.mass.gov/files/documents/2017/10/25/dam-construction-chapter-253-permit-application-form-june-2016.pdf> Accessed June 2018.

Munson, 1994. Munson, Young, and Okiishi (1994). Fundamentals of Fluid Mechanics. John Wiley & Sons, Inc., Second Edition. New York.

NRCC (2018). Massachusetts Climate Change Projections – Statewide and for Major Drainage Basins, published by MA EOEEA, March 2018. < http://resilientma.org/resources/resource::2152> accessed May, 2018.

Shamsi, U. and J. Koran. 2017. "Continuous Calibration." Journal of Water Management Modeling 25:C414.

USDA (1986). Urban Hydrology for Small Watersheds, TR 55.
<https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1044171.pdf> Accessed May, 2018.

USDA (1993). U.S. Department of Agriculture – National Resources Conservation Service. Web Soil Survey 1.1 National Cooperative Soil Survey. <http://websoilsurvey.nrcs.usda.gov>. Accessed March 2018.

USEPA (2015). Storm Water Management Model User's Manual Version 5.1. EPA/600/R-14/413b, revised September 2015.

USFWS (1999). Questions and Answers on the New England Flow Policy, Prepared by Vernon Lang, USFWS, May 11, 1999.
<https://www.fws.gov/newengland/pdfs/Flowpolicy.pdf> Accessed May, 2018.

USGS (2018). StreamStats Application. <https://water.usgs.gov/osw/streamstats/> Accessed May, 2018.

Weaver, L. (2018a). Personal communication (interview) with Leon Weaver of Littleton Clean Lakes Committee to discuss Spectacle Pond (typical stop log operation, anecdotal flood information, anecdotal low flow information). Interview on 3/15/2018 with D. Roman of Geosyntec Consultants.

Weston and Sampson (2011). Stony Brook Dam Phase I Inspection / Evaluation Report, December 8, 2011.

Weaver, L. (2018a). Stop Log Configuration History 2010-2018. Excel Spreadsheet prepared by Leon Weaver. Transmitted 5/6/2018.

Yule, C. (2018). Personal communication with Chris Yule of Abbot Mill during project kickoff meeting held on 3/28/2018 regarding the Abbott Mill Dam and various control structures.

Appendix A
Report Figures

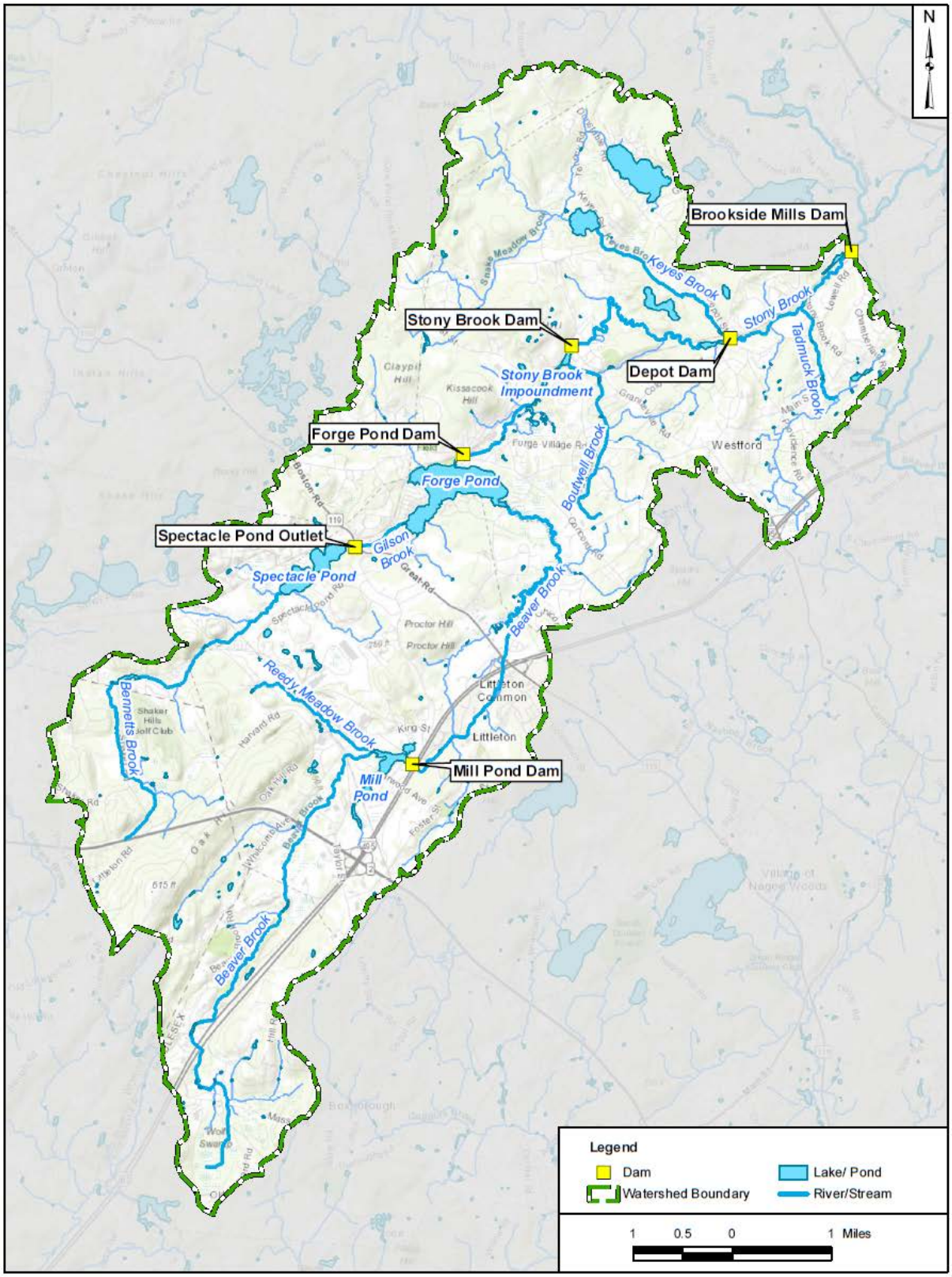


Figure 1.1: Study area vicinity map.

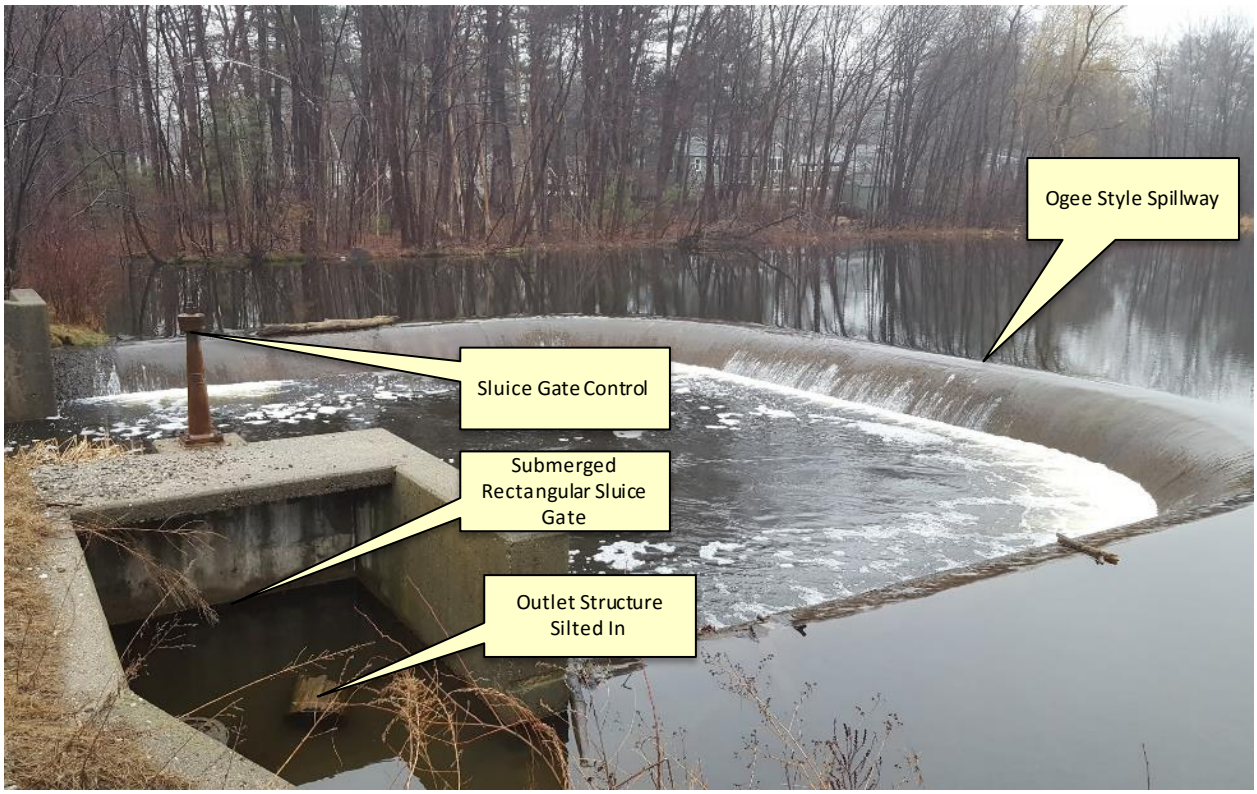


Figure 1.2: Mill Pond spillway and outlet control structure (date taken: 4/4/2018).



Figure 1.3: Spectacle Pond outlet control structure (Date taken: 7/28/2017). Pictured primary weir configured with one concrete stop log, typically configured with three in the summer.

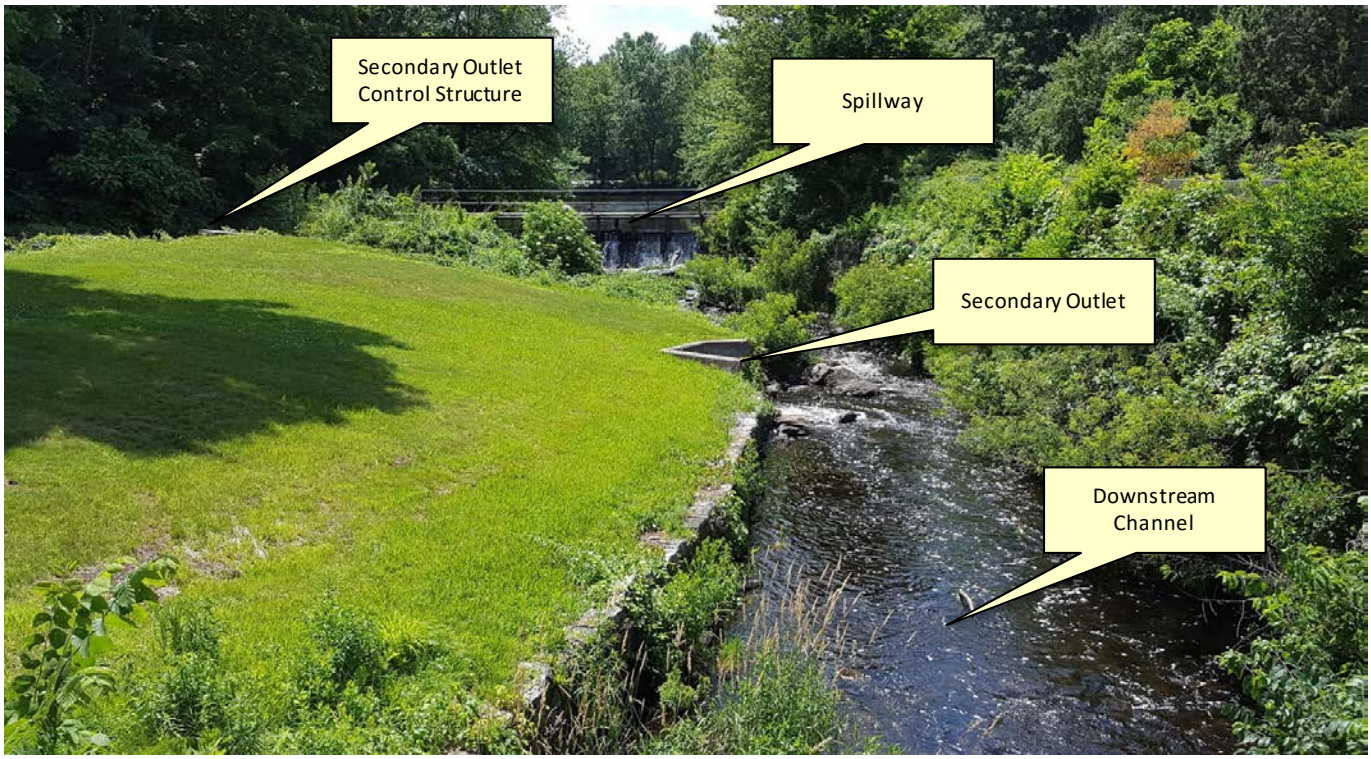


Figure 1.4a: Forge Pond spillway and secondary outlet structure (downstream, date taken: 6/28/2017).



Figure 1.4b: Forge Pond spillway and sluice gates (upstream, date taken: 6/28/2017).

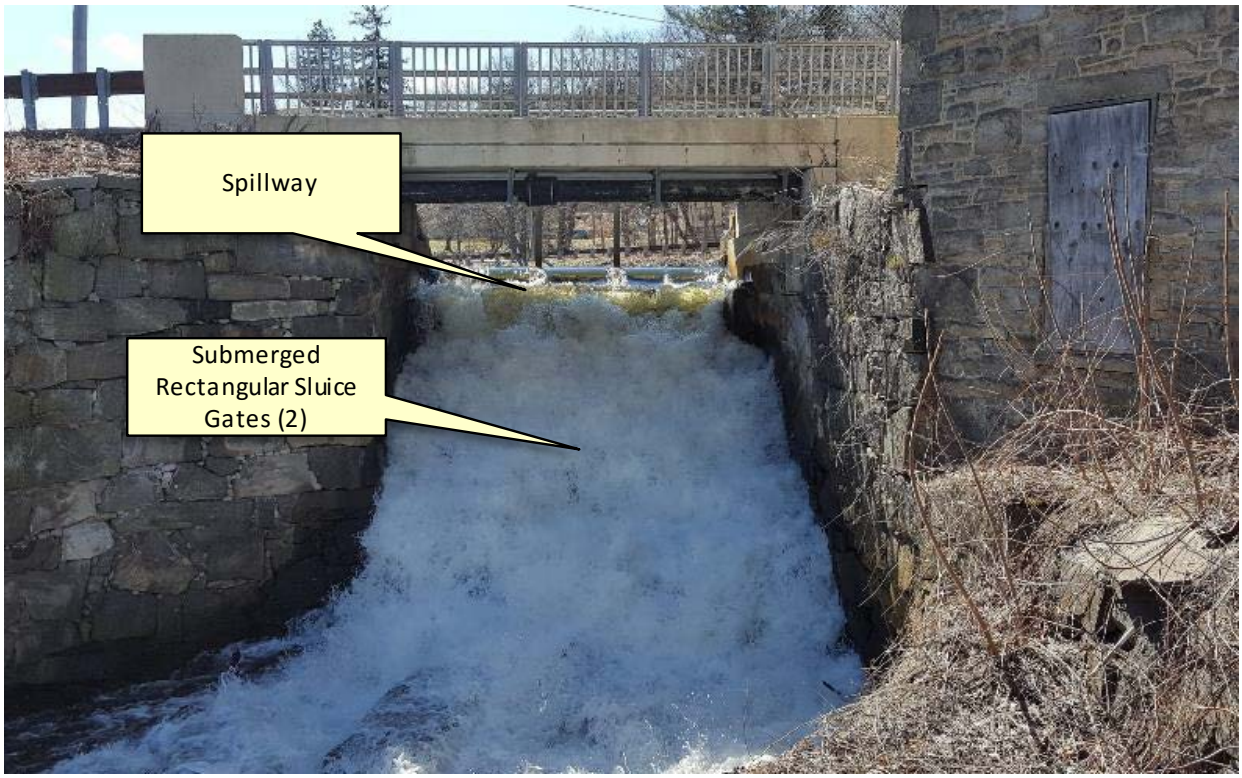


Figure 1.5a: Stony Brook spillway and outlet control structure (downstream, date taken: 4/5/2018).



Figure 1.5b: Stony Brook spillway and outlet control structure (upstream, date taken: 4/5/2018).

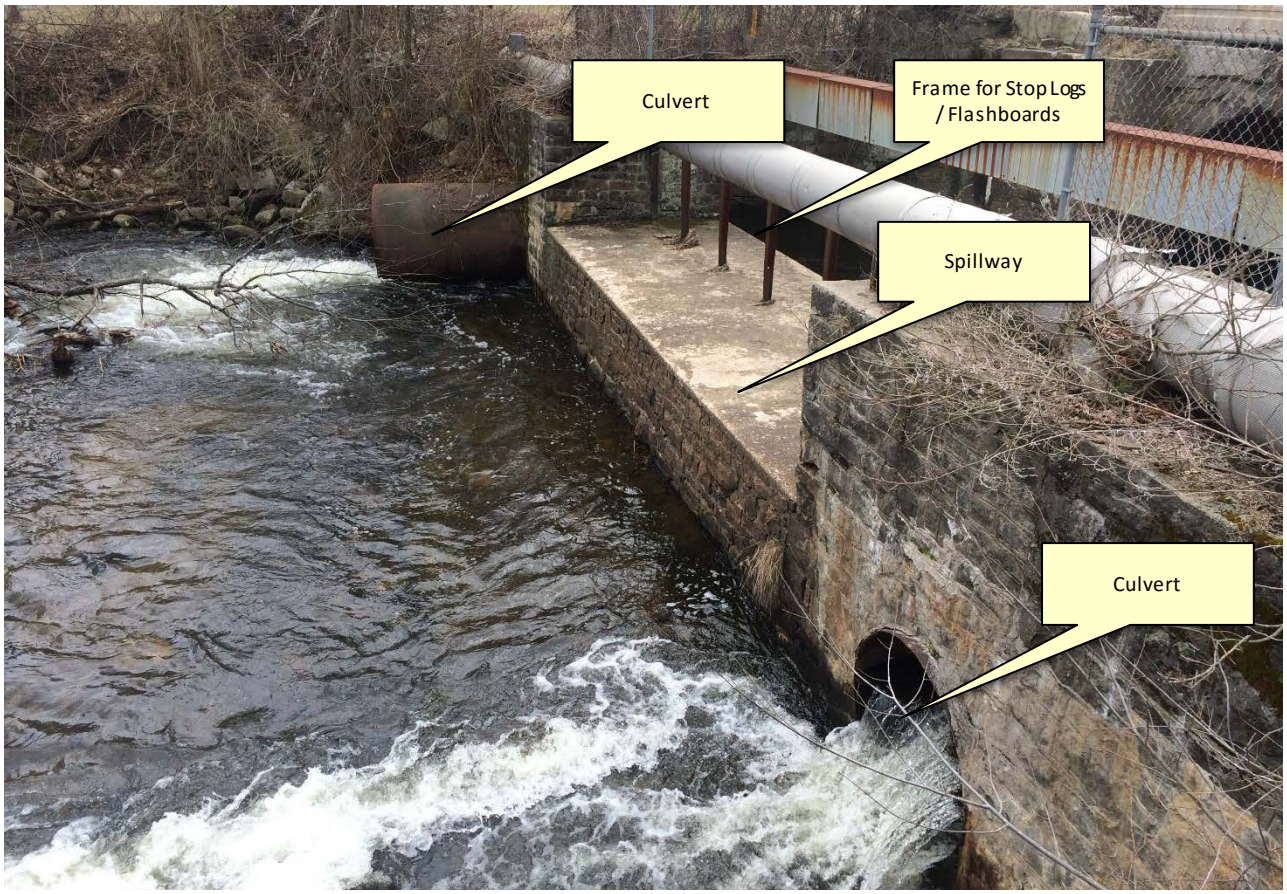


Figure 1.6: Depot Dam culverts and decommissioned spillway (date taken: 4/5/2018).

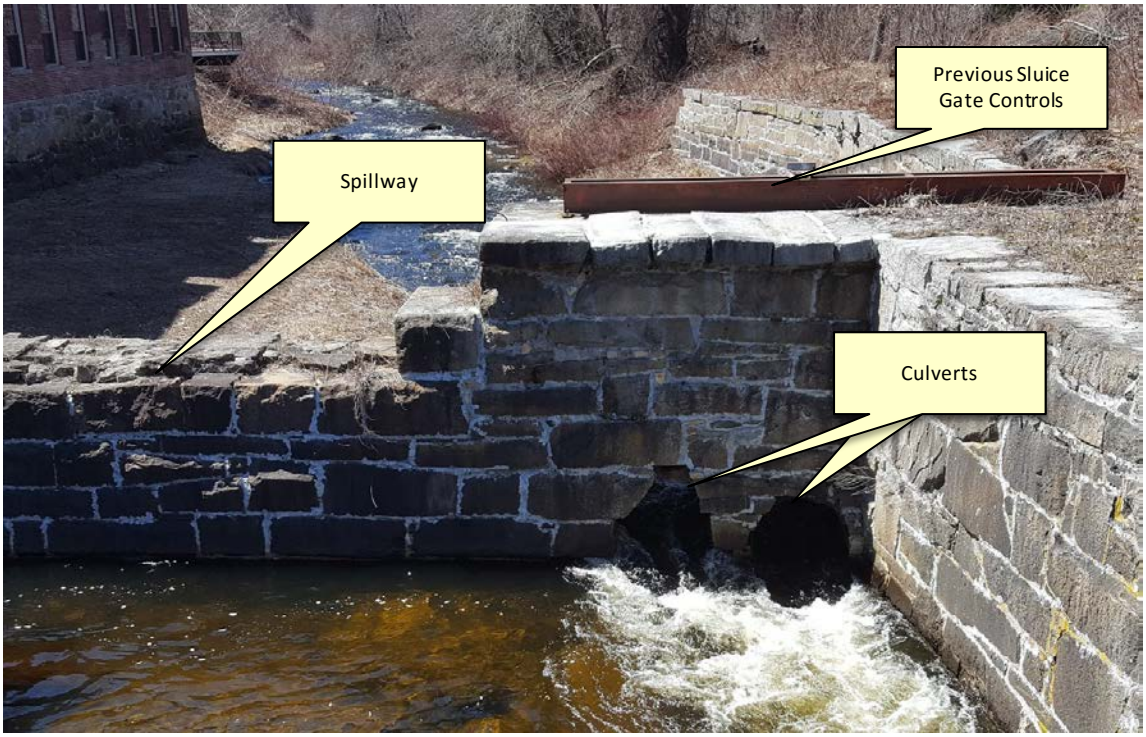


Figure 1.7: Brookside Mills Dam (date taken: 4/5/2018).

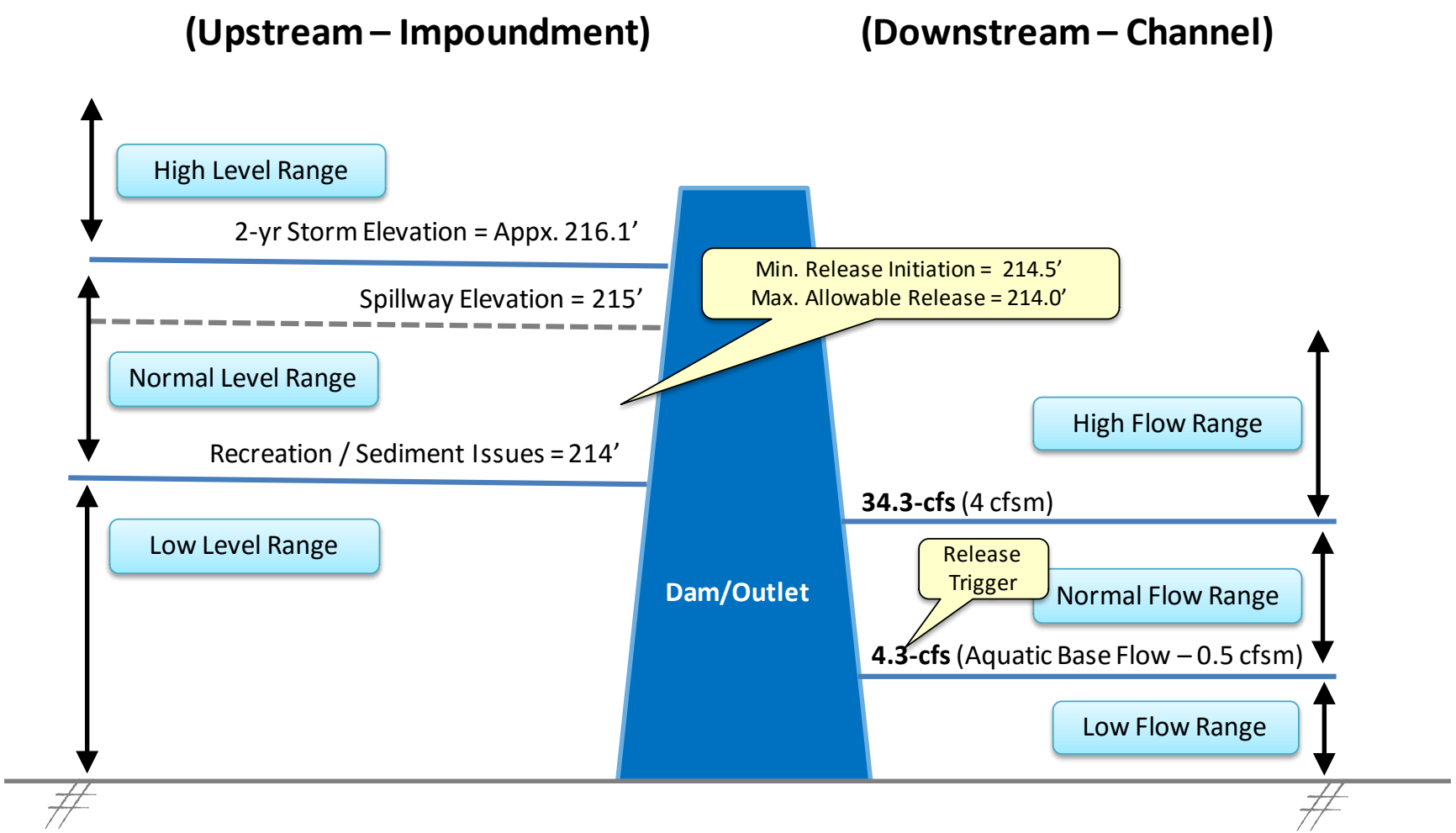


Figure 2.1: Mill Pond summary of evaluation indicators and thresholds. Release initiation, allowable release, and release triggers are discussed in Section 4 of this report.

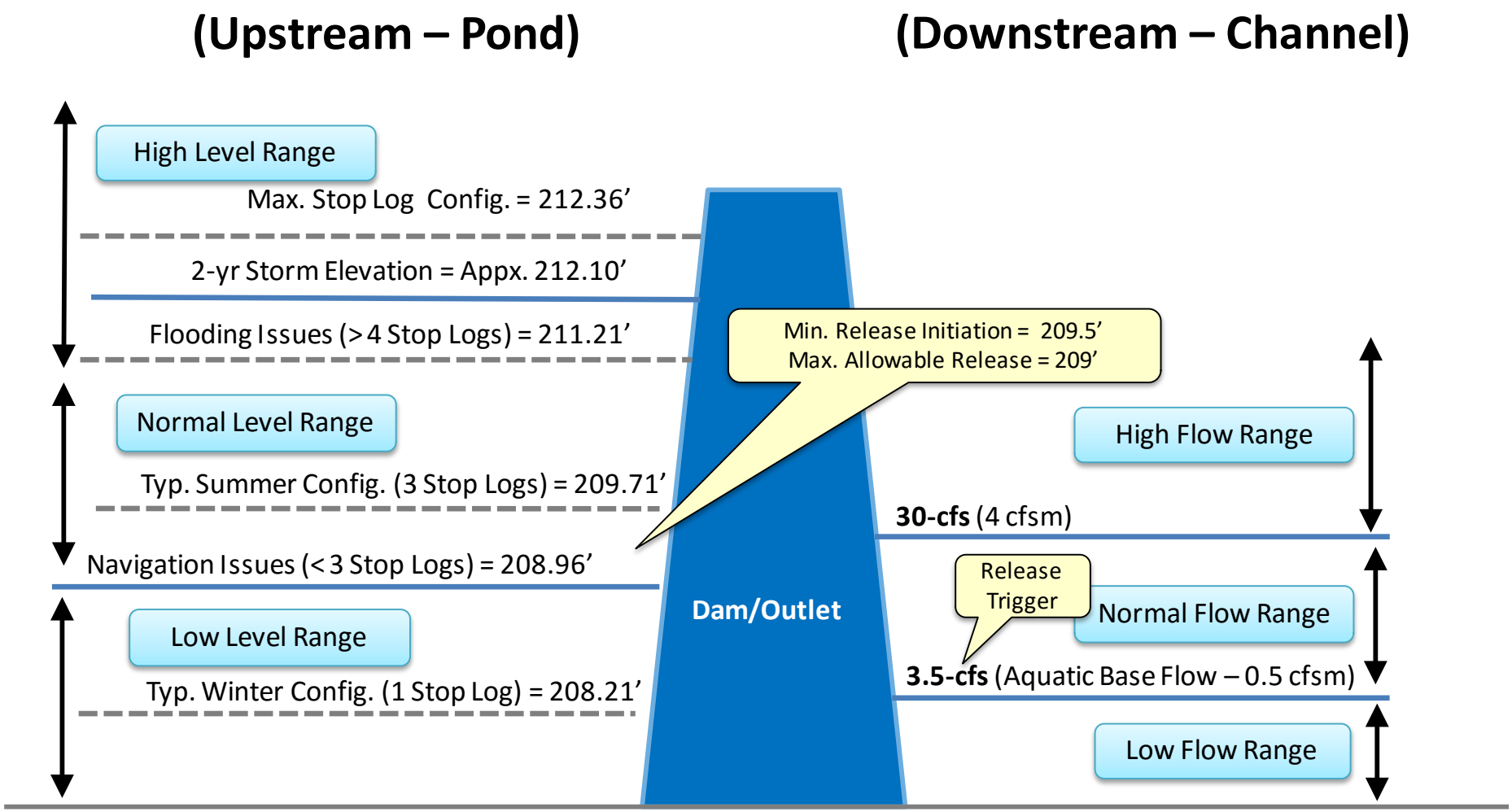


Figure 2.2: Spectacle Pond summary of evaluation indicators and thresholds. Release initiation, allowable release, and release triggers are discussed in Section 4 of this report.

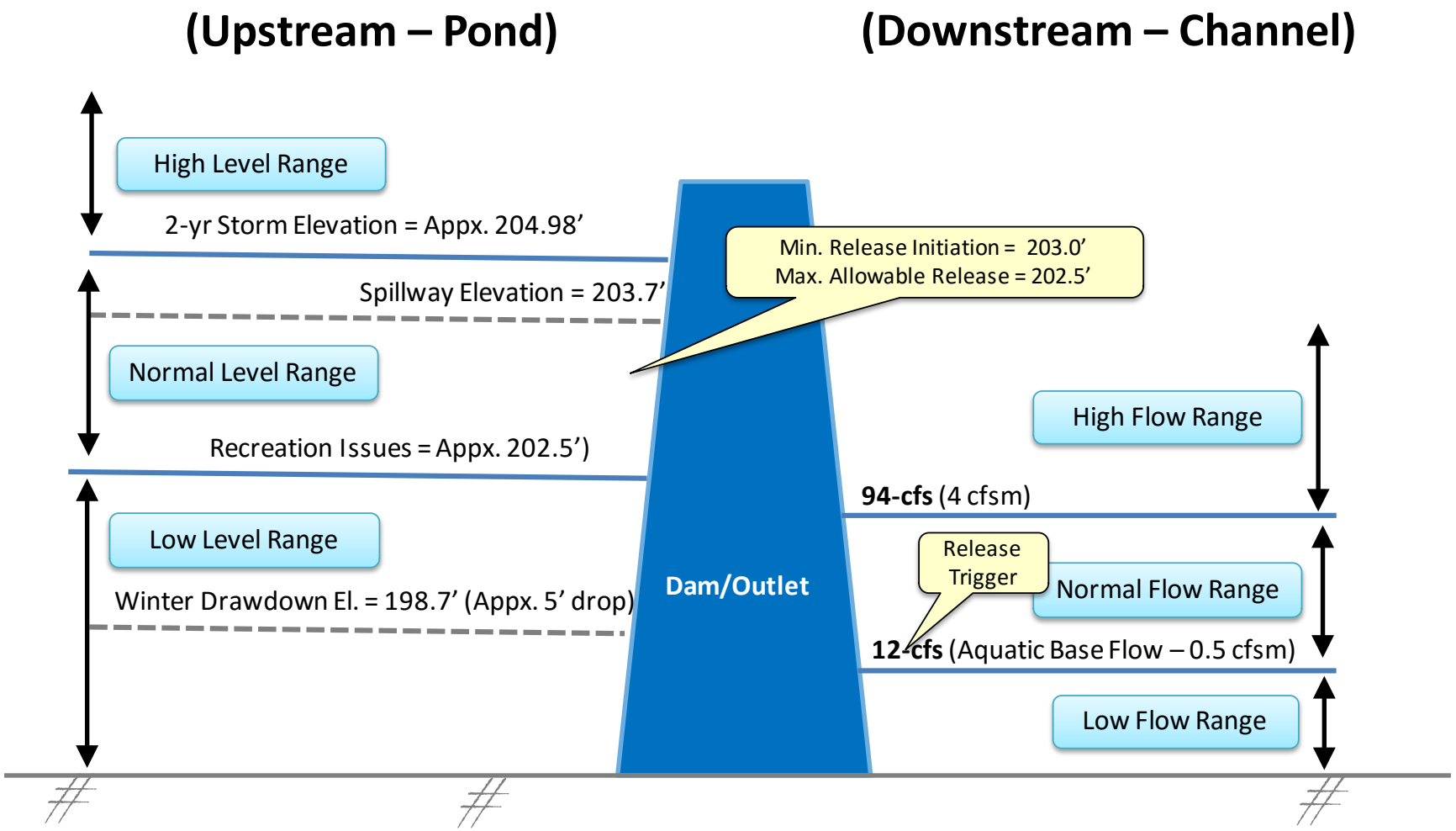


Figure 2.3: Forge Pond summary of evaluation indicators and thresholds. Release initiation, allowable release, and release triggers are discussed in Section 4 of this report.

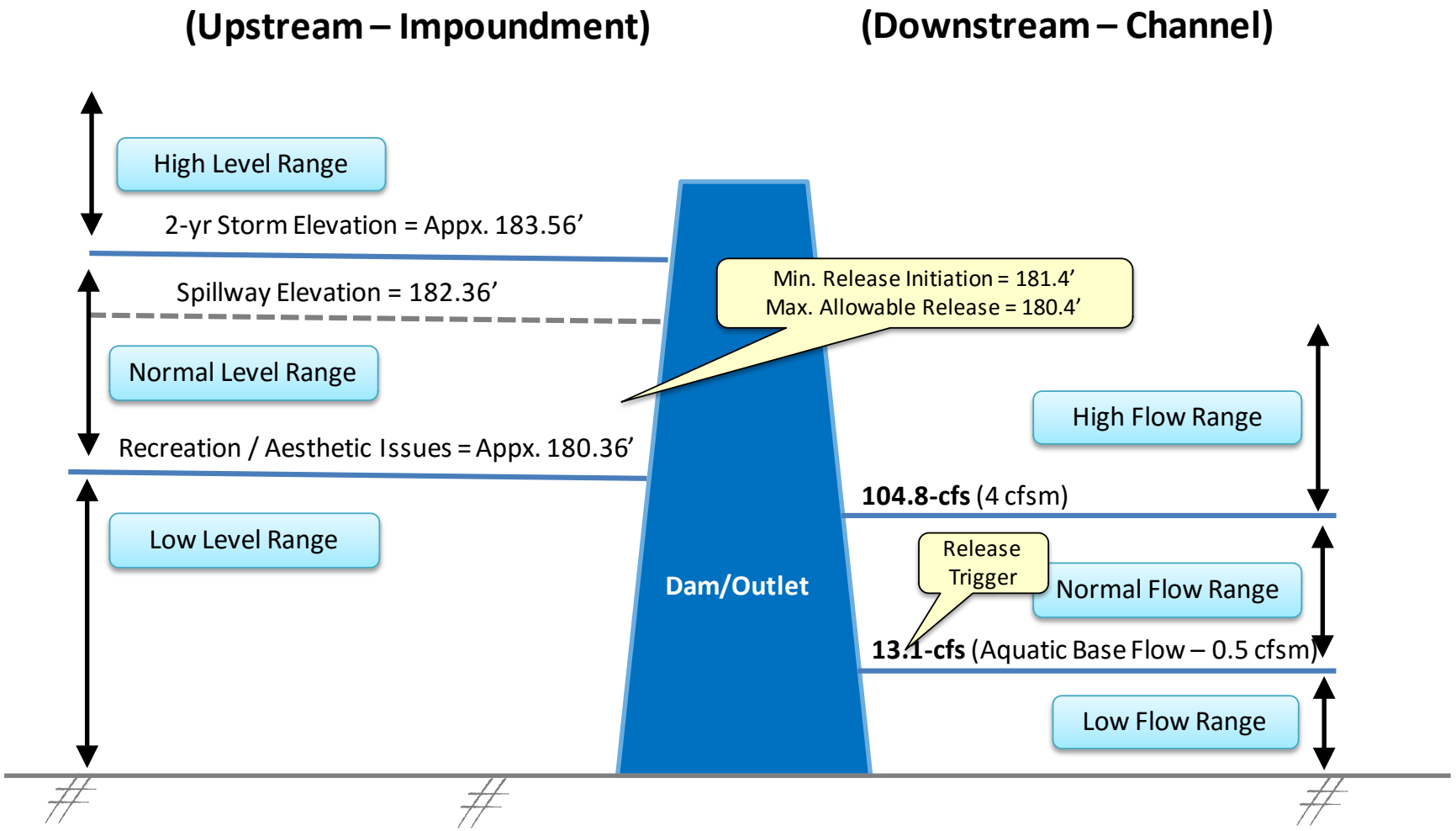


Figure 2.4: Stony Brook Dam summary of evaluation indicators and thresholds. Release initiation, allowable release, and release triggers are discussed in Section 4 of this report.

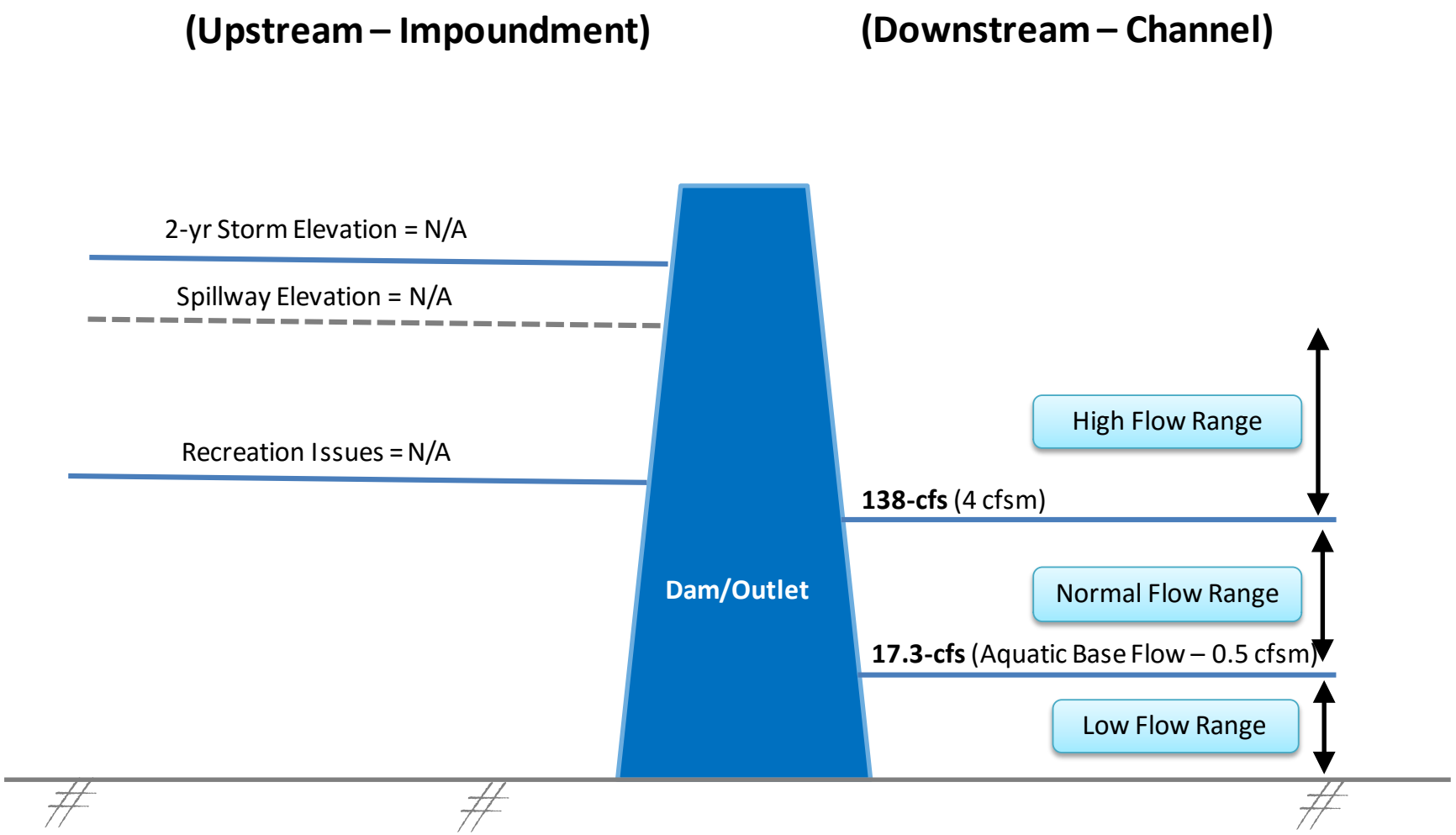


Figure 2.5: Depot Dam summary of evaluation indicators and thresholds.

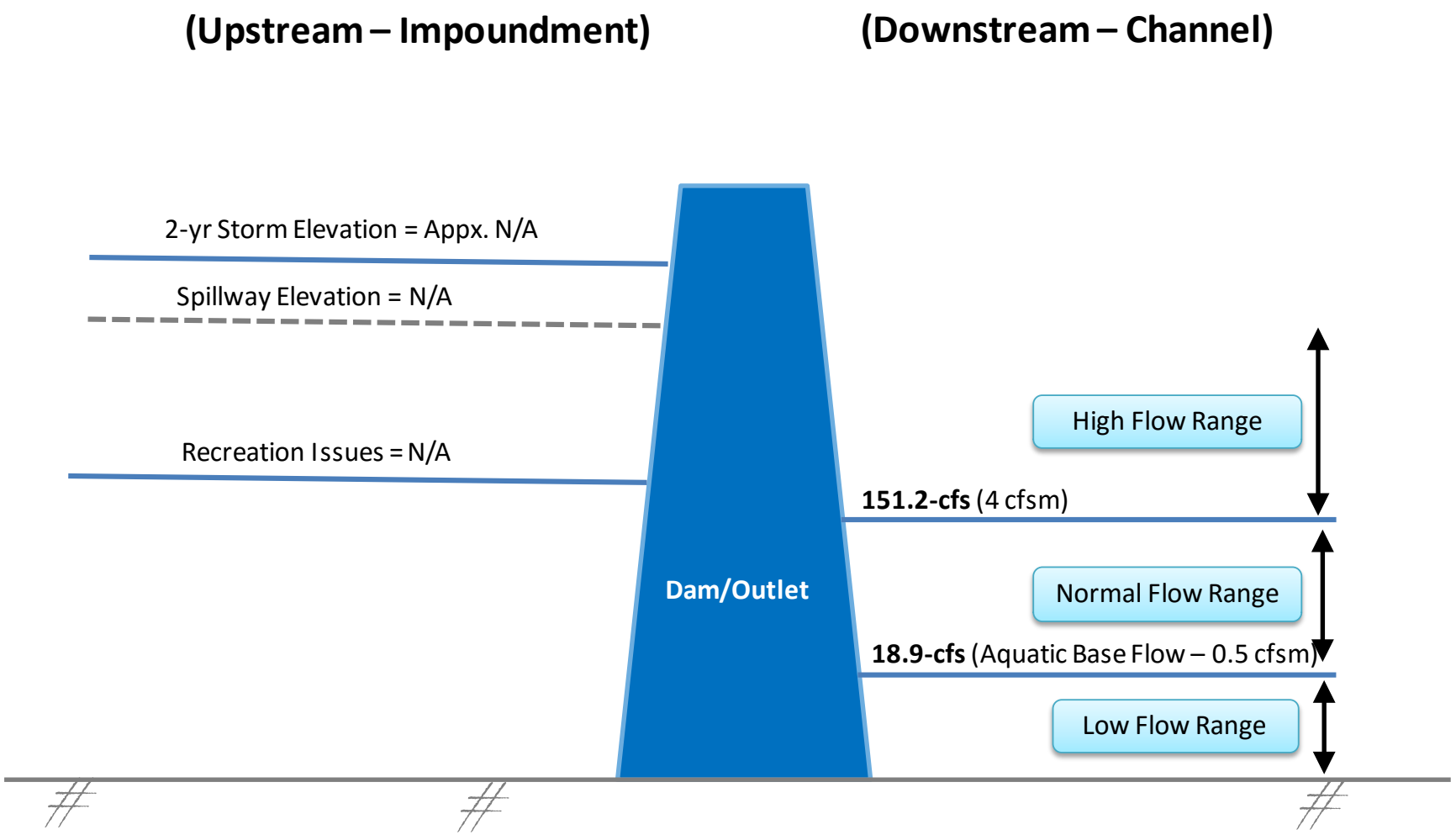


Figure 2.6: Brookside Mills Dam summary of evaluation indicators and thresholds.

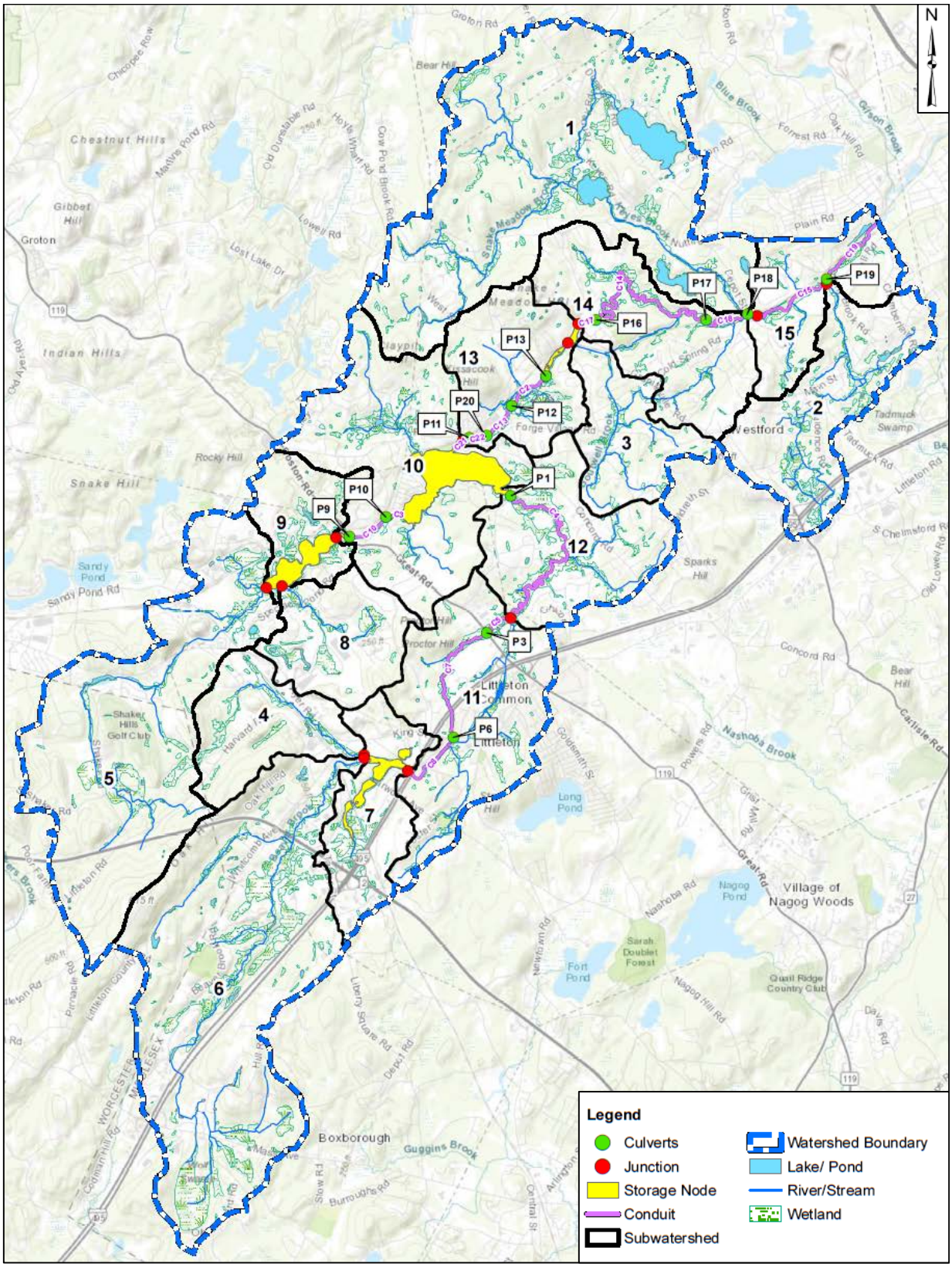


Figure 3.1: Overview of Hydrologic and Hydraulic Model Components

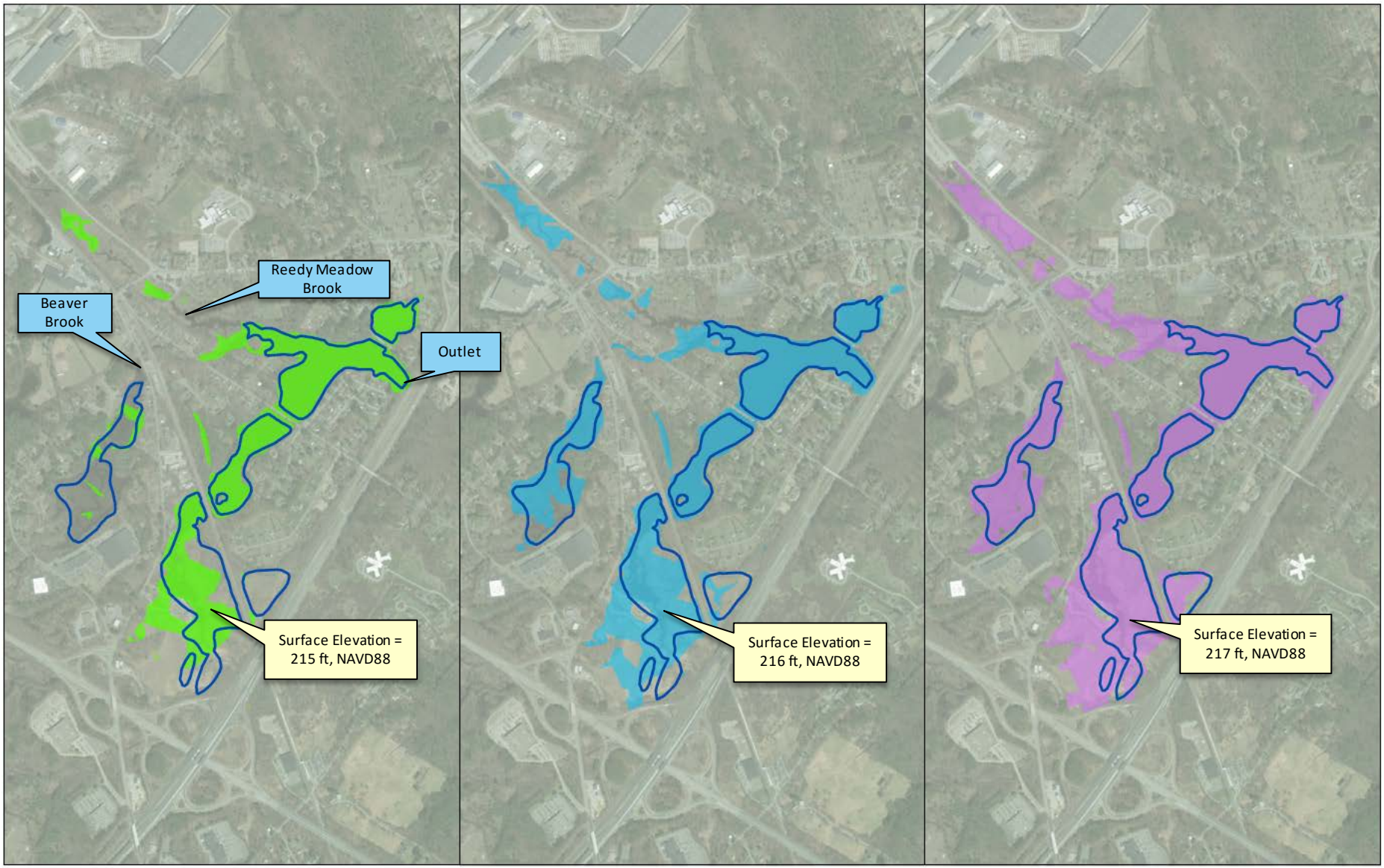


Figure 3.2a: Bathymetric representation of floodplain storage at Mill Pond based on LiDAR topographic data (MassGIS, 2012). Blue outline indicates visible extent of standing water. Surface elevation of 215 ft, NAVD88 represents approximately spillway elevation while elevation 217 ft, NAVD88 represents approximate maximum elevation of pond. For reference, approximate 2-year storm peak elevation Is 216.1 ft, NAVD88 (See Figure 2.1).

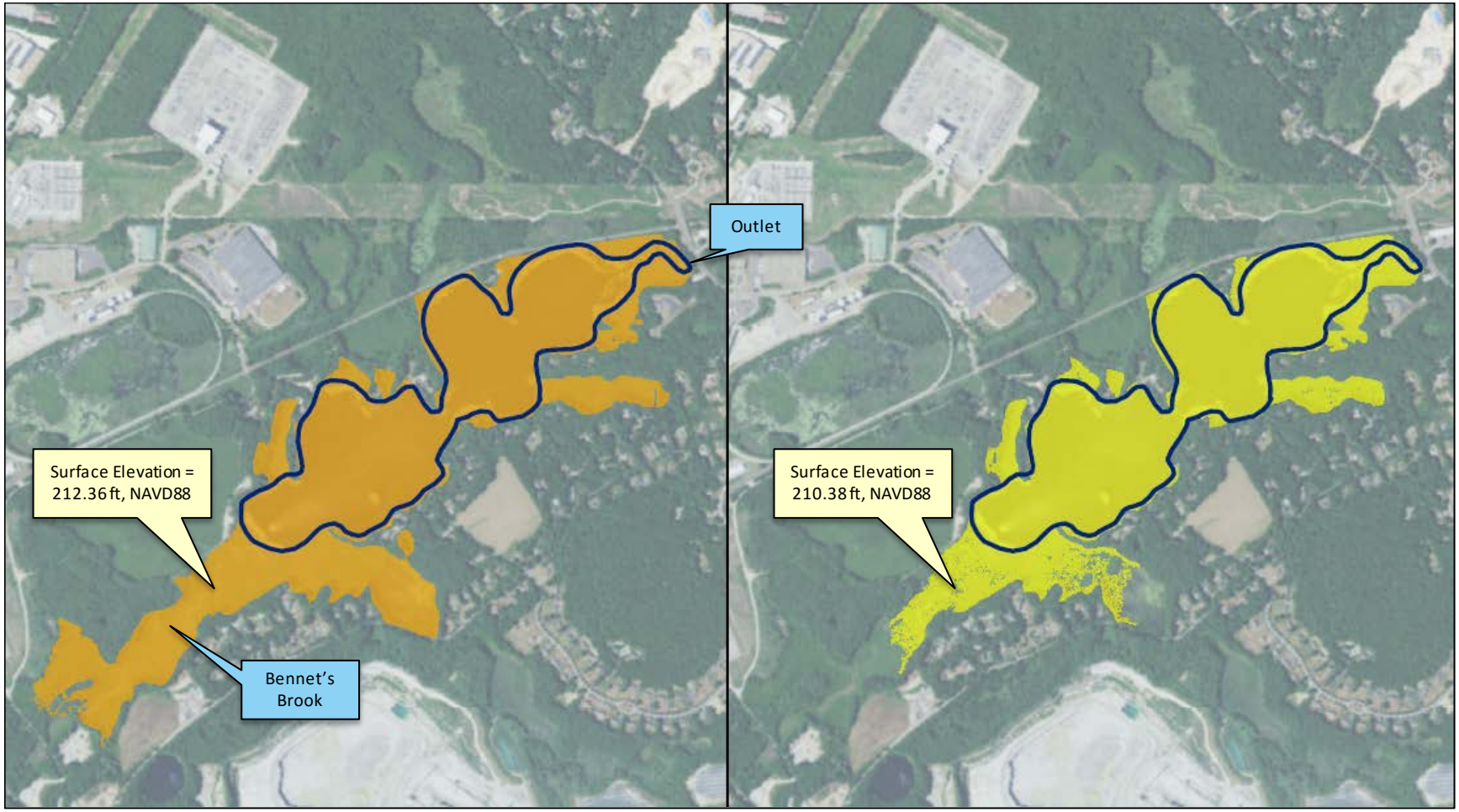


Figure 3.2b: Bathymetric representation of floodplain storage at Spectacle Pond based on LiDAR topographic data (MassGIS, 2012). Blue outline indicates visible extent of standing water. Surface elevation of 210.38 ft, NAVD88 represents approximate elevation of pond on 7/20/2000 when bathymetry data were collected (ESS, 2000) while elevation 212.36 ft, NAVD88 represents approximate top elevation of outlet control stop log structure. For reference, the approximate elevation of the pond with three (3) stop logs is 209.71 ft, NAVD88 and approximate 2-year storm peak elevation Is 212.1 ft, NAVD88 (See Figure 2.2).

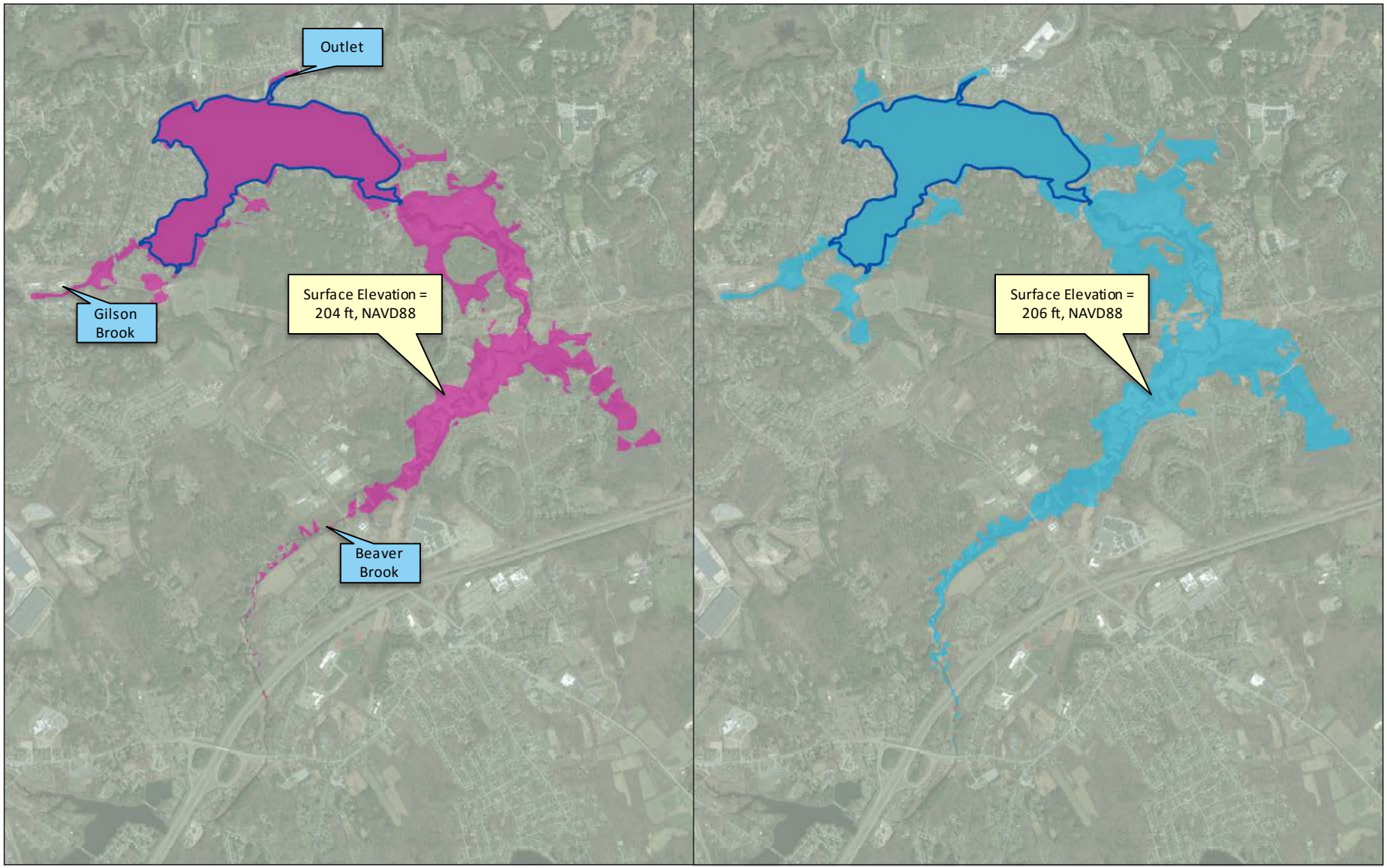


Figure 3.2c: Bathymetric representation of floodplain storage at Forge Pond based on LiDAR topographic data (MassGIS, 2012). Blue outline indicates visible extent of standing water. Surface elevation of 206 ft, NAVD88 represents approximate maximum elevation of pond. For reference, approximate spillway elevation is 203.68 ft, NAVD88 and approximate 2-year storm peak elevation Is 205.0 ft, NAVD88 (See Figure 2.3).

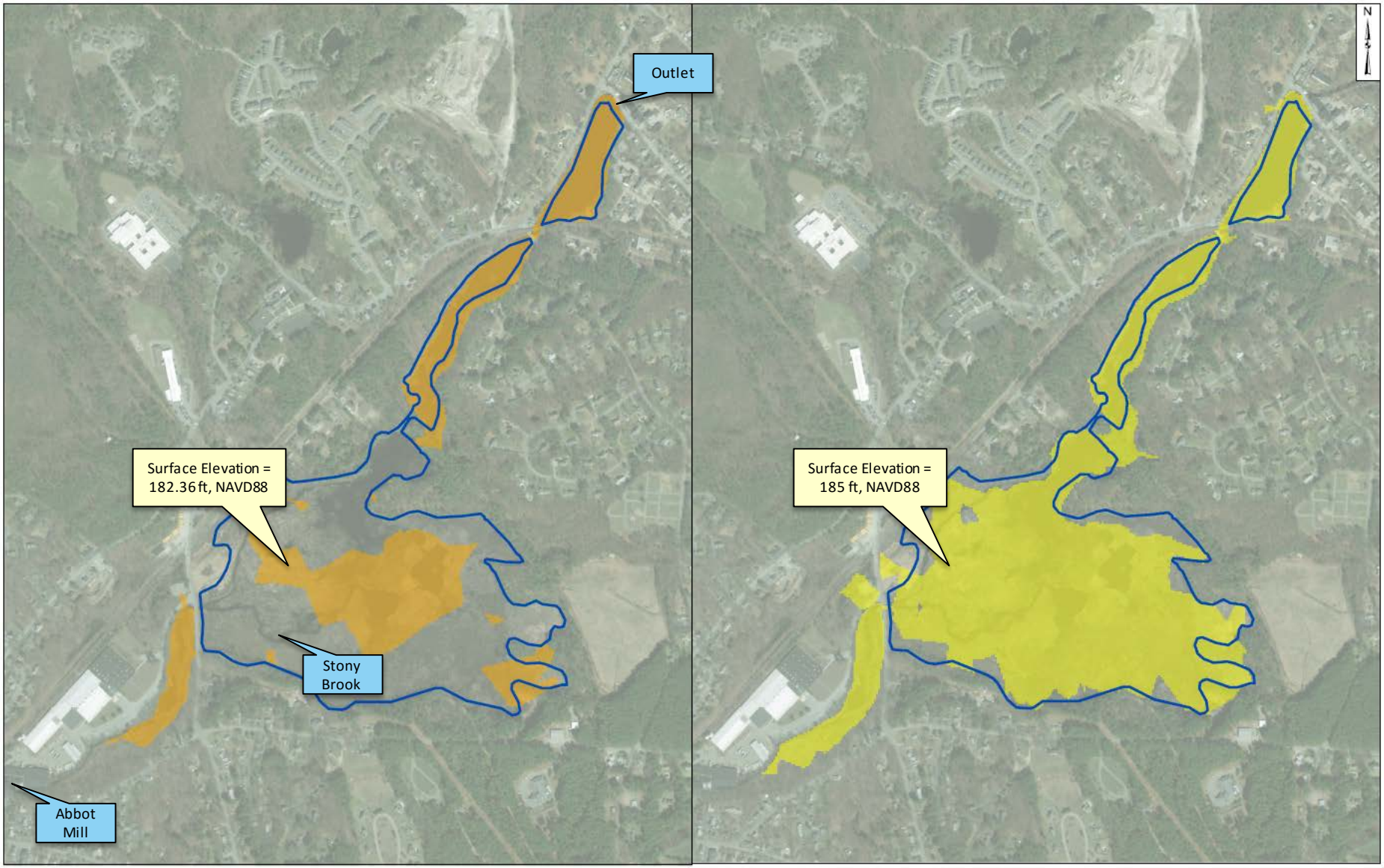


Figure 3.2d: Bathymetric representation of floodplain storage at Stony Brook Impoundment based on LiDAR topographic data (MassGIS, 2012). Blue outline indicates visible extent of standing water. Surface elevation of 182.36 ft, NAVD88 represents approximate spillway elevation of impoundment. For reference, approximate 2-year storm peak elevation Is 183.6 ft, NAVD88 (See Figure 2.4).

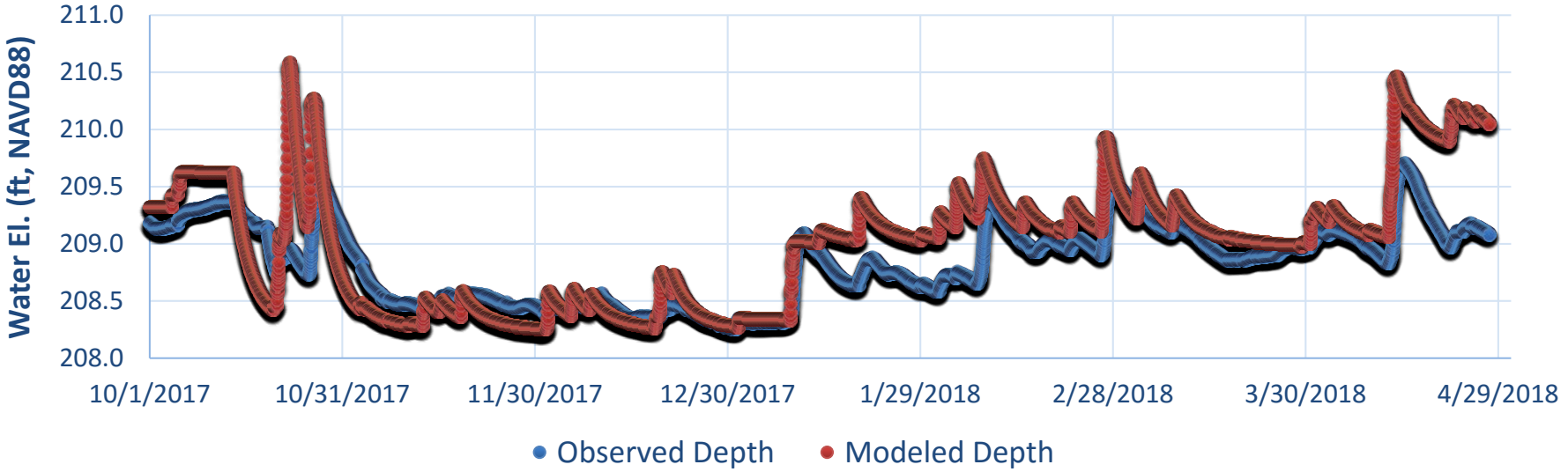


Figure 3.3: Spectacle Pond water elevation, 10/1/2017 through 5/1/2018.

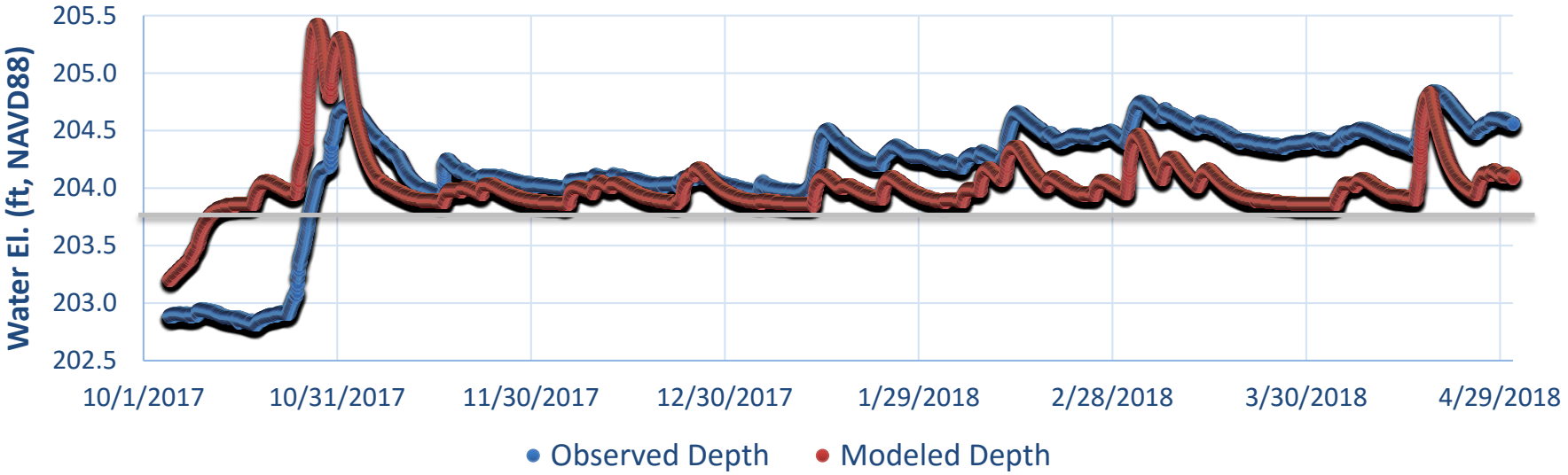


Figure 3.4: Forge Pond water elevation, 10/1/2017 through 5/1/2018 (grey line indicates spillway elevation).

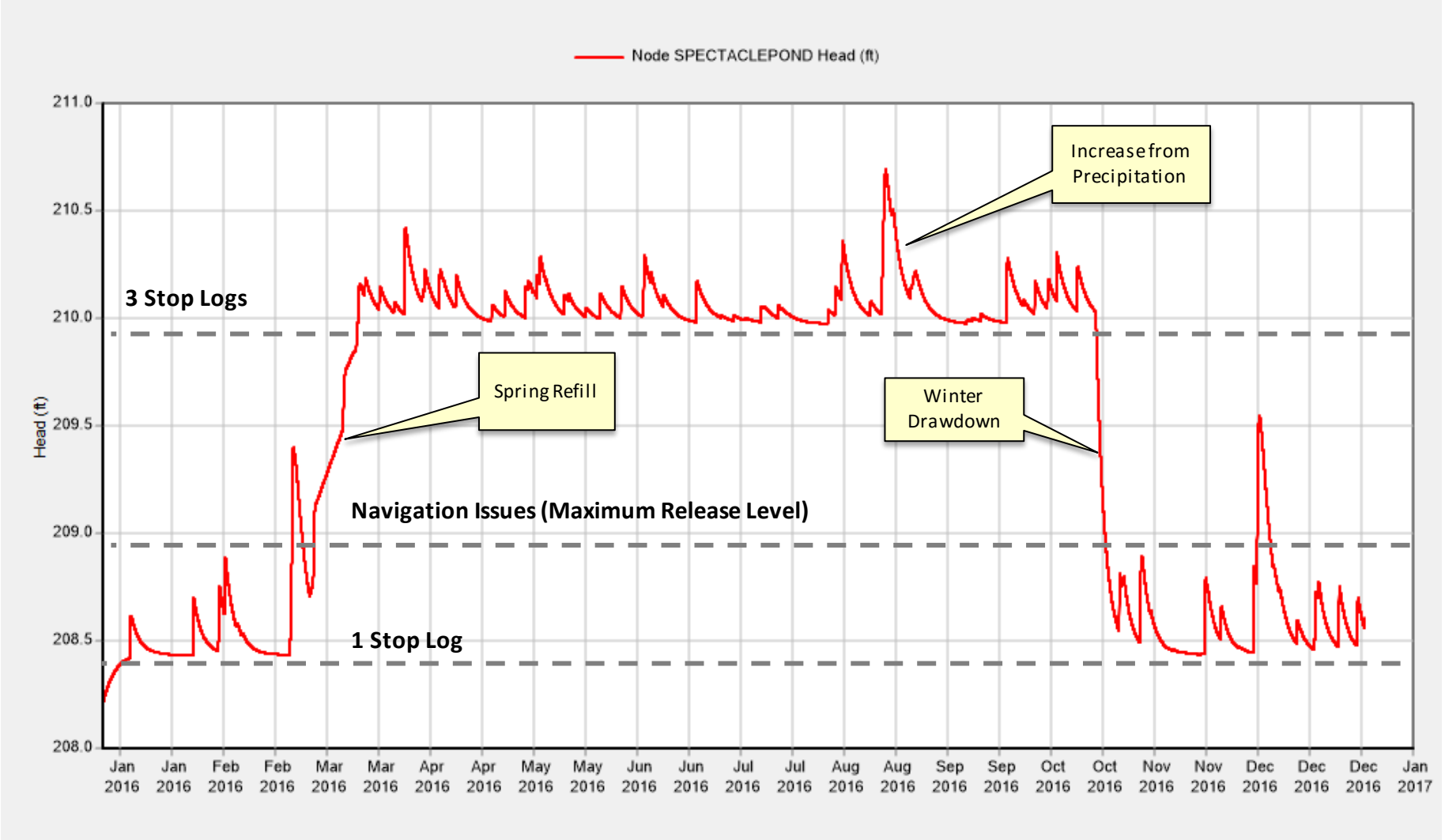


Figure 4.1: Spectacle Pond baseline conditions logic (2016 drought year). Red line represents impoundment water level; increases in water level indicate precipitation and subsequent runoff into the impoundment.

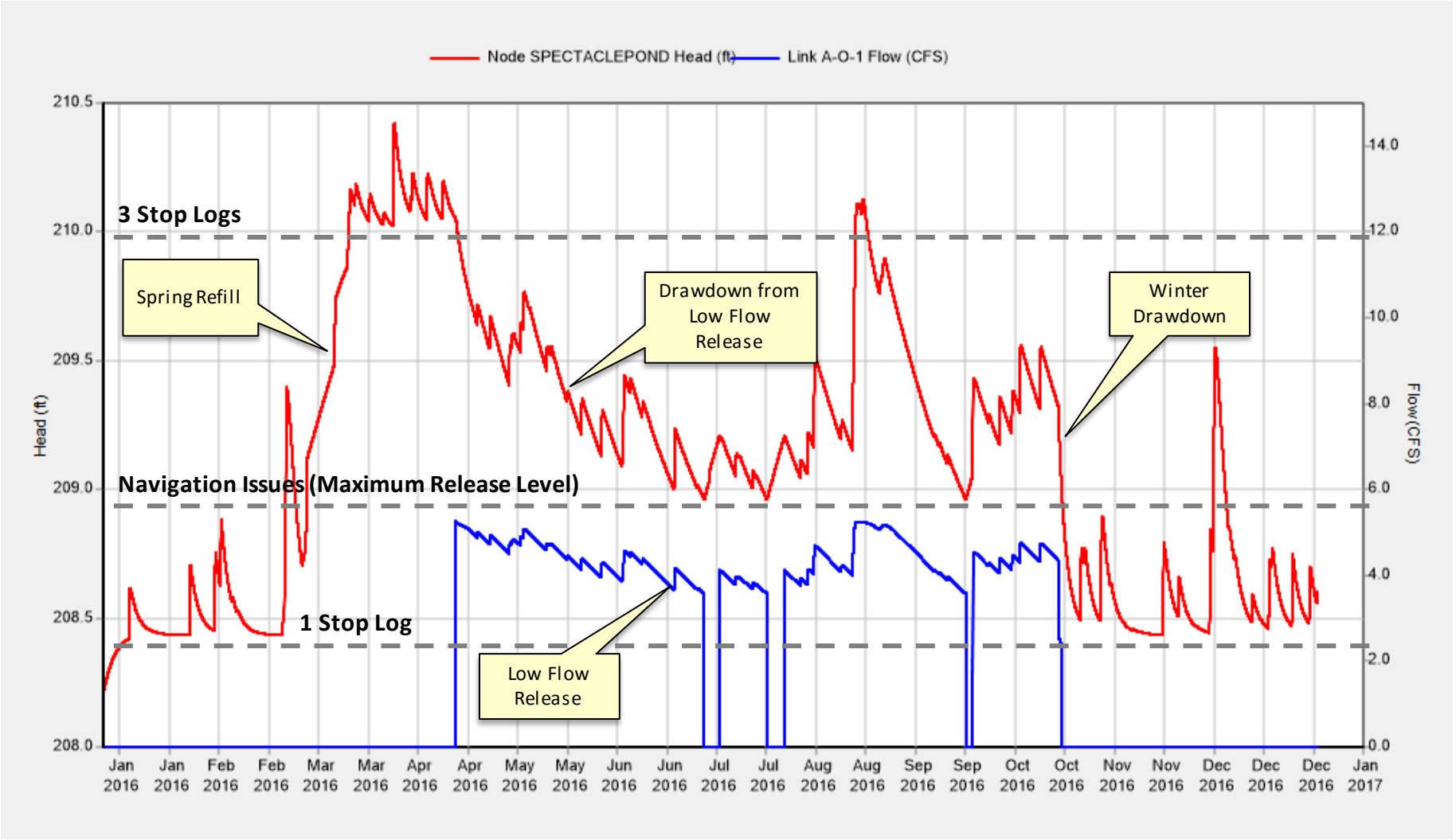


Figure 4.2: Spectacle Pond proposed conditions logic, Iteration 1 (2016 drought year). Blue line represents discharge from low flow orifice to downstream channel.

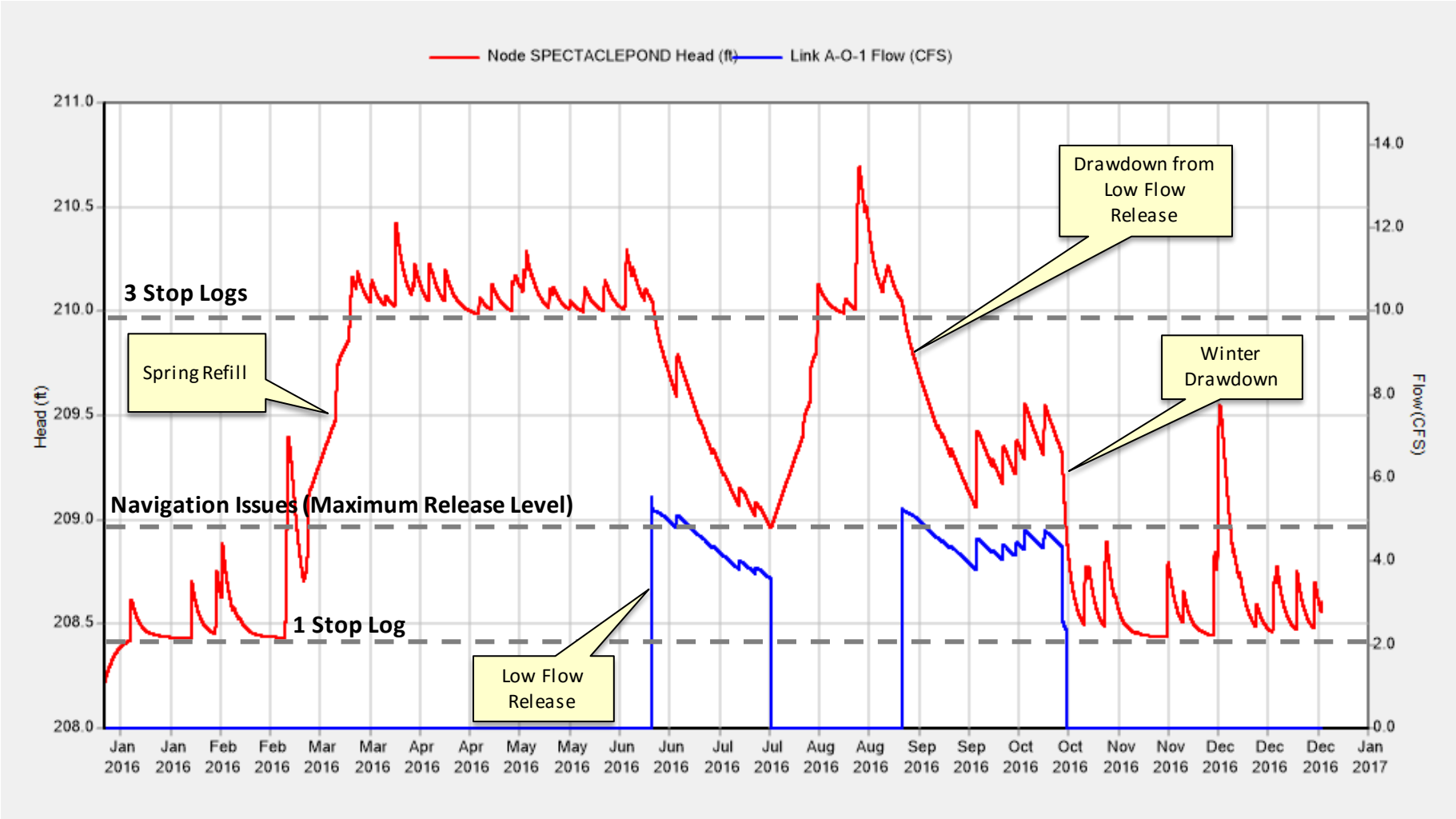


Figure 4.3: Spectacle Pond proposed conditions logic, Iteration 2 (2016 drought year). Water level is regulated more smoothly and releases are less frequent when waiting to release until less than 0.10" of precipitation is in the 7-day forecast.

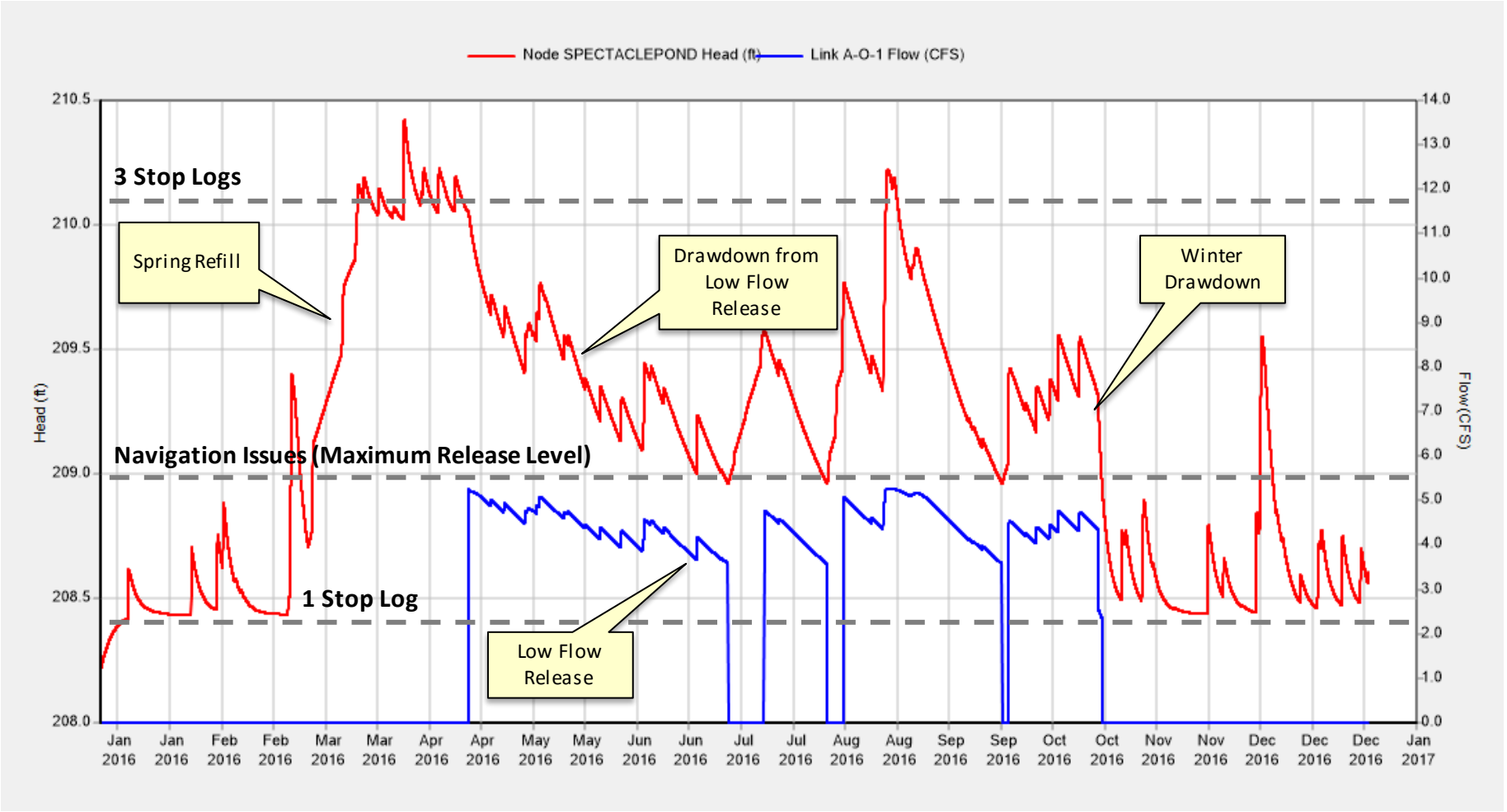


Figure 4.4: Spectacle Pond proposed conditions logic, Iteration 3 (2016 drought year). Releases are more frequent than Iteration 2 when increasing the forecast threshold to wait until less than 0.25" of precipitation is in the 7-day forecast.

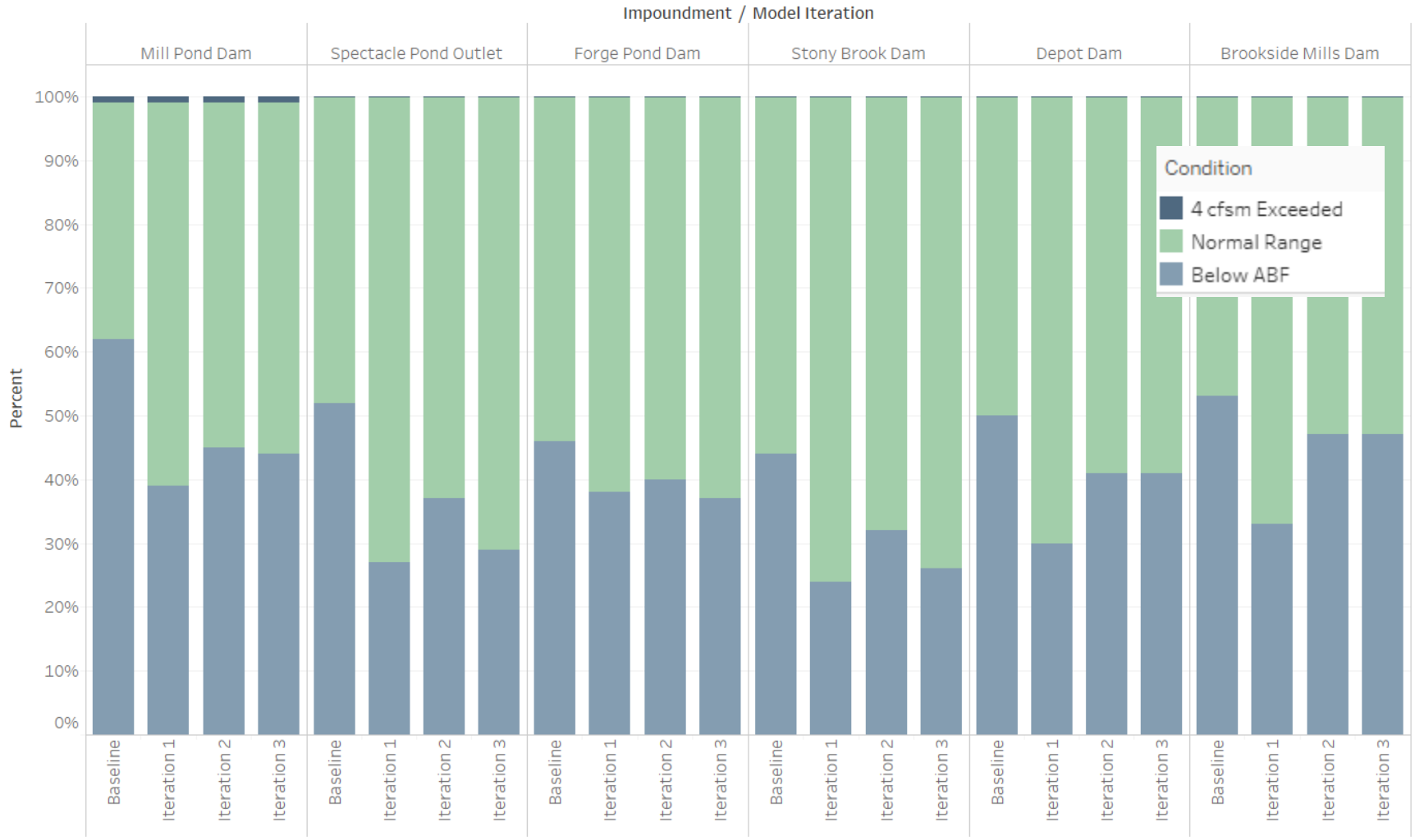


Figure 4.5: Summary of streamflow exceedance results by scenario (2016 – drought conditions).

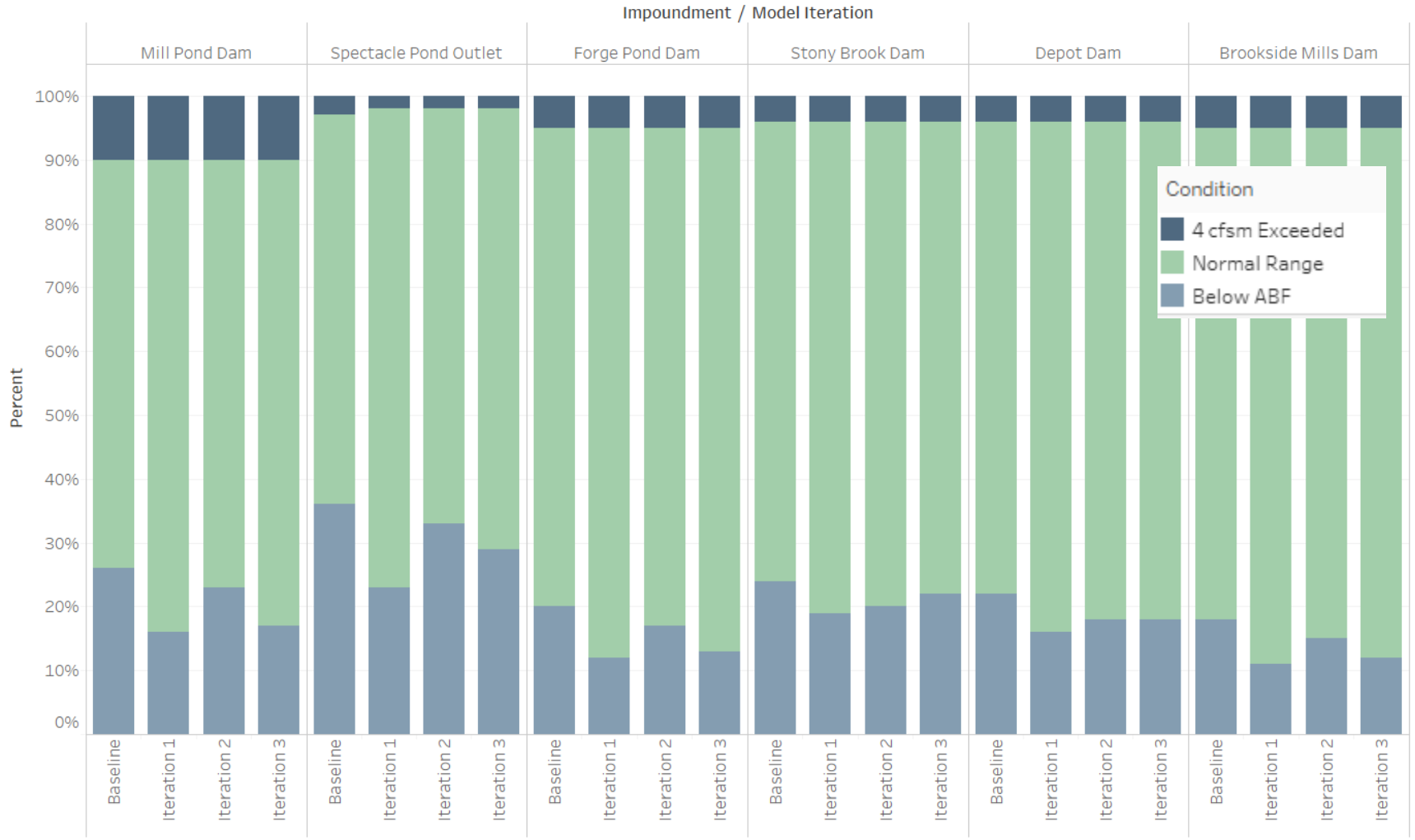


Figure 4.6: Summary of streamflow exceedance results by scenario (2017 – typical conditions).

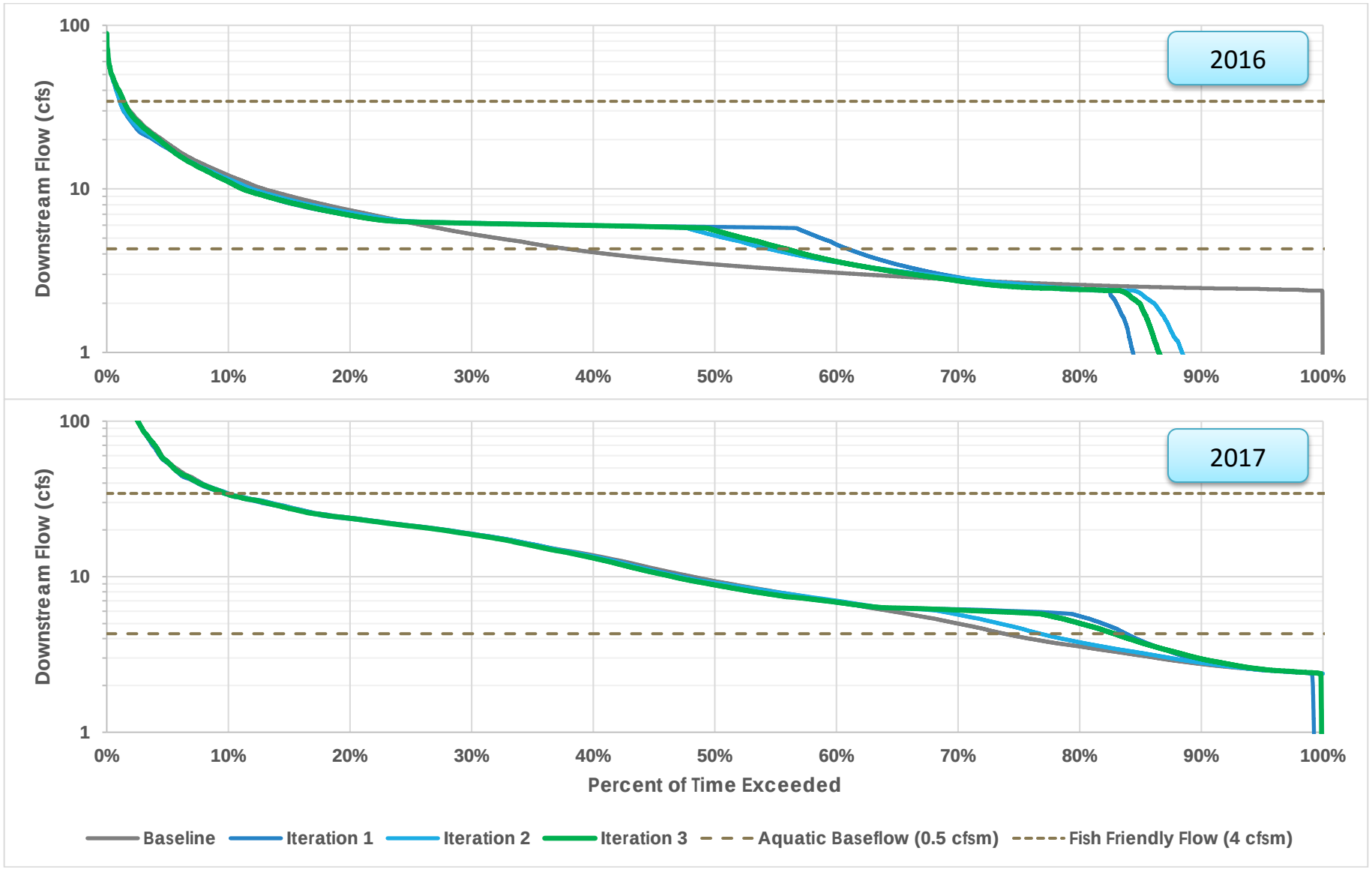


Figure 4.7: Mill Pond Dam downstream streamflow exceedance curve (2016 drought conditions vs. 2017 typical conditions). Improvements are more pronounced in the 2016 drought year. In 2016, ABF is exceeded approximately 38% of the time in the baseline scenario compared to 56% for Iteration 3.

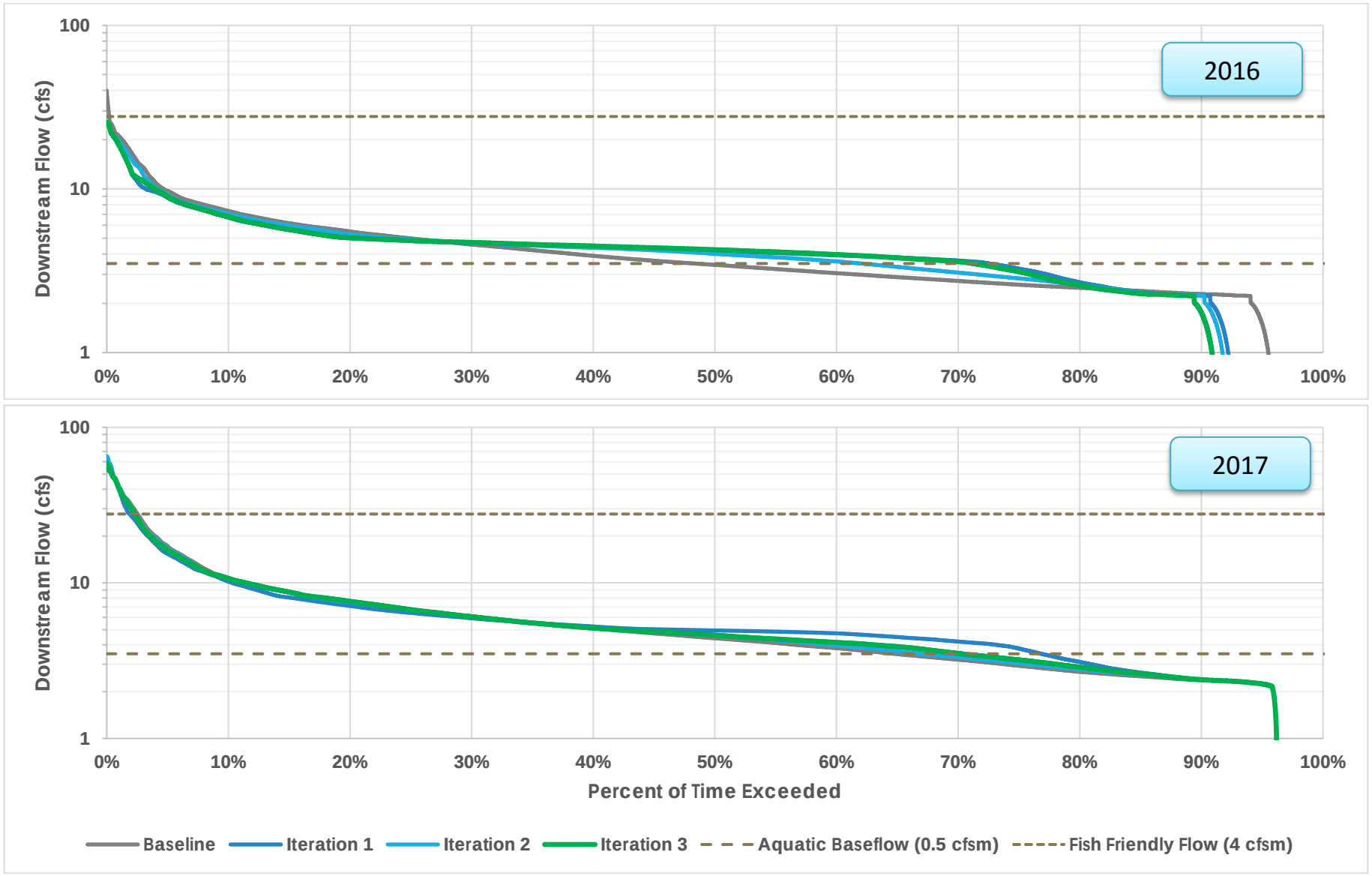


Figure 4.8: Spectacle Pond Outlet downstream streamflow exceedance curve (2016 drought conditions vs. 2017 typical conditions). Improvements are more pronounced in the 2016 drought year. In 2016, ABF is exceeded approximately 48% of the time in the baseline scenario compared to 71% for Iteration 3.

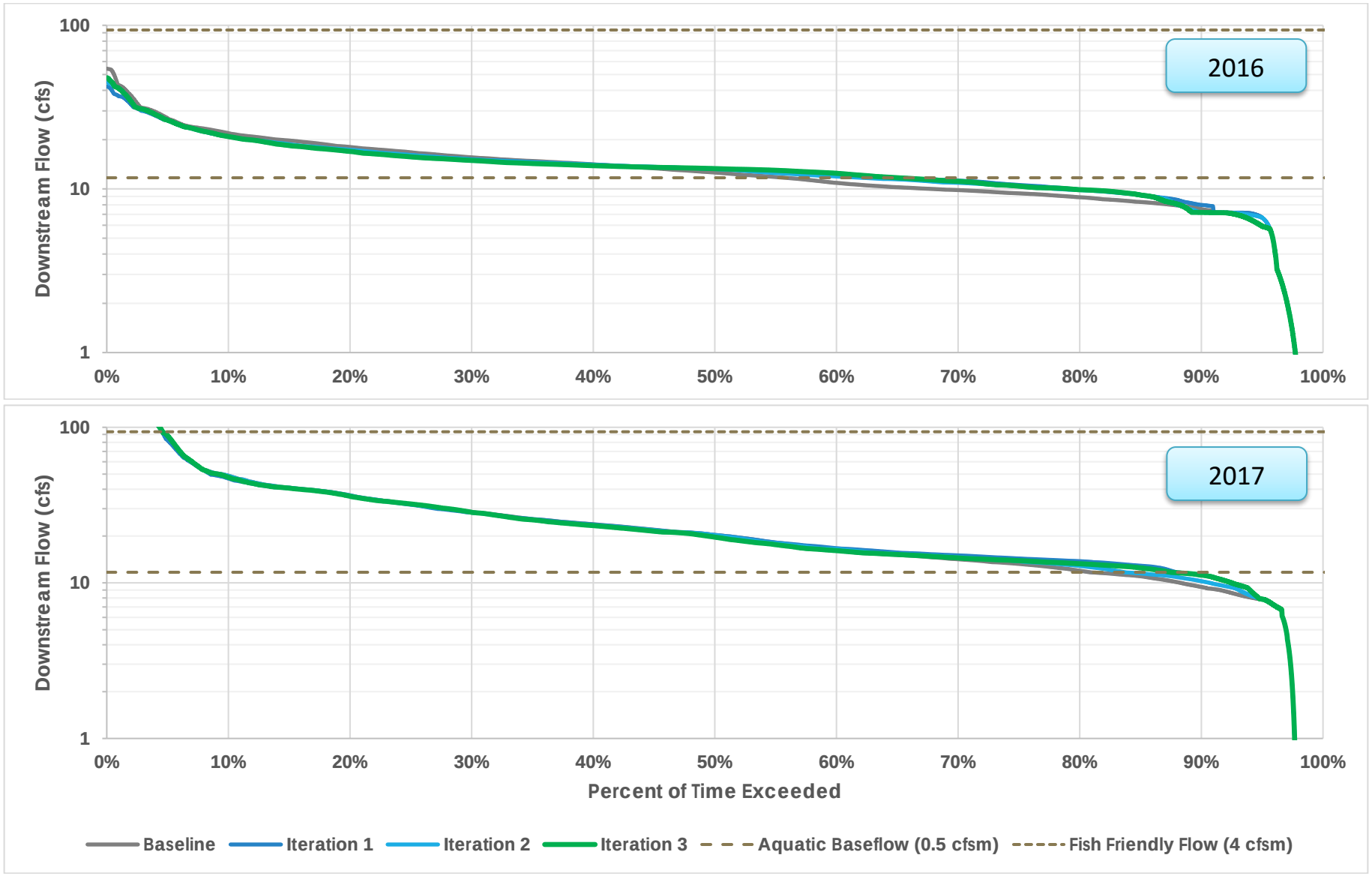


Figure 4.9: Forge Pond Outlet downstream streamflow exceedance curve (2016 drought conditions vs. 2017 typical conditions). Improvements are less pronounced than the headwater locations (Spectacle Pond Outlet and Mill Pond Dam); however, improvements in ABF ranging from 3% to 9% are expected. 2017 (typical) conditions where ABF is exceeded from 75% to 82% of the time are indicative of Forge Pond's ability to attenuate and maintain significant downstream streamflow, presumably from excess storage associated with extensive upstream wetland areas.

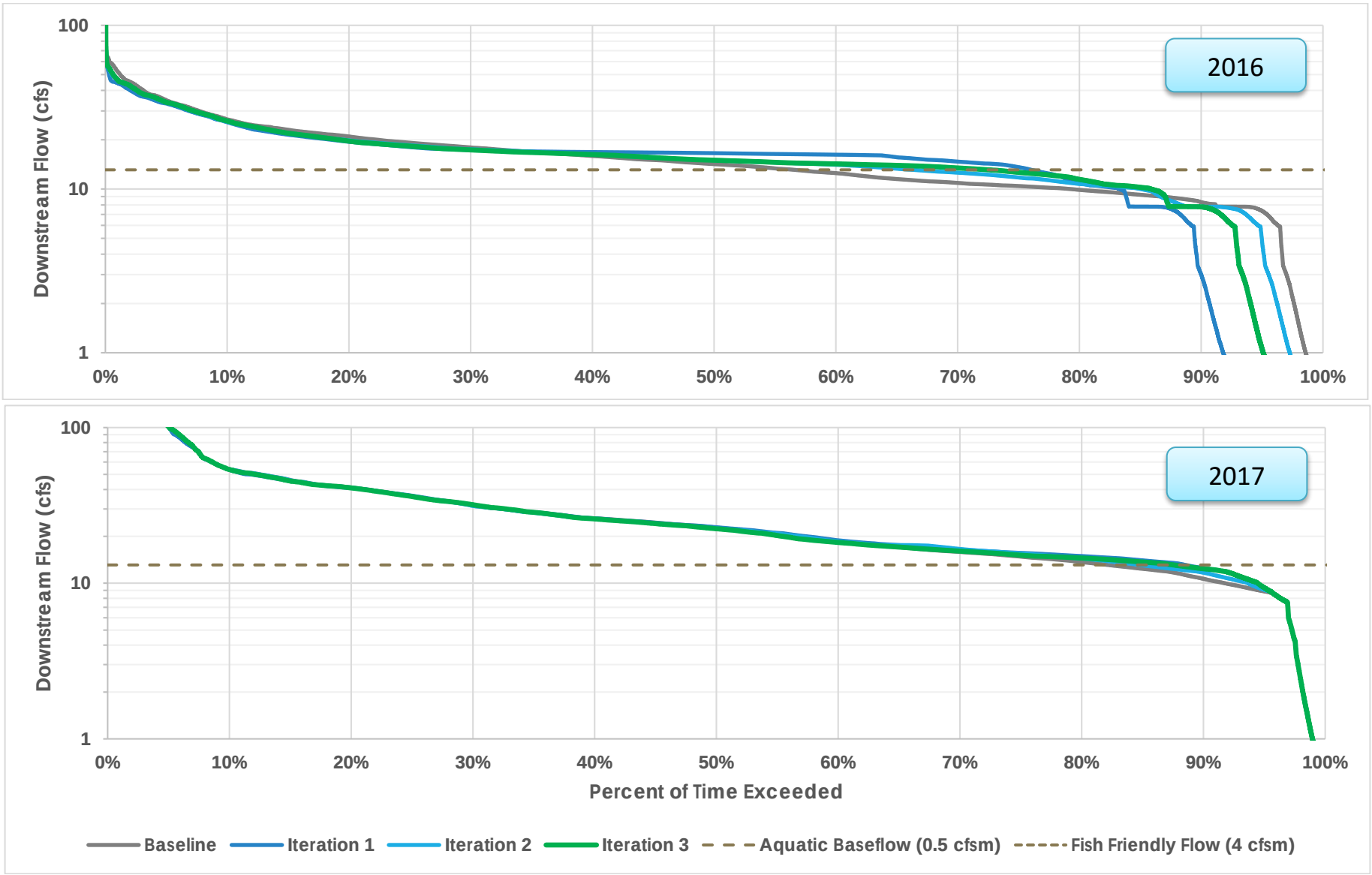


Figure 4.10: Stony Brook Dam downstream streamflow exceedance curve (2016 drought conditions vs. 2017 typical conditions) ("Fish friendly" flow of 104.8 cfs slightly out of axis display range). Significant improvements were simulated during the 2016 drought year, ranging from a baseline ABF exceedance of 56% to an exceedance of 76% for iteration 1. The tails on the right side of the exceedance curve are notable and indicate that releases are resulting in slightly worse streamflow during extreme low conditions. This phenomenon is likely a result of times of no or extremely low flow when the impoundment is refilling after reaching the maximum allowable release level.

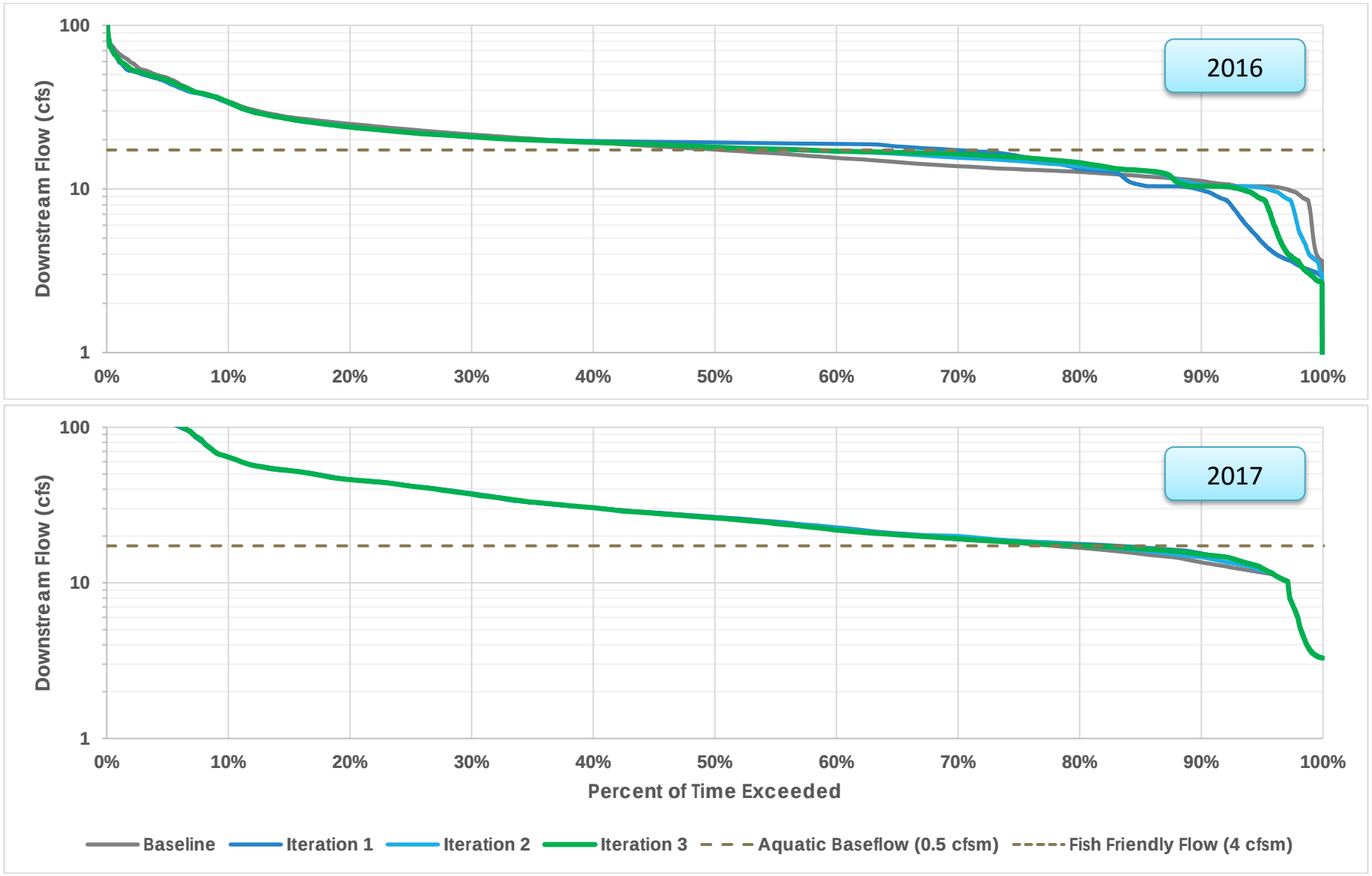


Figure 4.11: Depot Dam downstream streamflow exceedance curve (2016 drought conditions vs. 2017 typical conditions) ("Fish friendly" flow of 138 cfs slightly out of axis display range). It is notable that upstream adjustments can produce simulated improvements at Depot Dam during drought conditions (9%, Iteration 3) and typical conditions (4%, Iteration 3). Results indicate that Depot Dam is susceptible to drought conditions with a baseline ABF of 50% in 2016 as compared to 74% in 2017. Results further indicate that Depot Dam is sensitive to Stony Brook Dam when the impoundment water level is too low to release as evidenced by the far right of the 2016 curve.

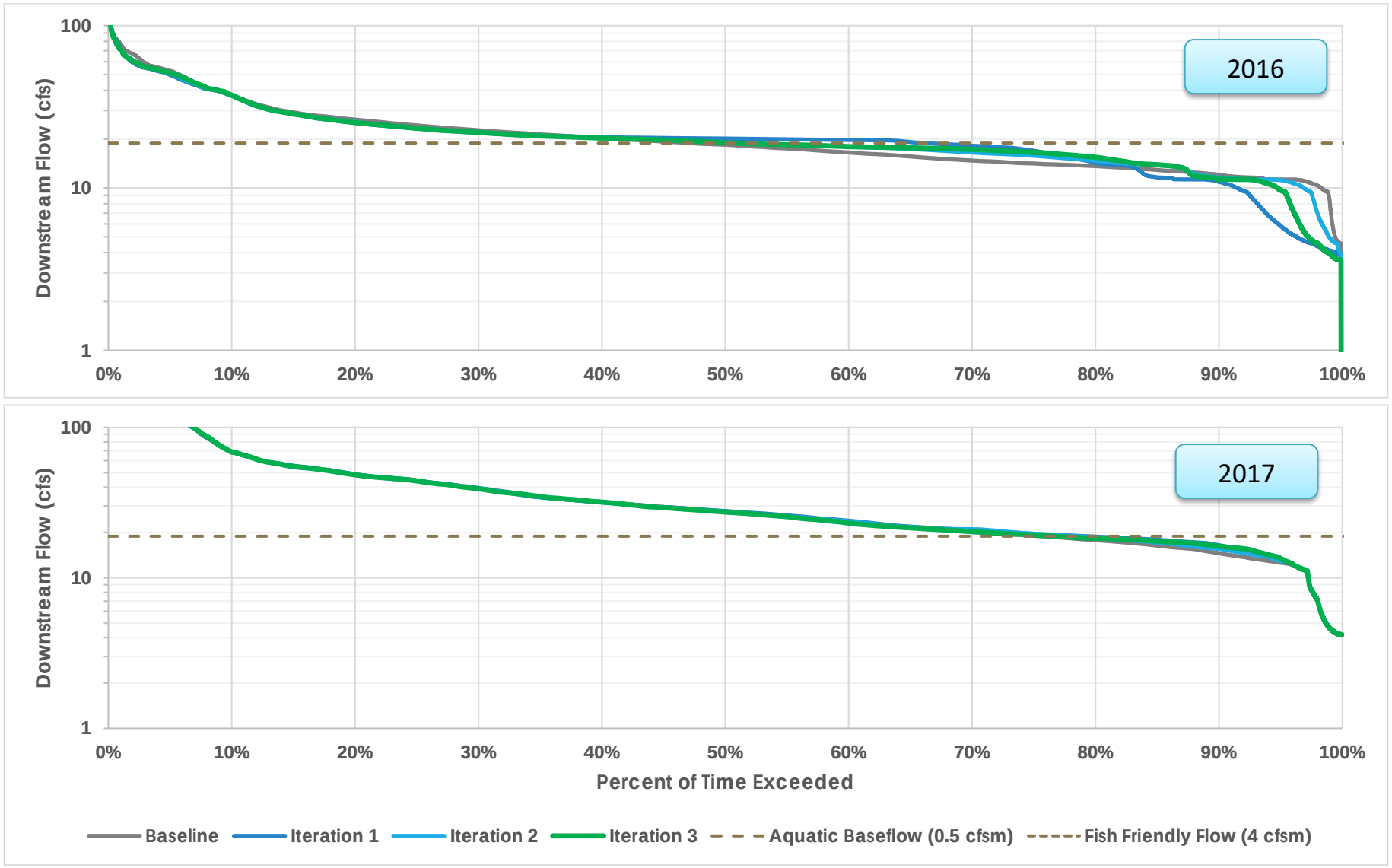


Figure 4.12: Brookside Mills Dam downstream streamflow exceedance curve (2016 drought conditions vs. 2017 typical conditions) ("Fish friendly" flow of 151.2 cfs slightly out of axis display range). It is notable that upstream adjustments can produce simulated improvements at Brookside Mills Dam during drought conditions (6%, Iteration 3) and typical conditions (3%, Iteration 3). Results indicate that Brookside Mills is more susceptible to drought conditions than Depot Dam with a baseline ABF of 47% in 2016 as compared to 77% in 2017 and that Brookside Mills Dam is sensitive to Stony Brook Dam when the impoundment water level is too low to release the ABF.

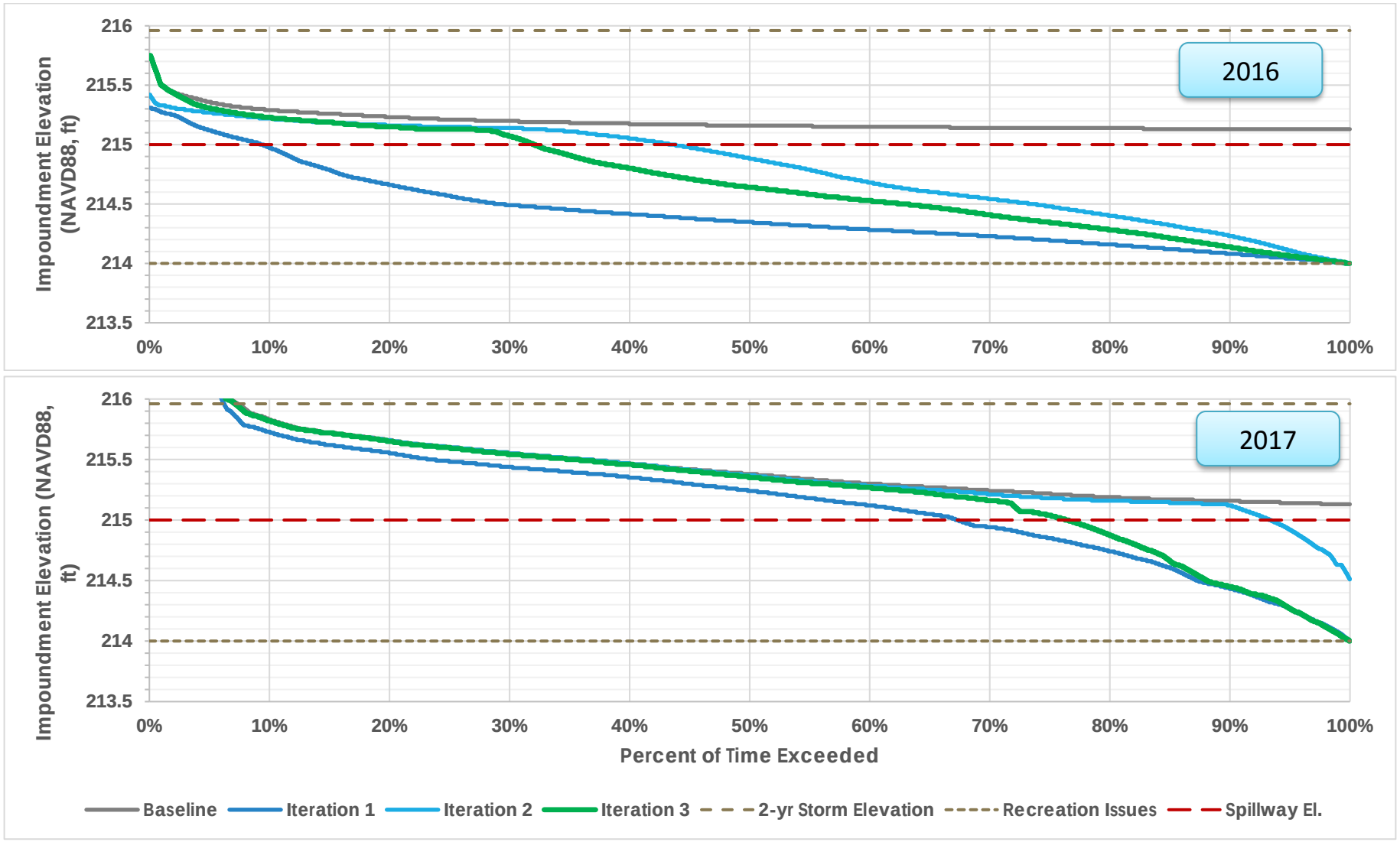


Figure 4.13: Mill Pond Dam impoundment water level exceedance curve (2016 drought conditions vs. 2017 typical conditions, April 1 through October 31). The water level is effectively managed between the spillway and the maximum allowable release level (i.e. "recreation issues") for all model scenarios. Results indicate that low flow releases are frequently made to maintain downstream ABF. For Iteration 1, the water level was below the spillway 90% of the time in April through October during the drought year as compared to approximately 35% in 2017. This was improved in subsequent iterations to approximately 70% in the drought year by incorporating forecasting into the logic to minimize release frequency.

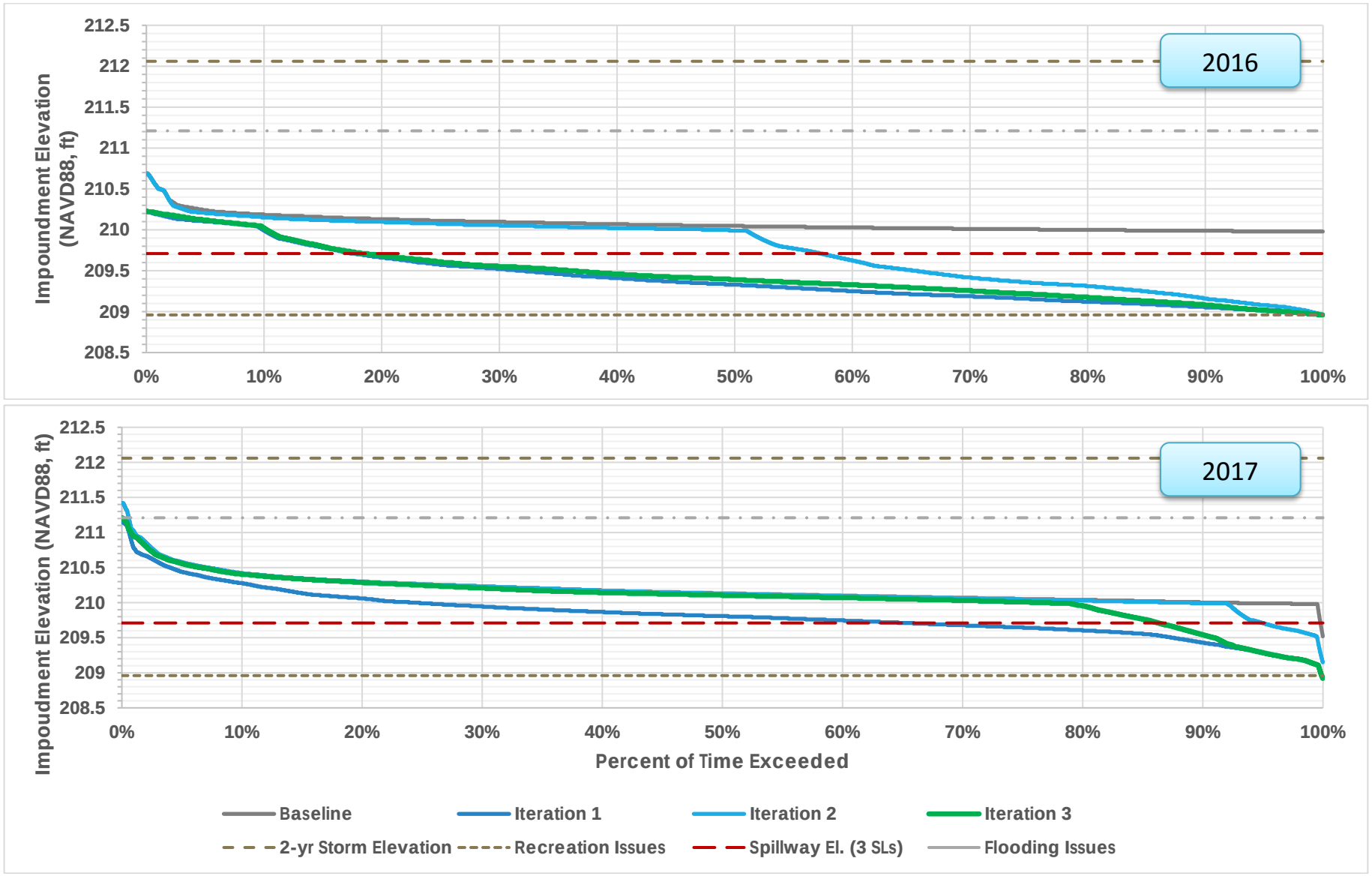


Figure 4.14: Spectacle Pond Outlet impoundment water level exceedance curve (2016 drought conditions vs. 2017 typical conditions, April 1 through October 15). The water level is effectively managed between the spillway and the maximum allowable release level (i.e. "recreation issues") for all model scenarios. Results indicate that low flow releases are frequently made to maintain downstream ABF, particularly in the drought year. Like Mill Pond Dam, implementation of forecasting into the release logic results in more effective management of simulated water levels.

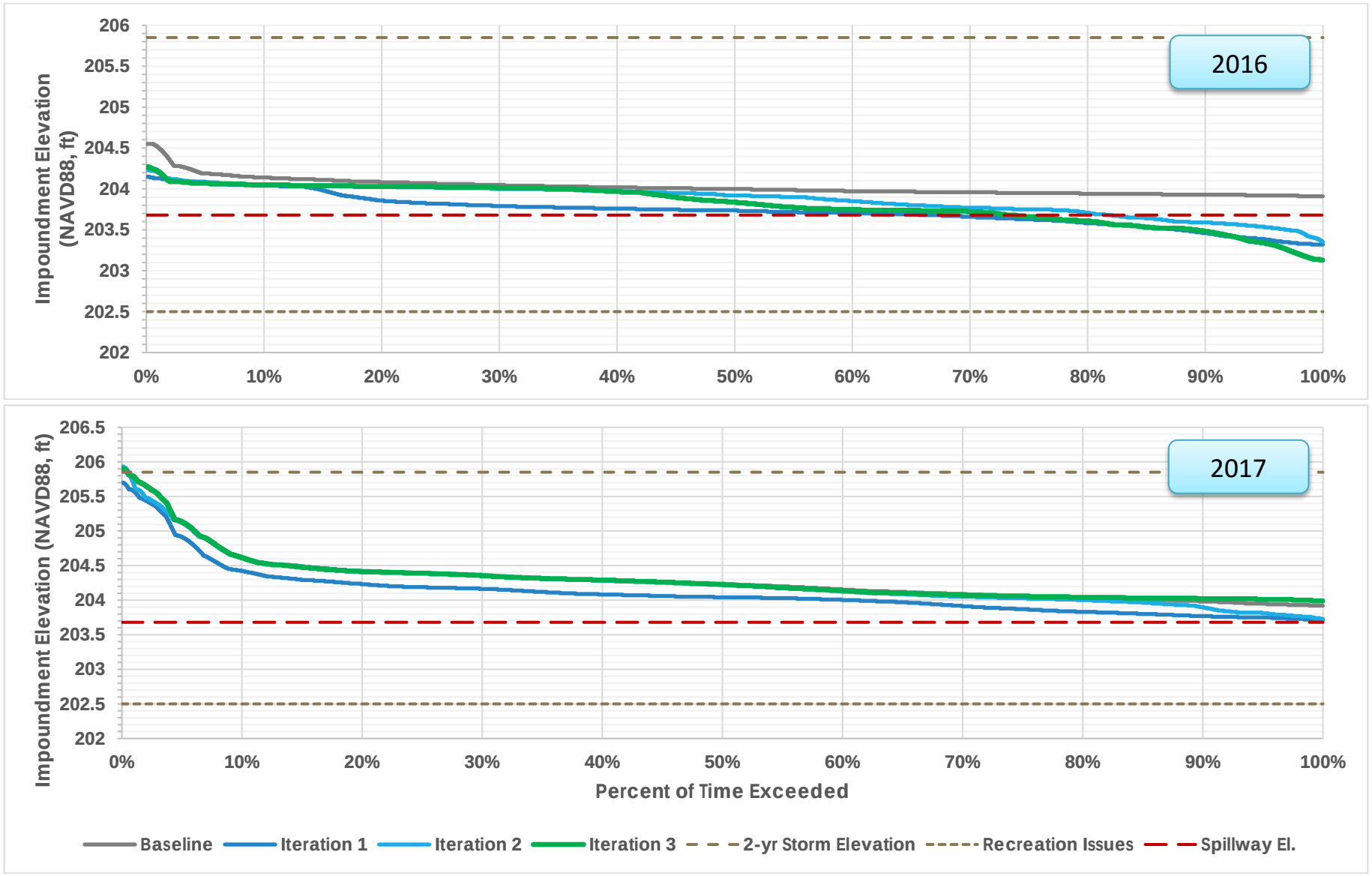


Figure 4.15: Forge Pond Dam impoundment water level exceedance curve (2016 drought conditions vs. 2017 typical conditions, April 1 through October 31). The water level is effectively managed between the spillway and the maximum allowable release level (i.e. "recreation issues") for all model scenarios. The response of Forge Pond to releases is more muted than its upstream counterparts (Spectacle Pond and Mill Pond); however, similar behavior was simulated where releases were frequent in the drought year, resulting in water levels slightly below the spillway approximately 30% of the time.

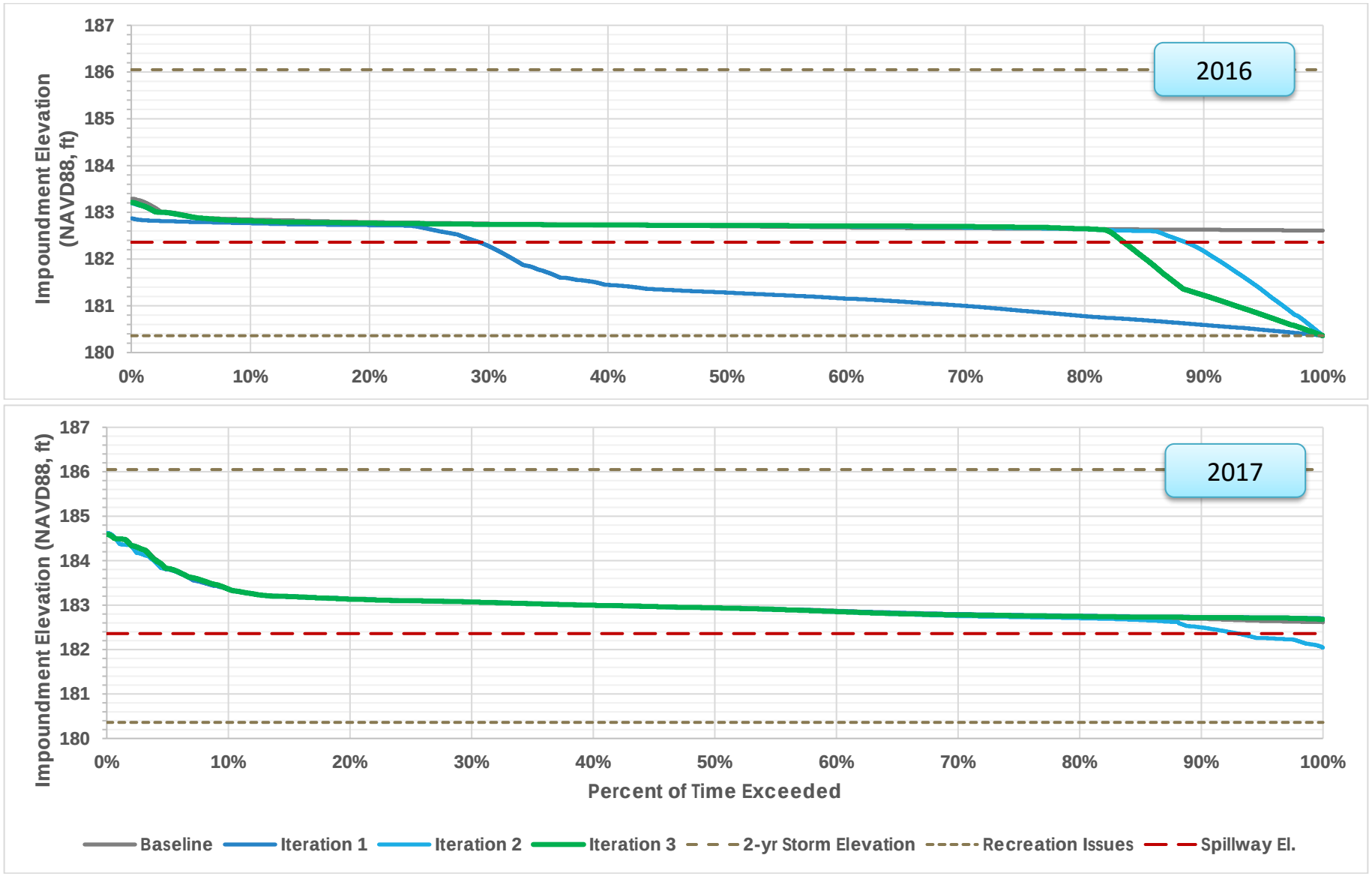


Figure 4.16: Stony Brook Dam impoundment water level exceedance curve (2016 drought conditions vs. 2017 typical conditions, April 1 through October 31). The water level is effectively managed between the spillway and the maximum allowable release level (i.e. "recreation issues") for all model scenarios. Given the relatively small amount of storage beneath the spillway, Stony Brook Dam rapidly draws down when releases are made. Therefore, implementation of forecasting into the release logic results in more effective management of simulated water levels.

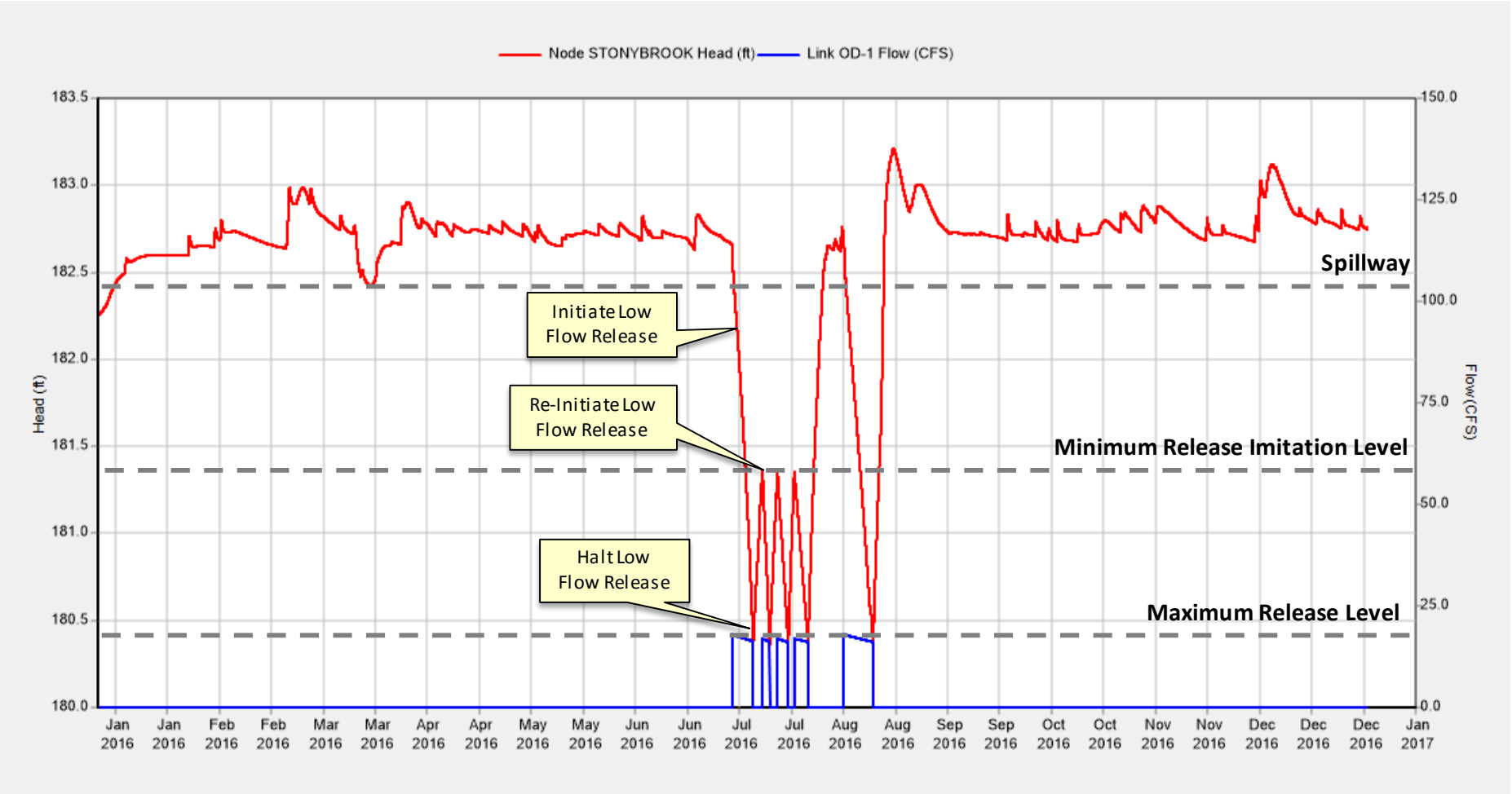


Figure 4.17a: Stony Brook Impoundment sensitivity comparison – Iteration 3 results. Five (5) simulated releases were required during the drought year of 2016. Note the rapid rate of drawdown of the impoundment during the low flow release required to maintain ABF of at least 13 cfs.

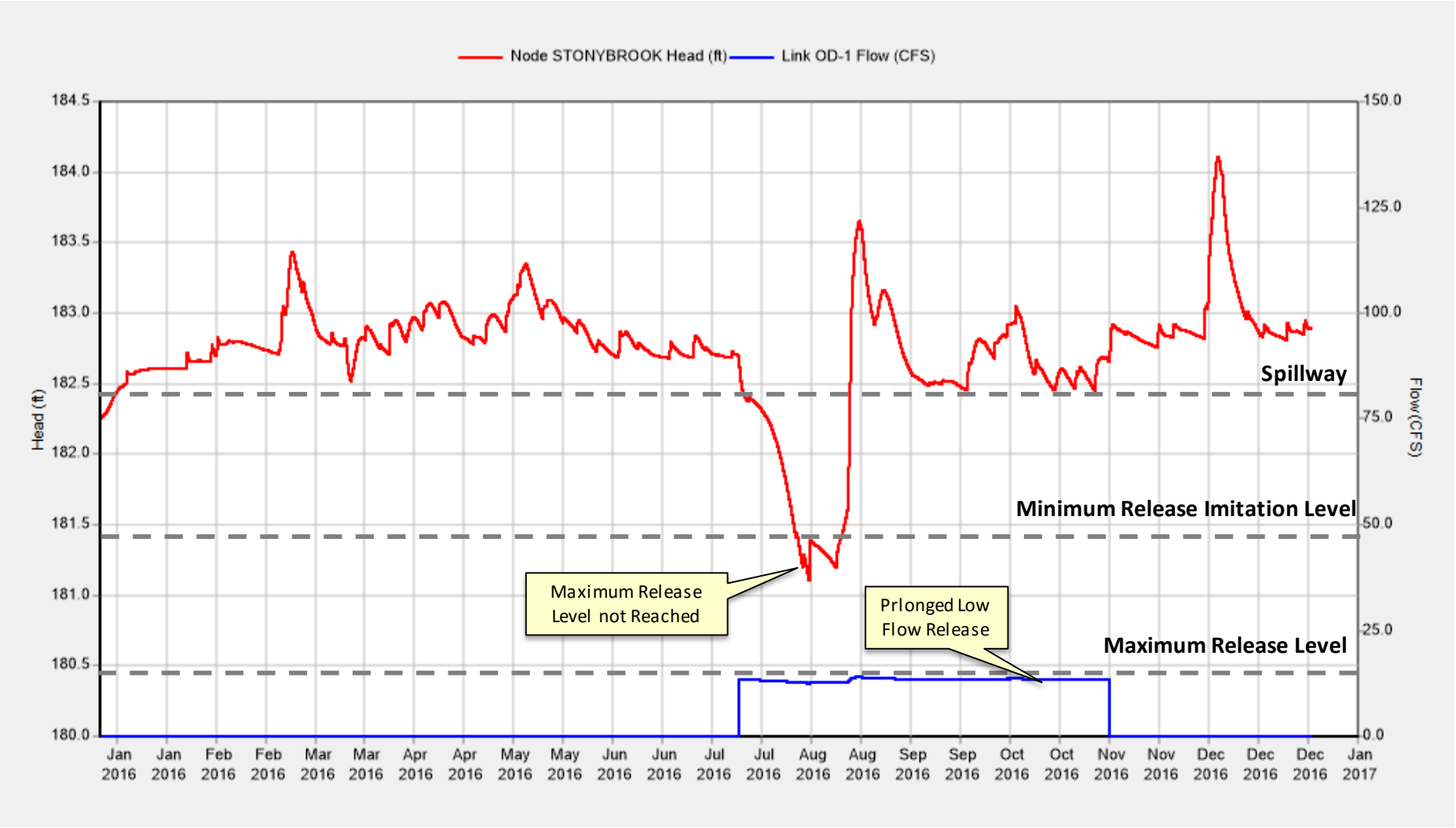


Figure 4.17b: Stony Brook Impoundment sensitivity comparison – modified Iteration 3 results (decreased sluice gate opening from 4 inches to 3 inches). Just one (1) prolonged release was required during the drought year of 2016; however, the flow release is reduced to approximately 13.5 cfs which is in line with Stony Brook's ABF (13), but below the ABF of downstream locations, Depot Dam (17.3 cfs) and Brookside Mills Dam (18.9 cfs).

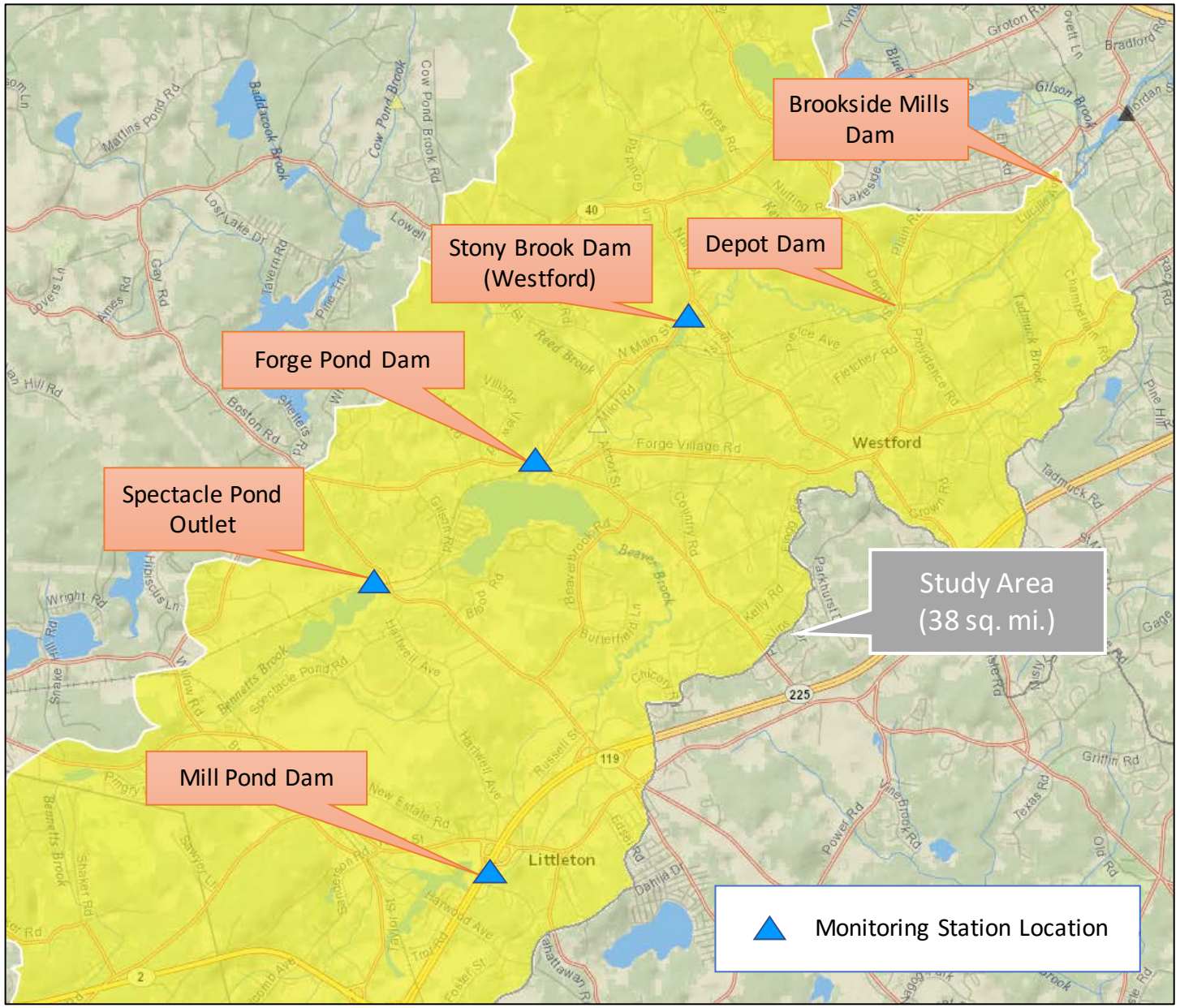


Figure 5.1: Monitoring Station Locations. Yellow shaded area represents approximate watershed boundary.

Appendix B
Supporting Model Input Data

Table B-1: Calibrated Subcatchment Characteristics

Subwatershed ID	Subwatershed Area (acres)	Percent Impervious	Width (ft)	Average Percent Slope	N-Imperv (mannings)	N-Perv (mannings)	S-Imperv (dep. Storage)	S-Perv (dep. Storage)	Weighted CN	Drying Time (days)
1	3959	5.5%	4135	9.1%	0.013	0.53	0.05	0.05	61.1	7
2	1278	12.6%	1745	6.8%	0.013	0.46	0.05	0.05	69.3	7
3	756	11.1%	1535	6.8%	0.013	0.48	0.05	0.05	65.5	7
4	841	12.1%	2530	9.4%	0.013	0.50	0.05	0.05	64.0	7
5	2979	10.2%	3445	9.3%	0.013	0.51	0.05	0.05	69.2	7
6	3814	8.8%	3345	9.4%	0.013	0.51	0.05	0.05	68.8	7
7	838	18.5%	6210	6.6%	0.013	0.44	0.05	0.05	66.8	7
8	827	30.2%	3170	8.8%	0.013	0.46	0.05	0.05	65.8	7
9	623	9.7%	3180	8.6%	0.013	0.48	0.05	0.05	61.0	7
10	2105	12.1%	5865	6.7%	0.013	0.59	0.05	0.05	62.5	7
11	1675	13.4%	3240	7.6%	0.013	0.46	0.05	0.05	70.1	7
12	1262	8.1%	4590	5.5%	0.013	0.48	0.05	0.05	64.8	7
13	1027	13.1%	2620	9.3%	0.013	0.51	0.05	0.05	62.5	7
14	1354	13.6%	2420	8.6%	0.013	0.50	0.05	0.05	62.2	7
15	861	10.4%	2125	7.4%	0.013	0.44	0.05	0.05	63.9	7

1. Values that were changed during calibration are highlighted.
2. Calibration width is half the value of the original width.
3. Original “N-Imperv mannings” was 0.010

Table B-2: Mill Pond Stage-Storage Curve Data

Elevation (ft, NAVD88)	Depth from Bottom (ft)	Cumulative Area (ft^2)	Source
207.00	0	0	ESS (1999)
208.00	1	10,890	ESS (1999)
209.00	2	186,795	ESS (1999)
210.00	3	450,525	ESS (1999)
211.00	4	944,727	ESS (1999)
212.00	5	1,355,945	ESS (1999)
215.00	8	4,100,764	LiDAR Calculation (Spillway El.) (MassGIS, 2012)
217.00	10	7,563,500	LiDAR Calculation (MassGIS, 2012)

Table B-3: Spectacle Pond Stage-Storage Curve Data

Elevation (ft, NAVD88)	Depth from Bottom (ft)	Cumulative Area (ft^2)	Source
170.38	0	0	ESS (2000)
175.38	5	31,507	ESS (2000)
180.38	10	119,728	ESS (2000)
185.38	15	237,601	ESS (2000)
190.30	20	386,983	ESS (2000)
195.38	25	614,205	ESS (2000)
200.38	30	1,413,006	ESS (2000)
205.38	35	2,300,213	ESS (2000)
208.33	38	3,468,860	LiDAR Calculation (MassGIS, 2012)
210.38	40	5,306,845	LiDAR Calculation (MassGIS, 2012)
212.36	42	6,649,519	LiDAR Calculation (MassGIS, 2012), Appx. top elevation of stop log weir

Table B-4: Forge Pond Stage-Storage Curve Data

Elevation (ft, NAVD88)	Depth from Bottom (ft)	Cumulative Area (ft^2)	Source
173.68	0	135,535	Geosyntec Consultants (2017)
175.68	2	397,531	Geosyntec Consultants (2017)
177.68	4	663,137	Geosyntec Consultants (2017)
179.68	6	986,644	Geosyntec Consultants (2017)
181.68	8	1,346,959	Geosyntec Consultants (2017)
183.68	10	1,777,377	Geosyntec Consultants (2017)
185.68	12	2,407,529	Geosyntec Consultants (2017)
187.68	14	3,143,985	Geosyntec Consultants (2017)
189.68	16	3,874,578	Geosyntec Consultants (2017)
191.68	18	4,842,546	Geosyntec Consultants (2017)
193.68	20	5,709,050	Geosyntec Consultants (2017)
195.68	22	6,327,590	Geosyntec Consultants (2017)
197.68	24	6,745,849	Geosyntec Consultants (2017)
199.68	26	7,265,868	Geosyntec Consultants (2017)
201.68	28	8,038,722	Geosyntec Consultants (2017)
203.68	30	8,671,915	Geosyntec Consultants (2017) (Spillway El.)

Table B-5: Stony Brook Dam Impoundment Stage-Storage Curve Data

Elevation (ft, NAVD88)	Depth from Bottom (ft)	Cumulative Area (ft^2)	Source
167.36	0	58	ESS (2015)
172.36	5	46,432	ESS (2015)
177.36	10	236,108	ESS (2015)
182.36	15	2,236,982	LiDAR Calculation (Spillway El.) (MassGIS, 2012)

Table B-6: Channel Characteristics (Irregular Transects / Cross Sections)[1]

Conduit ID	General Location	Length (ft)	Slope (ft/ft)	Friction Factor (n)	Source	Notes
C2	Stony Brook, Upstream of Stony Brook Impoundment	2450	0.00080	0.07	FEMA (2012)	FEMA Station ID: 32865; valley section 850 ft. D/S from town farm rd. bridge
C3	Gilson Brook	650	0.00031	0.08	MassGIS (2012)	Invert was assumed based on estimated water depth of nearest culvert (Gilson Road) and water surface elevation measured by LiDAR data.
C4	Beaver Brook	7133	0.00056	0.08	MassGIS (2012)	Invert was assumed based on estimated water depth of nearest culvert (Beaver Brook Road) and water surface elevation measured by LiDAR data.
C5	Beaver Brook	95	0.02000	0.08	MassGIS (2012)	Invert was assumed based on estimated water depth of nearest culvert (Great Road) and water surface elevation measured by LiDAR data.
C7	Beaver Brook	7799	0.00008	0.08	MassGIS (2012)	Invert was assumed based on estimated water depth of nearest culvert (Great Road) and water surface elevation measured by LiDAR data.
C8	Beaver Brook	4609	0.00017	0.08	MassGIS (2012)	Invert was assumed based on estimated water depth of nearest culvert (MA-2A) and water surface elevation measured by LiDAR data.
C10	Gilson Brook	2200	0.00182	0.08	MassGIS (2012)	Invert was assumed based on estimated water depth of nearest culvert (Gilson Road) and water surface elevation measured by LiDAR data.
C13	Stony Brook, Upstream of Stony Brook Impoundment	1924	0.00156	0.07	FEMA (2012)	FEMA Station ID: 34695; valley section 949 ft. U/S from town farm rd. bridge
C14	Stony Brook, Downstream of Stony Brook Impoundment	10974	0.00027	0.08	FEMA (2012)	FEMA Station ID: 16336; U/S valley section at boston and maine rr bridge near westford station
C15	Stony Brook, Downstream of Stony Brook Impoundment	5585	0.00122	0.075	FEMA (2012)	FEMA Station ID: 8235; U/S valley section at stony brook road bridge
C17	Stony Brook, Downstream of Stony Brook Impoundment	799	0.00638	0.07	FEMA (2012)	FEMA Station ID: 27380; U/S valley section at river st. bridge
C18	Stony Brook, Downstream of Stony Brook Impoundment	2427	0.00049	0.075	FEMA (2012)	FEMA Station ID: 13868; U/S valley section at depot road bridge
C19	Stony Brook, Downstream of Stony Brook Impoundment	3964	0.00191	0.07	FEMA (2012)	FEMA Station ID: 6505; valley section 1665 ft. D/S from stony brook road bridge

Conduit ID	General Location	Length (ft)	Slope (ft/ft)	Friction Factor (n)	Source	Notes
C21	Stony Brook, Upstream of Stony Brook Impoundment	166	0.01325	0.07	FEMA (2012)	FEMA Station ID: 36860; valley section 51 ft. D/S from dam between forge pond and stony brook
C22	Stony Brook, Upstream of Stony Brook Impoundment	765	0.01007	0.07	Geosyntec Consultants (2017)	Field observations from Geosyntec DAM Dashboard pilot project at the Abbot Mill Property
C23	Stony Brook, Downstream of Stony Brook Impoundment	45	0.06444	0.08	FEMA (2012)	FEMA Station ID: 4198; D/S valley section at spillway U/S of chamberlain road bridge

1. Actual cross section data transmitted electronically with SWMM model as part of final report deliverable.

Table B-7: Culvert Conduit Characteristics

Conduit ID	Location	Shape	Number of Barrels	Height (ft)	Width (ft)	Radius (ft)	Length (ft)	Slope (ft/ft)	Friction Factor (n)	Source
P1	Beaver Brook, Culvert under Beaver Brook Road	Arch	2	7	13	-	32	0.0156	0.08	Limited field observations performed by WWD and LWD in April 2018 to supplement and verify FEMA (2012) data
P3	Beaver Brook, Culvert under Great Road	Modified Baskethandle	1	6.3	22	2.3	42	0.0048	0.08	Assumed geometry of most probable FEMA cross section (station: 2.262), based on culvert width (culvert was not visible at the time of field investigation)
P6	Beaver Brook, Culvert under MA-2A	Closed Rectangular	1	3.5	17	-	32	0.0094	0.08	Limited field observations performed by WWD and LWD in April 2018 to supplement and verify FEMA (2012) data
P9	Gilson Brook, Culvert under Great Road	Circular	2	-	-	4	112	0.0009	0.013	MA DOT (2010)
P10	Gilson Brook, Culvert under Gilson Road	Circular	2	-	-	4	36	0.0139	0.013	Limited field observations performed by WWD and LWD in April 2018
P11	Stony Brook, Culvert under Pleasant Street	Rectangular Triangular	1	5.1	25	0.35	70	0.0114	0.07	FEMA (2012)
P12	Stony Brook, Culvert under Town Farm Road	Arch	2	5	10	-	31	0.0010	0.07	FEMA (2012)
P13	Stony Brook, Culvert under Stone Arch Bridge	Modified Baskethandle	1	22.9	34.4	13.5	25	0.0040	0.07	FEMA (2012)
P16	Stony Brook, Culvert under River Street	Closed Rectangular	1	8	40	-	21	0.0003	0.08	FEMA (2012)
P17	Stony Brook, Culvert under railroad track near Westford Station	Rectangular Triangular	1	6.8	21.7	0.8	41	0.0005	0.08	FEMA (2012)
P18	Stony Brook, Culvert under Depot Road	Arch	2	9	12.5	-	21	0.0048	0.075	FEMA (2012)
P19	Stony Brook, Culvert under Stony Brook Road	Arch	2	6.5	15	-	15	0.0020	0.075	FEMA (2012)
P20	Stony Brook, Upstream Culvert under Abbot MIll	Arch	2	7	10	-	240	0.07	0.0017	FEMA (2012)
DEPOT DAM	Just downstream of Depot Dam, Depot Road	Circular	2	-	-	5	8	0.0625	0.013	Limited field observations performed by WWD and LWD in April 2018 to supplement and verify FEMA (2012) data

Conduit ID	Location	Shape	Number of Barrels	Height (ft)	Width (ft)	Radius (ft)	Length (ft)	Slope (ft/ft)	Friction Factor (n)	Source
BROOKSIDE DAM	Just upstream of Brookside Dam, Brookside Road	Horseshoe	2	6	-	-	8	0.0625	0.017	Limited field observations performed by WWD and LWD in April 2018 to supplement and verify FEMA (2012) data

Appendix C
Raw Model Output for Study Impoundments

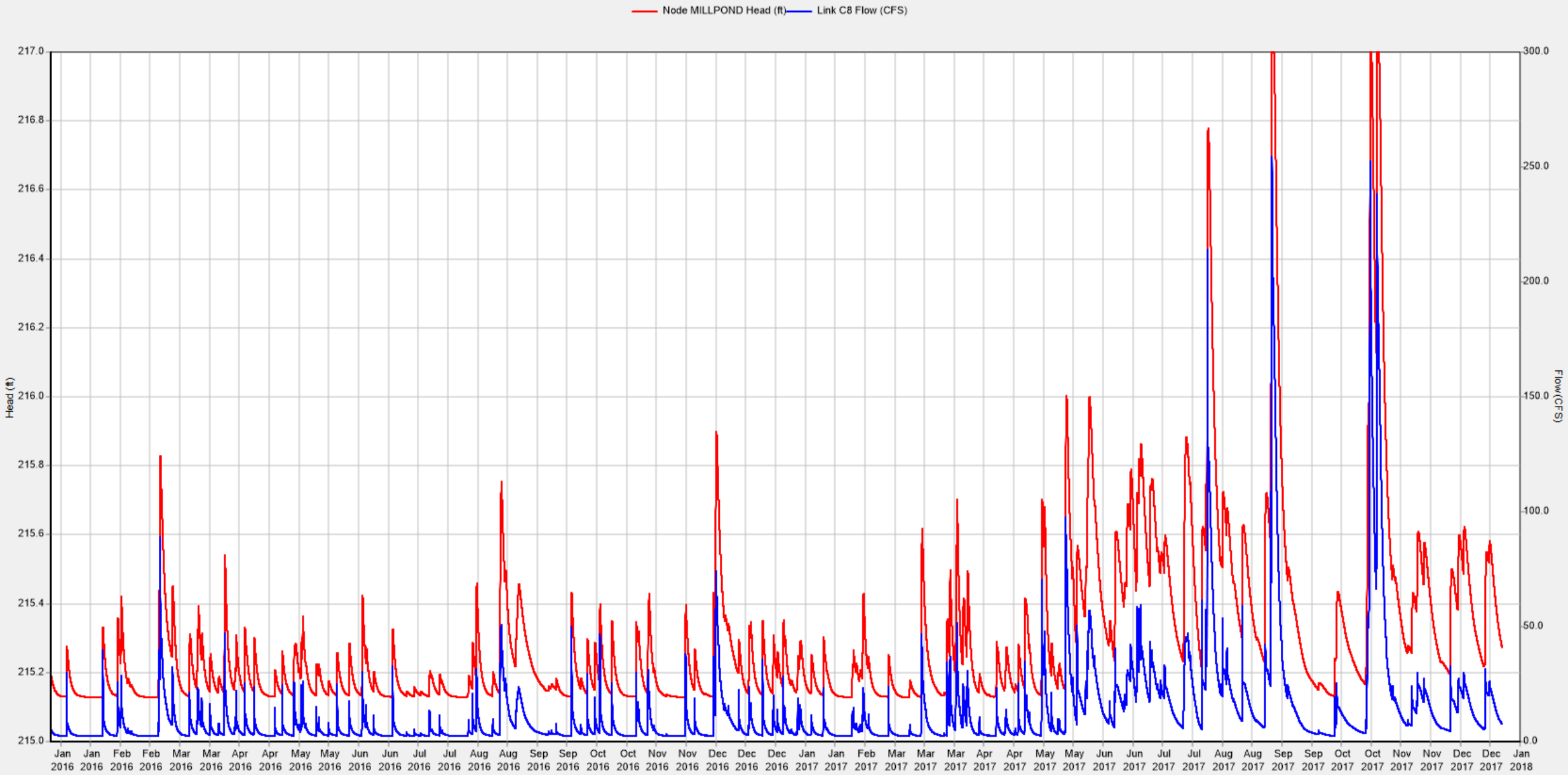


Figure C.1: Baseline – Mill Pond: Water Level and Downstream Streamflow (Link C8)

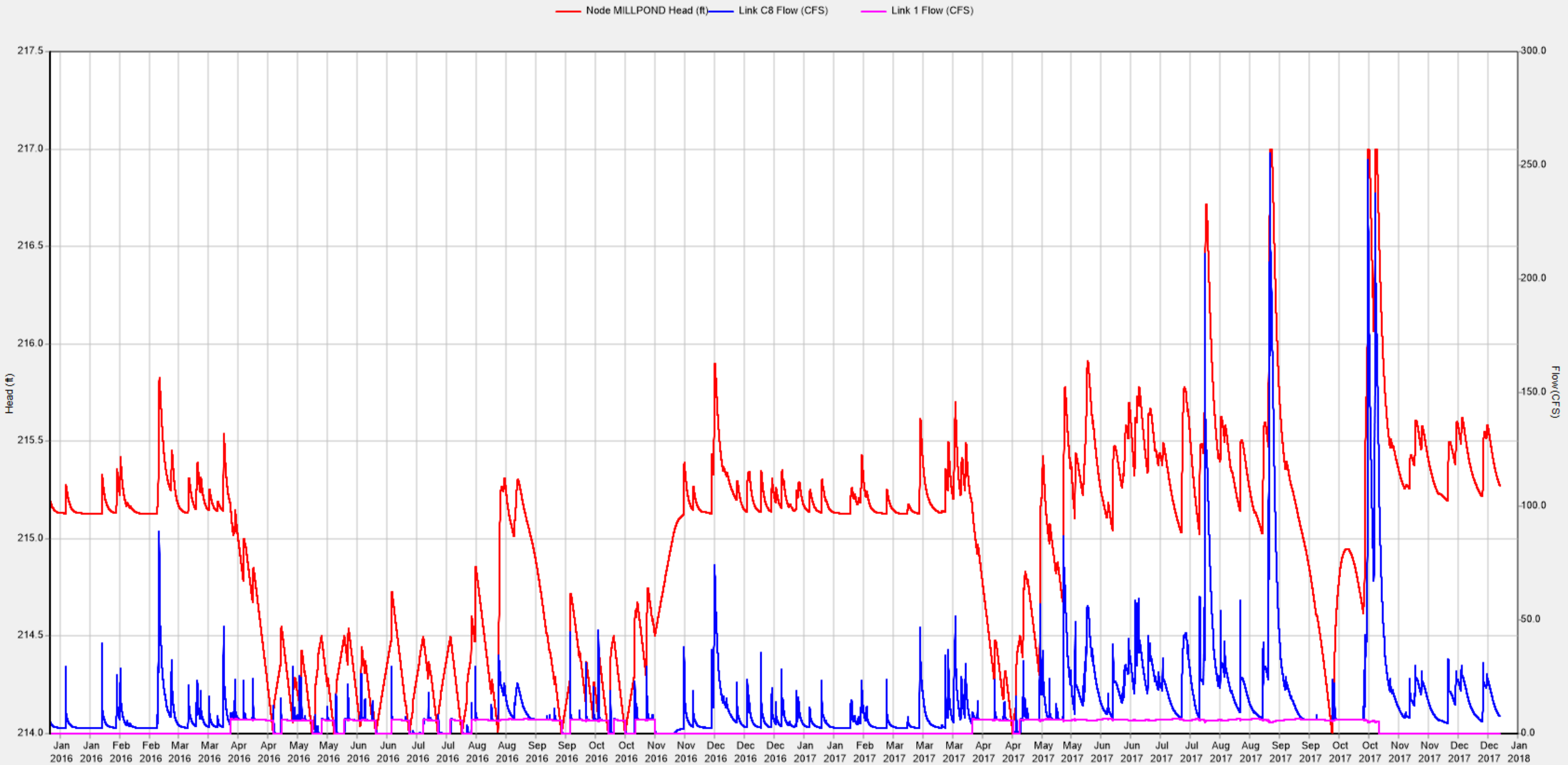


Figure C.2: Iteration 1 – Mill Pond: Water Level, Low Flow Release (Link 1), and Downstream Streamflow (Link C8)

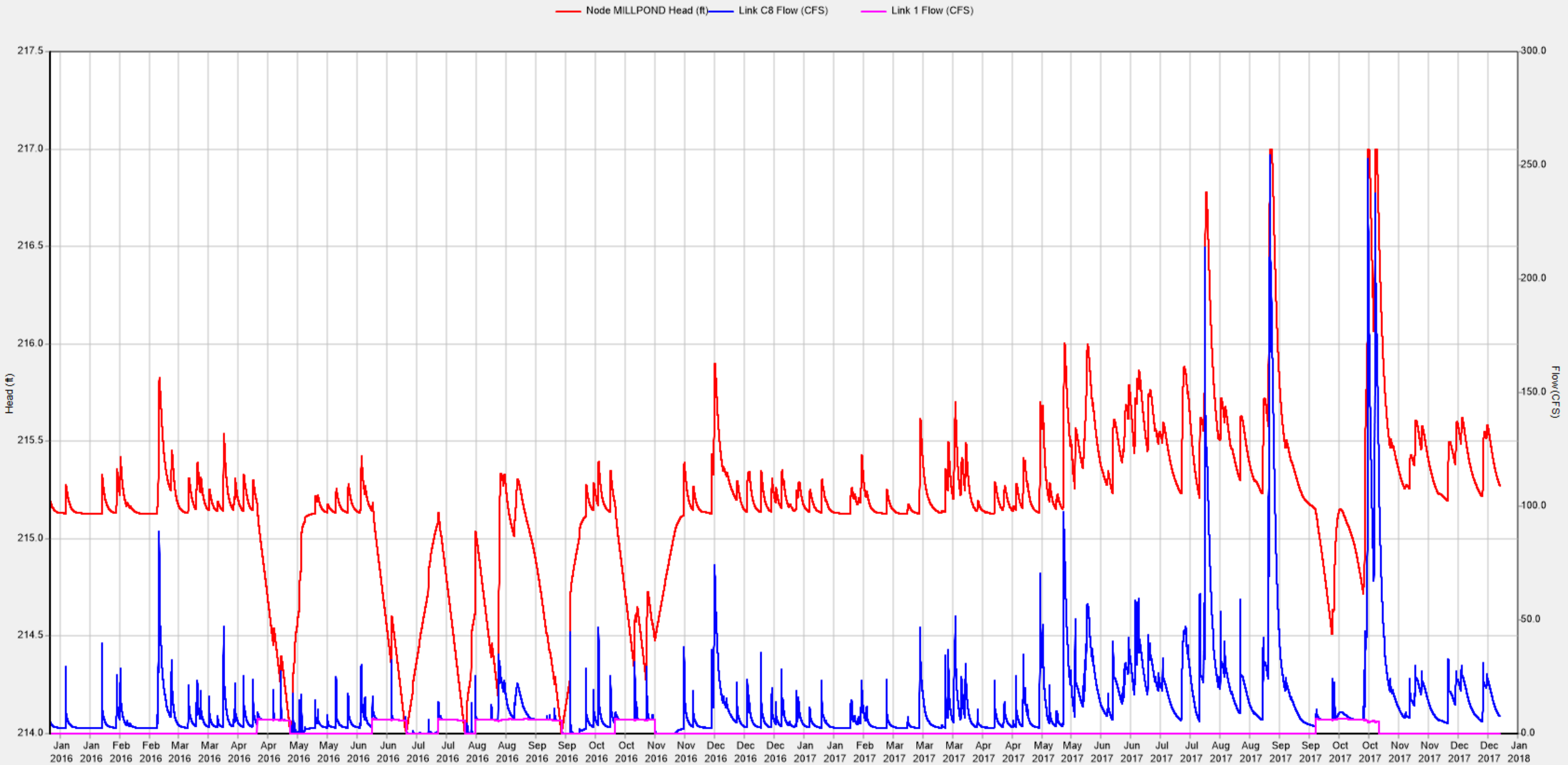


Figure C.3: Iteration 2 – Mill Pond: Water Level, Low Flow Release (Link 1), and Downstream Streamflow (Link C8)

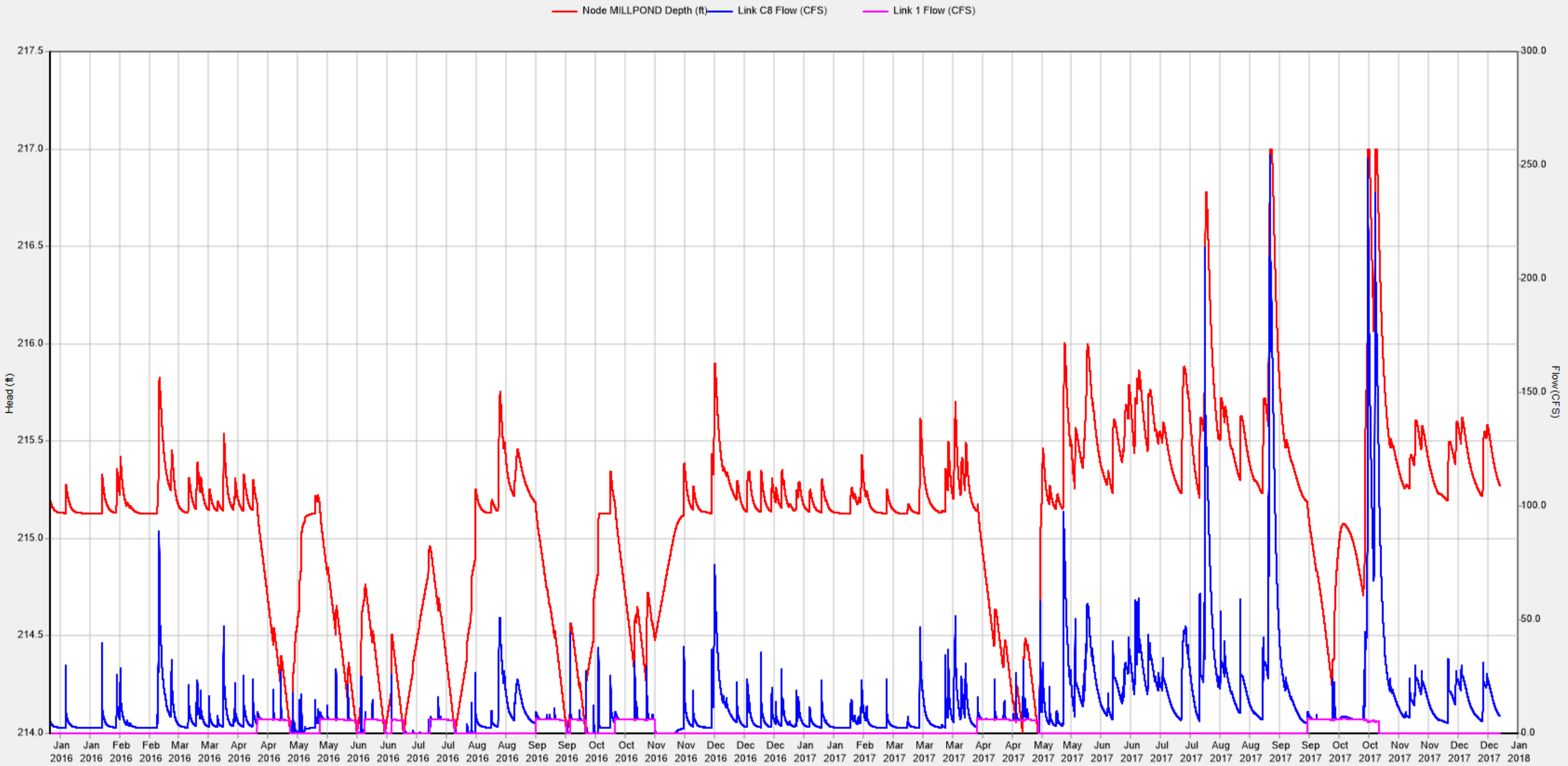


Figure C.4: Iteration 3 – Mill Pond: Water Level, Low Flow Release (Link 1), and Downstream Streamflow (Link C8)

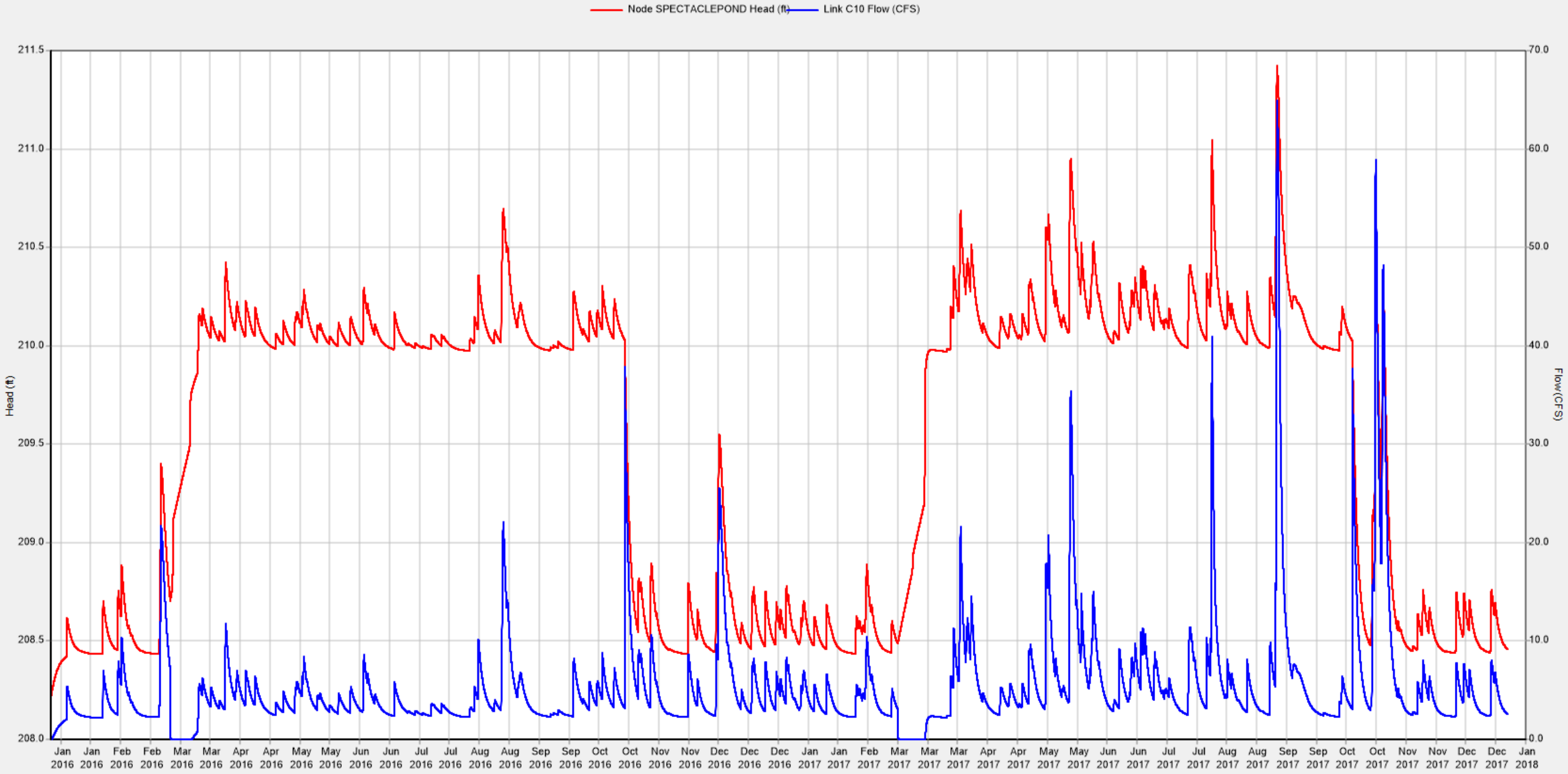


Figure C.5: Baseline – Spectacle Pond: Water Level and Downstream Streamflow (Link 10)

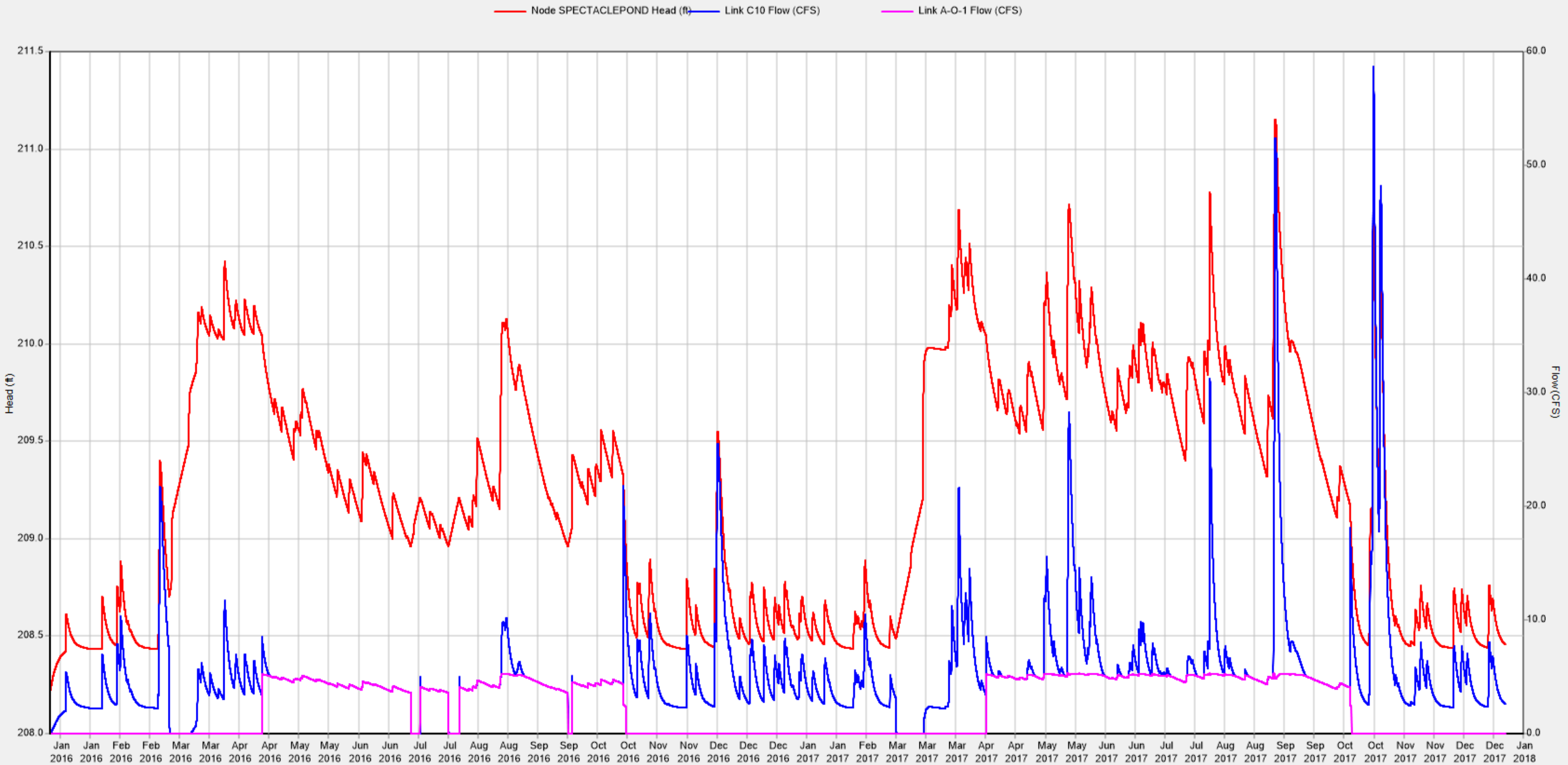


Figure C.6: Iteration 1 – Spectacle Pond: Water Level, Low Flow Release (Link A-O-1), and Downstream Streamflow (Link 10)

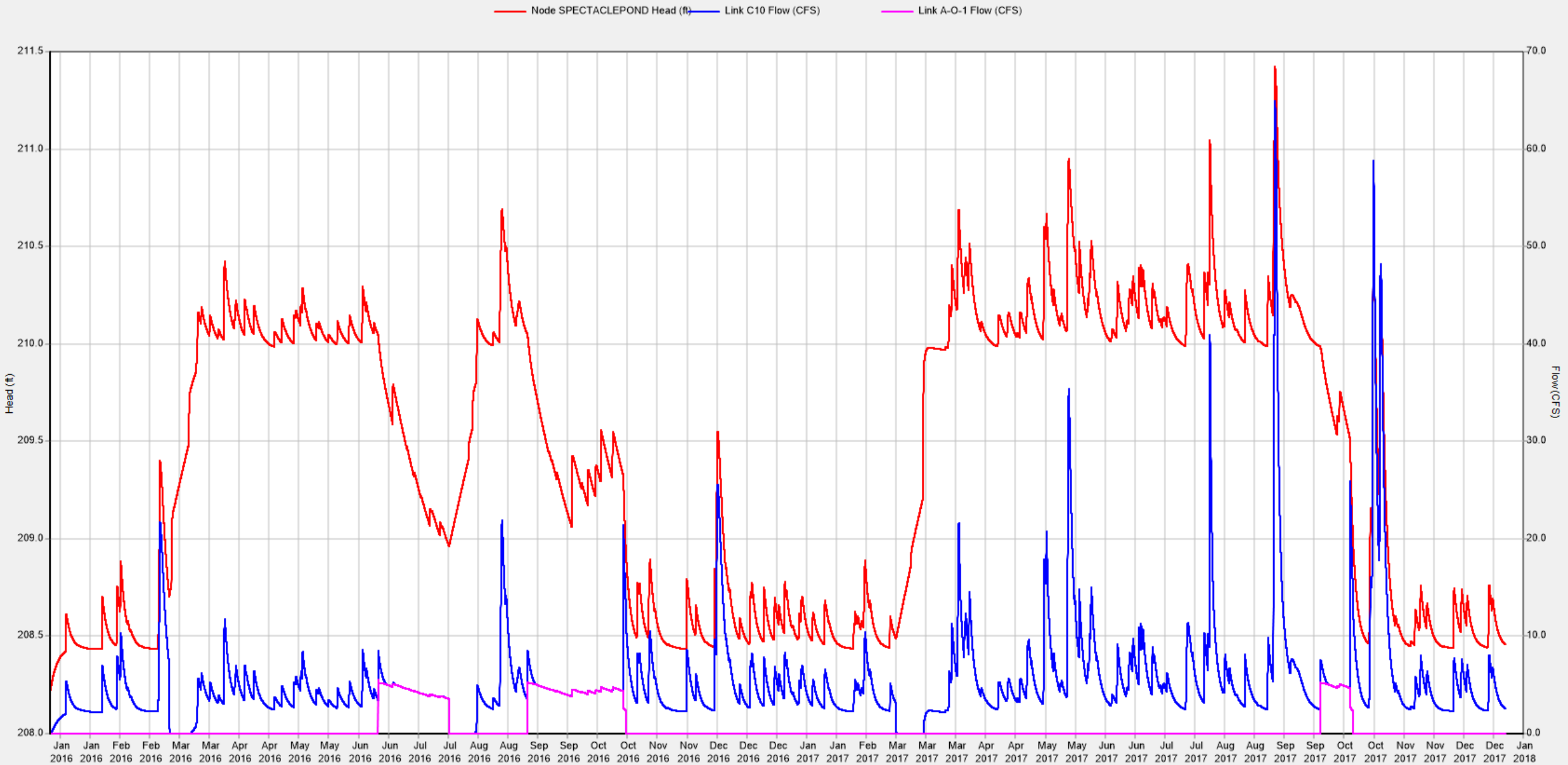


Figure C.7: Iteration 2 – Spectacle Pond: Water Level, Low Flow Release (Link A-O-1), and Downstream Streamflow (Link 10)

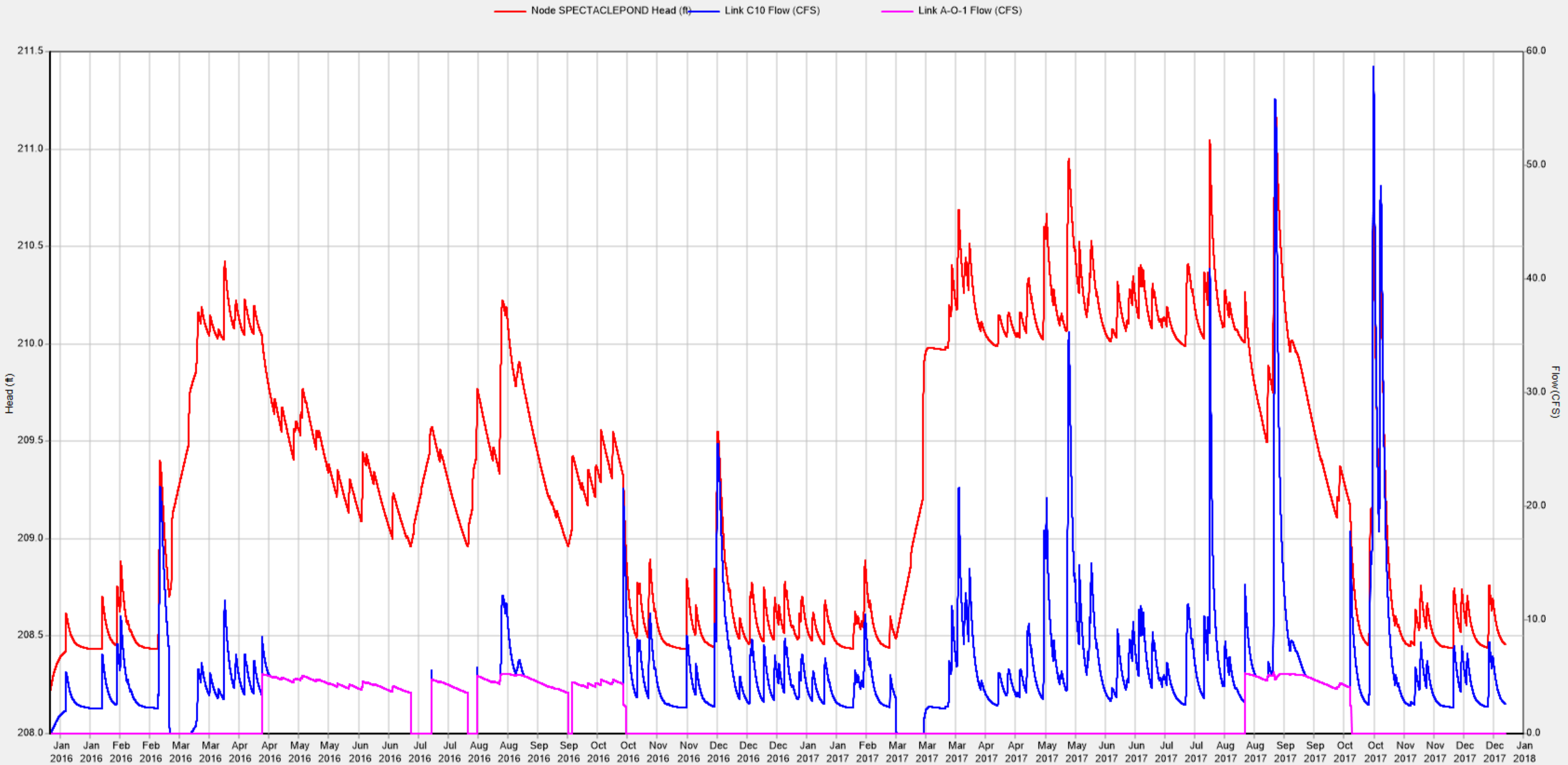


Figure C.8: Iteration 3 – Spectacle Pond: Water Level, Low Flow Release (Link A-O-1), and Downstream Streamflow (Link 10)

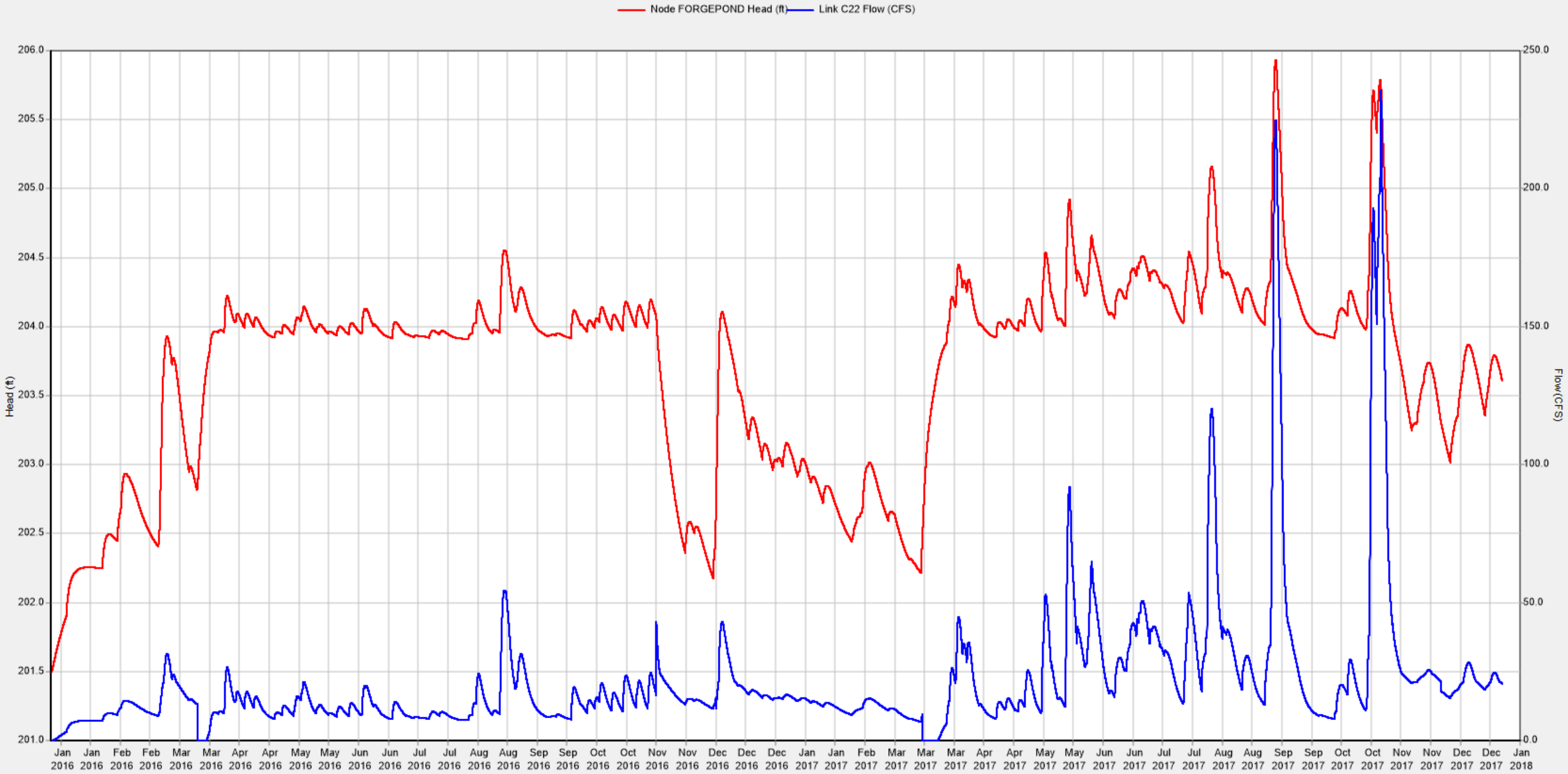


Figure C.9: Baseline – Forge Pond: Water Level and Downstream Streamflow (Link 22)

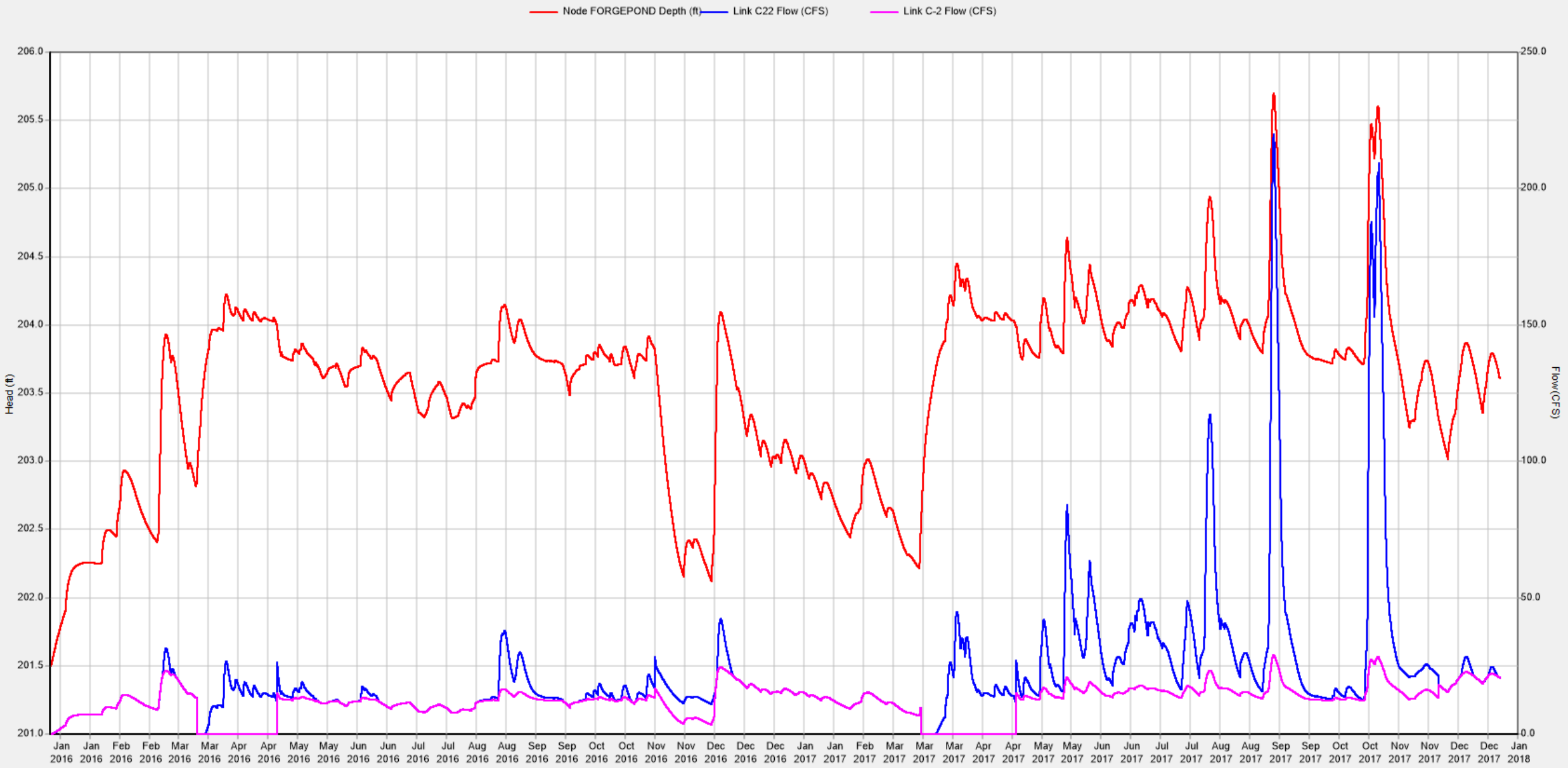


Figure C.10: Iteration 1 – Forge Pond: Water Level, Low Flow Release (Link C-2), and Downstream Streamflow (Link 22)

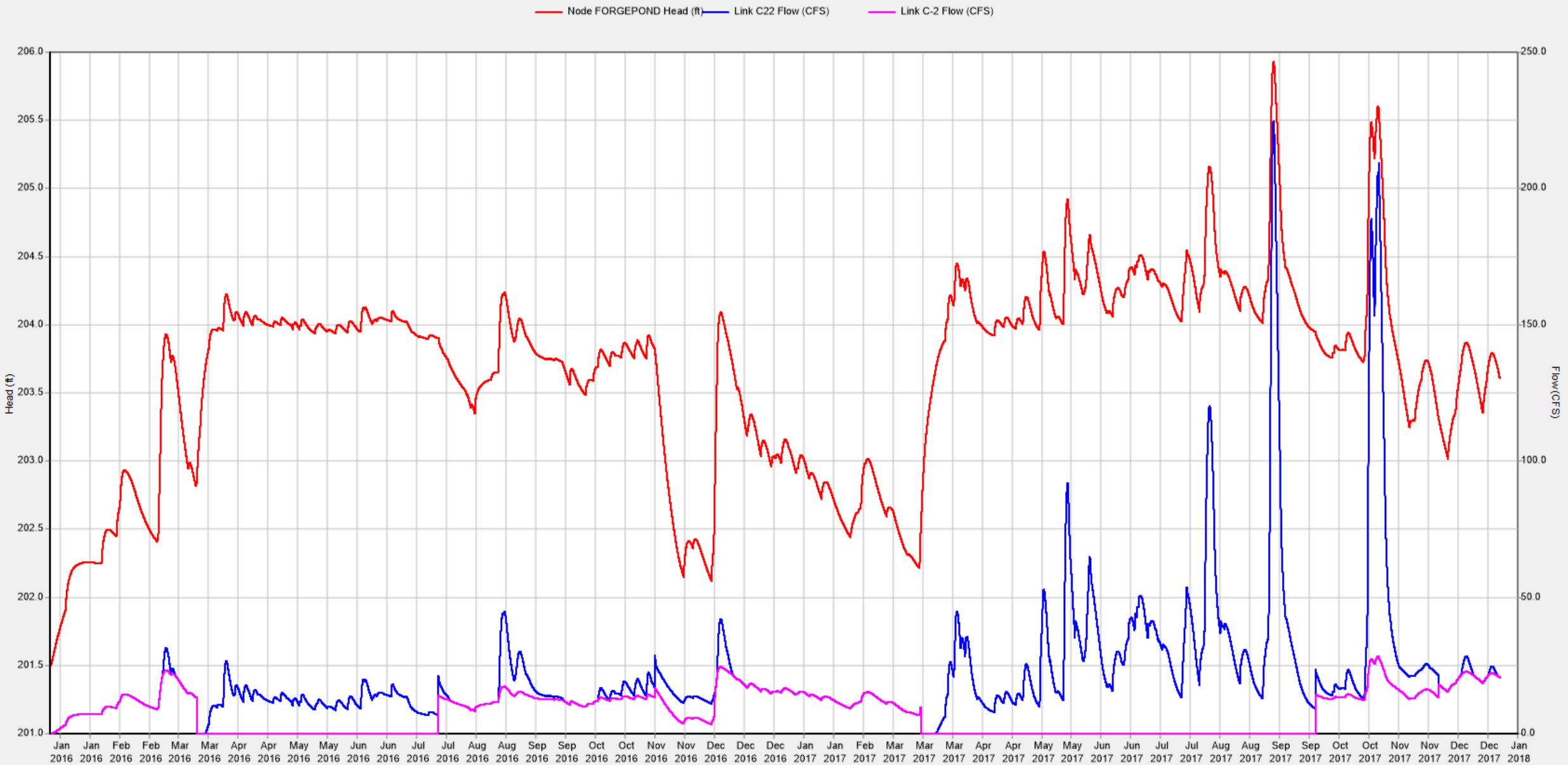


Figure C.11: Iteration 2 – Forge Pond: Water Level, Low Flow Release (Link C-2), and Downstream Streamflow (Link 22)

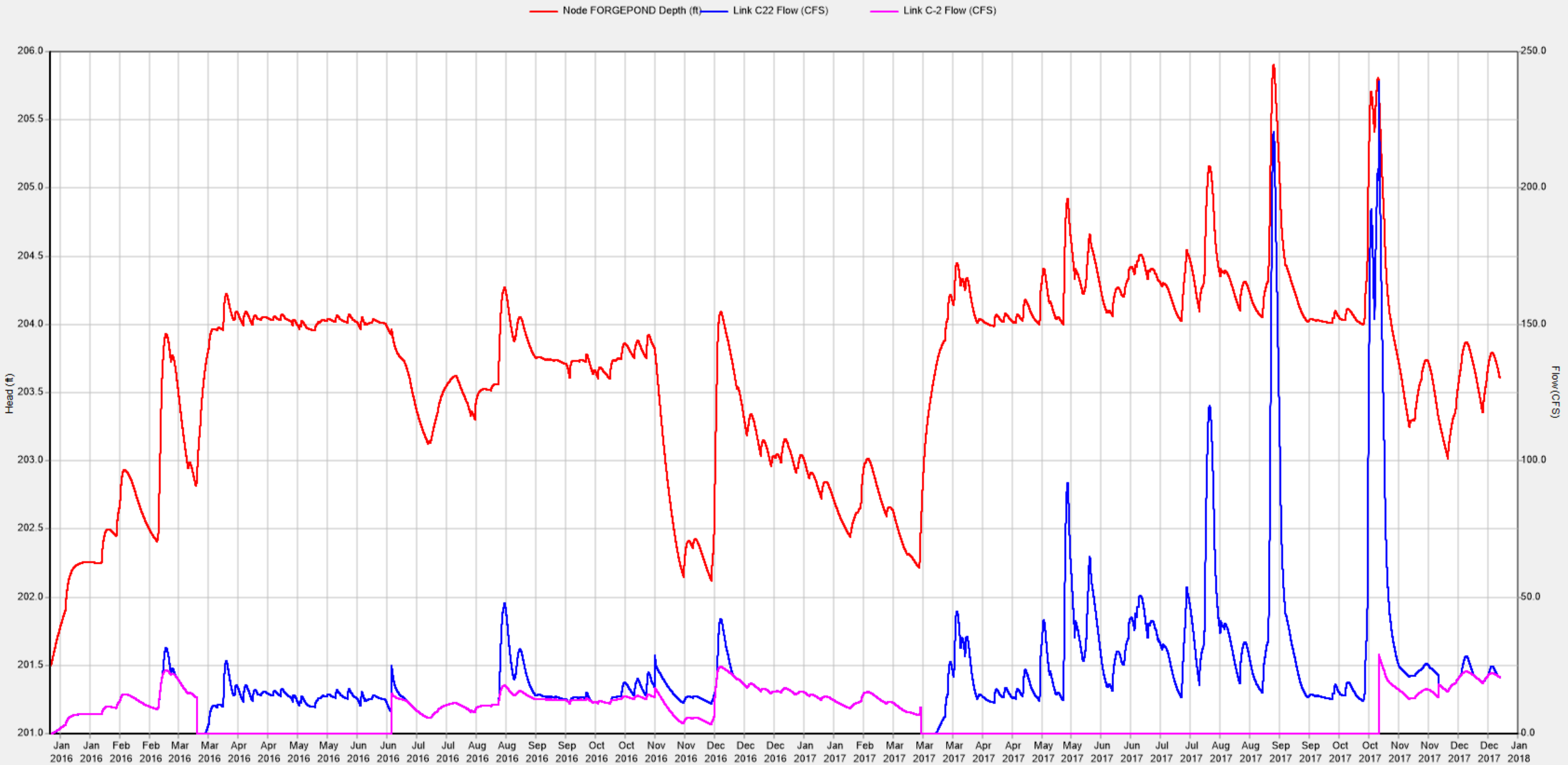


Figure C.12: Iteration 3 – Forge Pond: Water Level, Low Flow Release (Link C-2), and Downstream Streamflow (Link 22)

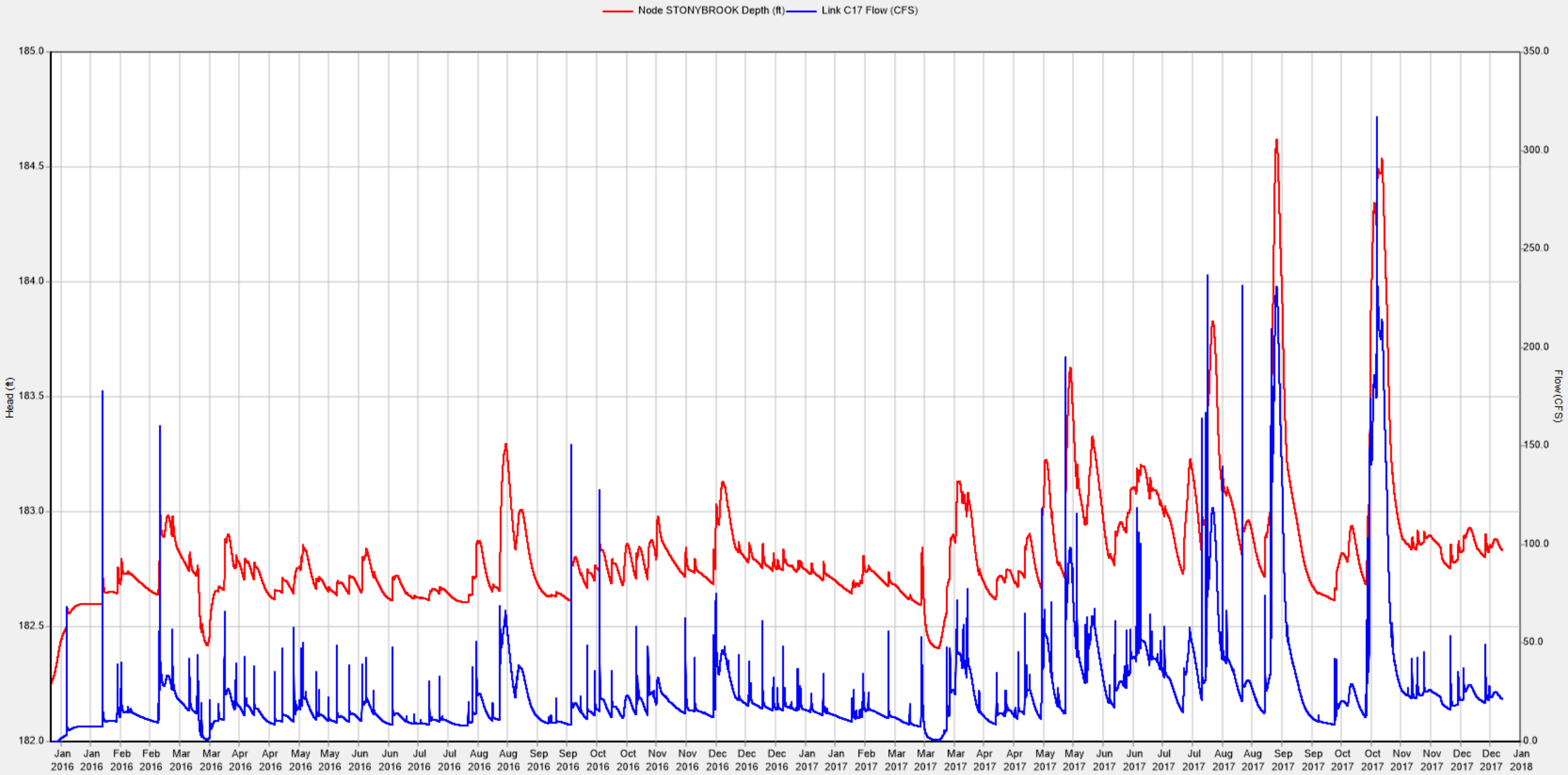


Figure C.13: Baseline – Stony Brook: Water Level and Downstream Streamflow (Link 17)

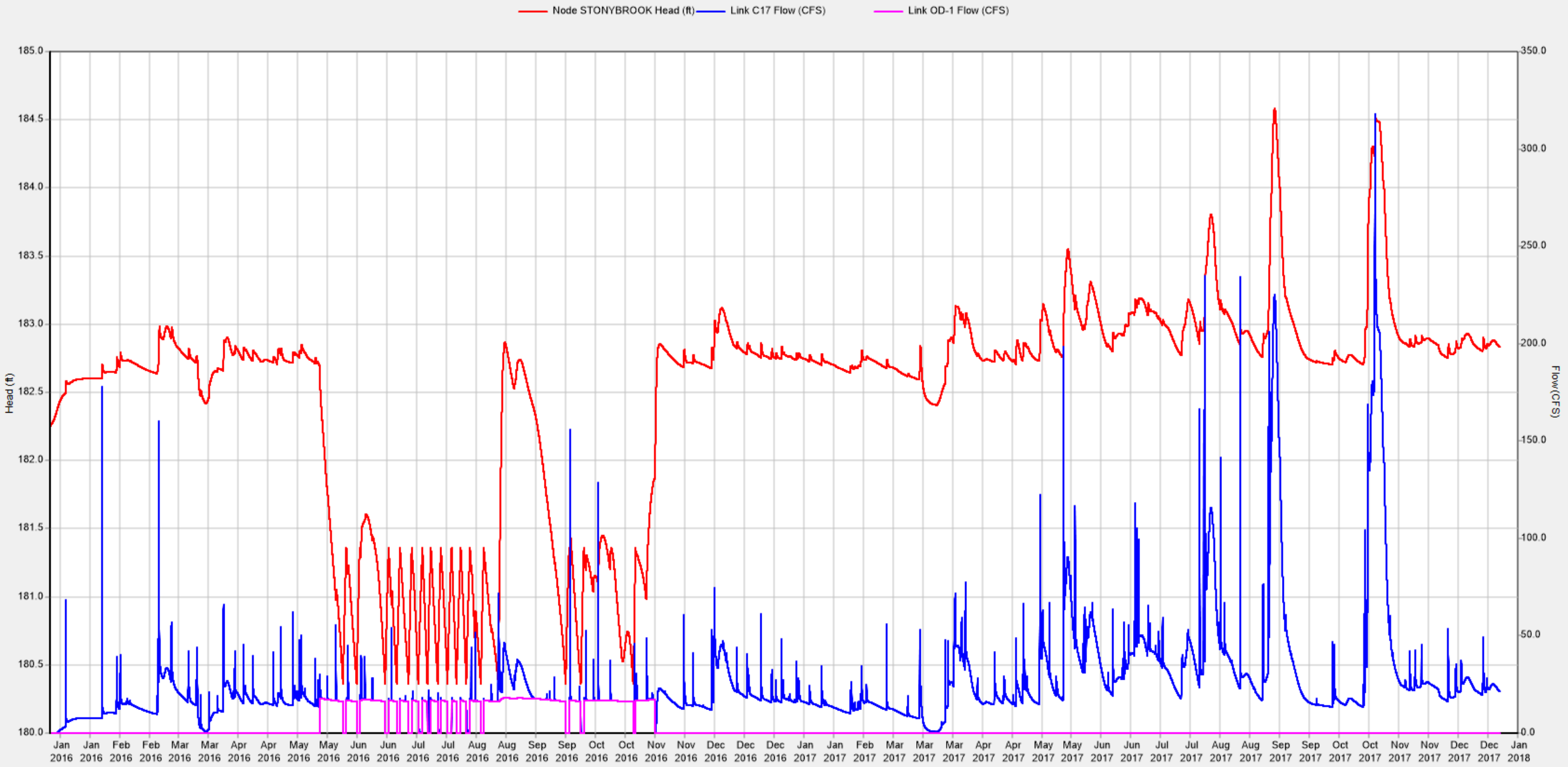


Figure C.14: Iteration 1 – Stony Brook: Water Level, Low Flow Release (Link OD-1), and Downstream Streamflow (Link 17)

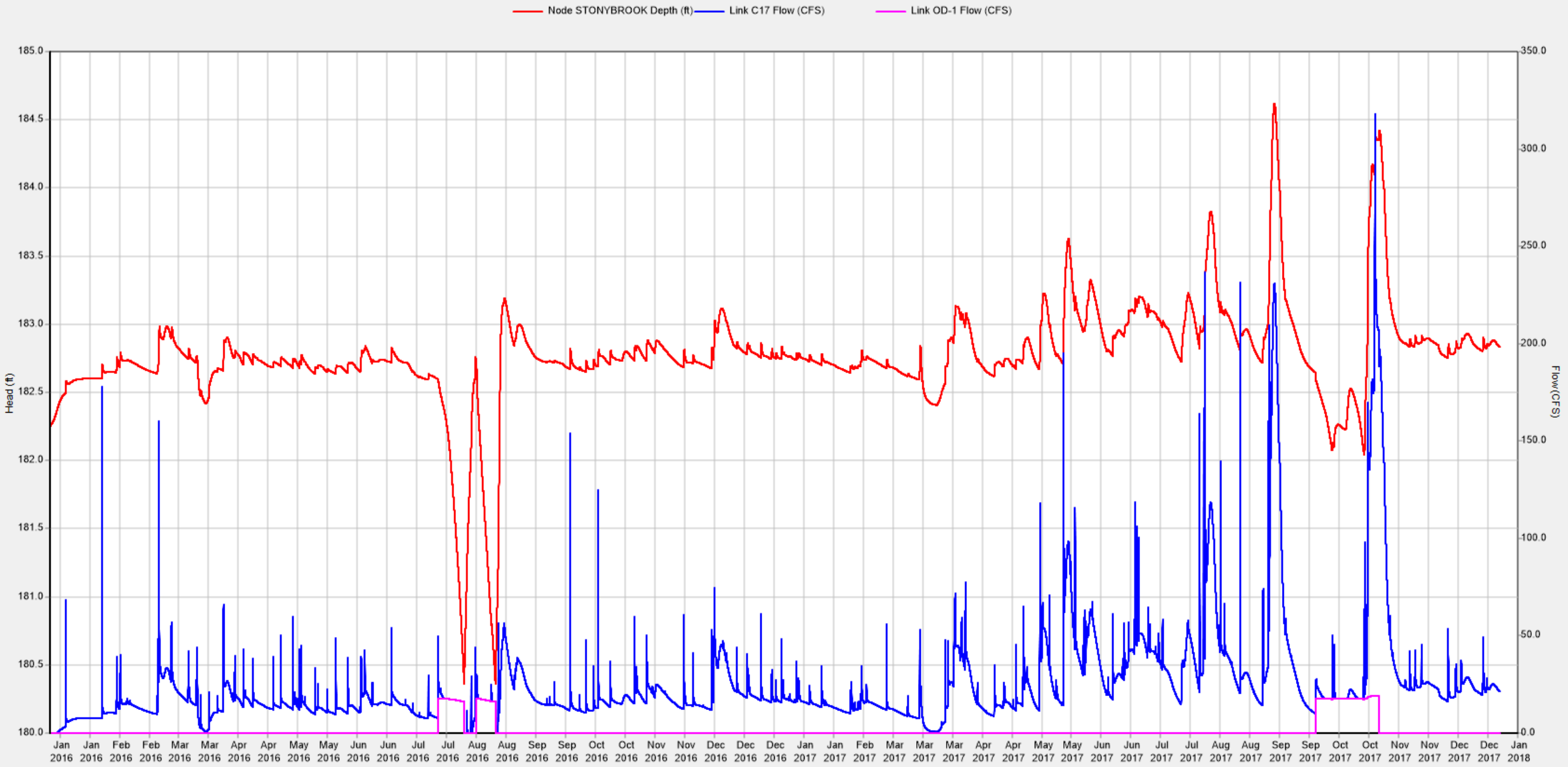


Figure C.15: Iteration 2 – Stony Brook: Water Level, Low Flow Release (Link OD-1), and Downstream Streamflow (Link 17)

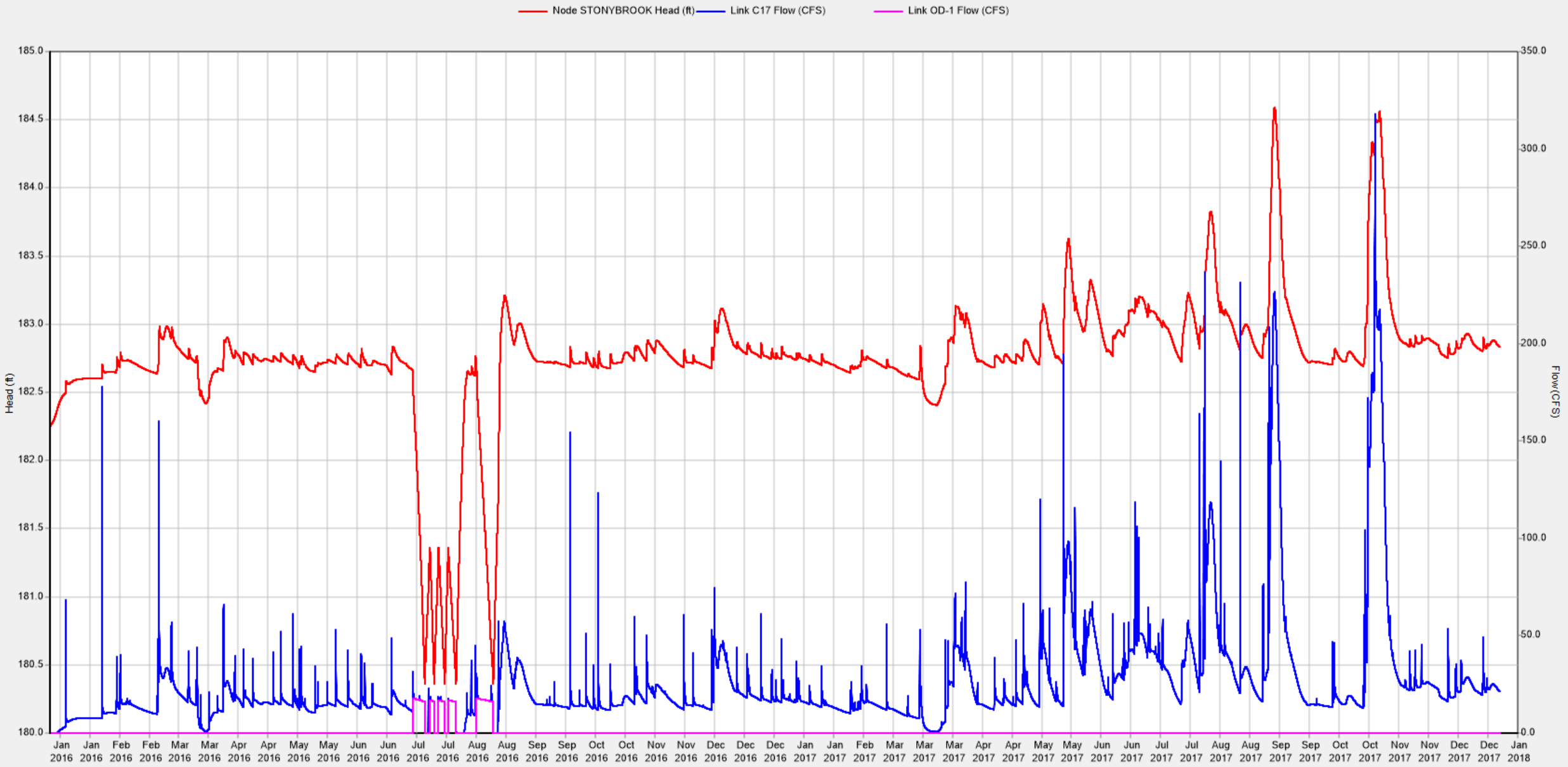


Figure C.16: Iteration 3 – Stony Brook: Water Level, Low Flow Release (Link OD-1), and Downstream Streamflow (Link 17)

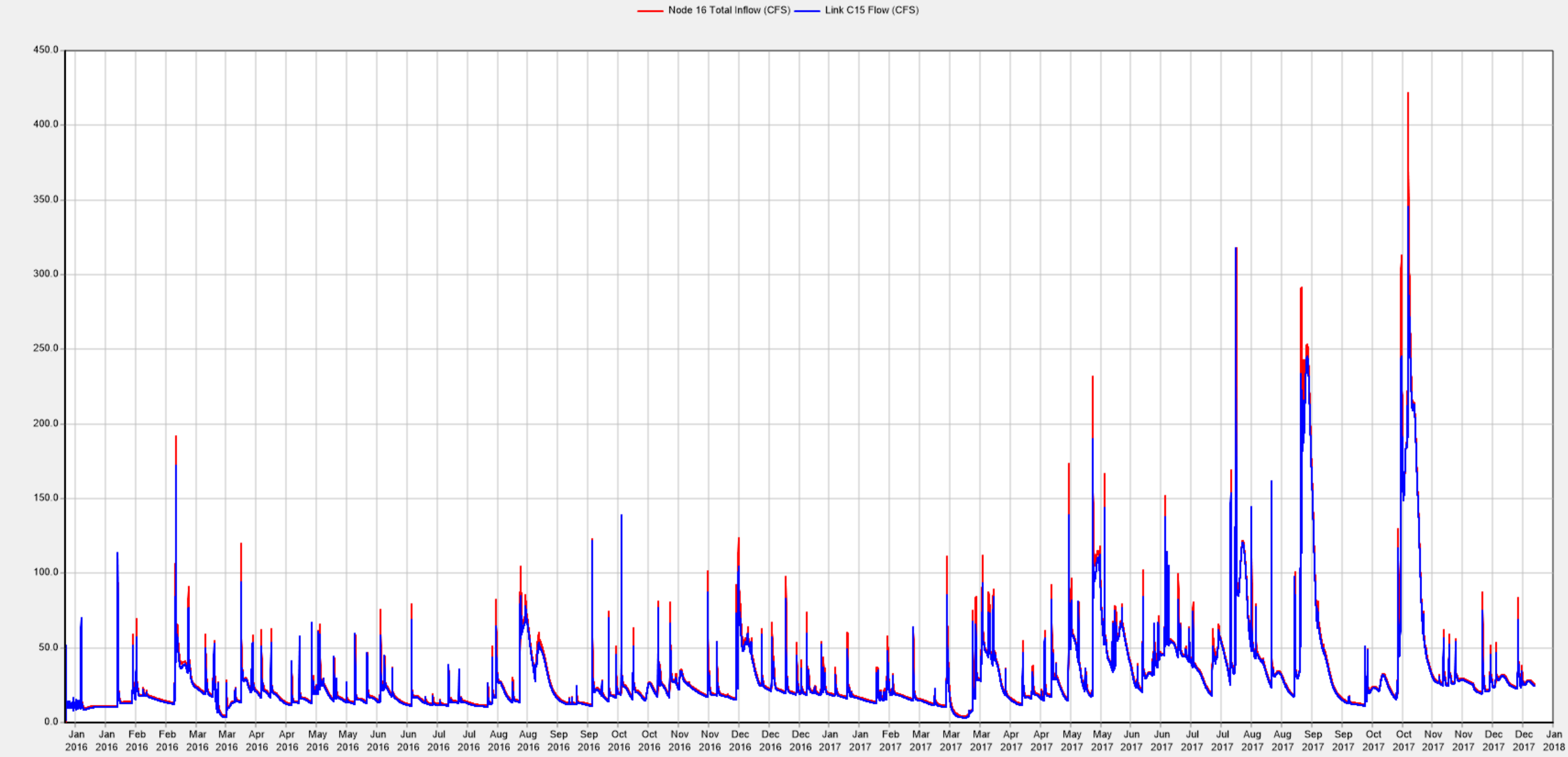


Figure C.17: Baseline – Downstream Streamflow at Depot Dam (Link 16) and Brookside Mills Dam (Node 16)

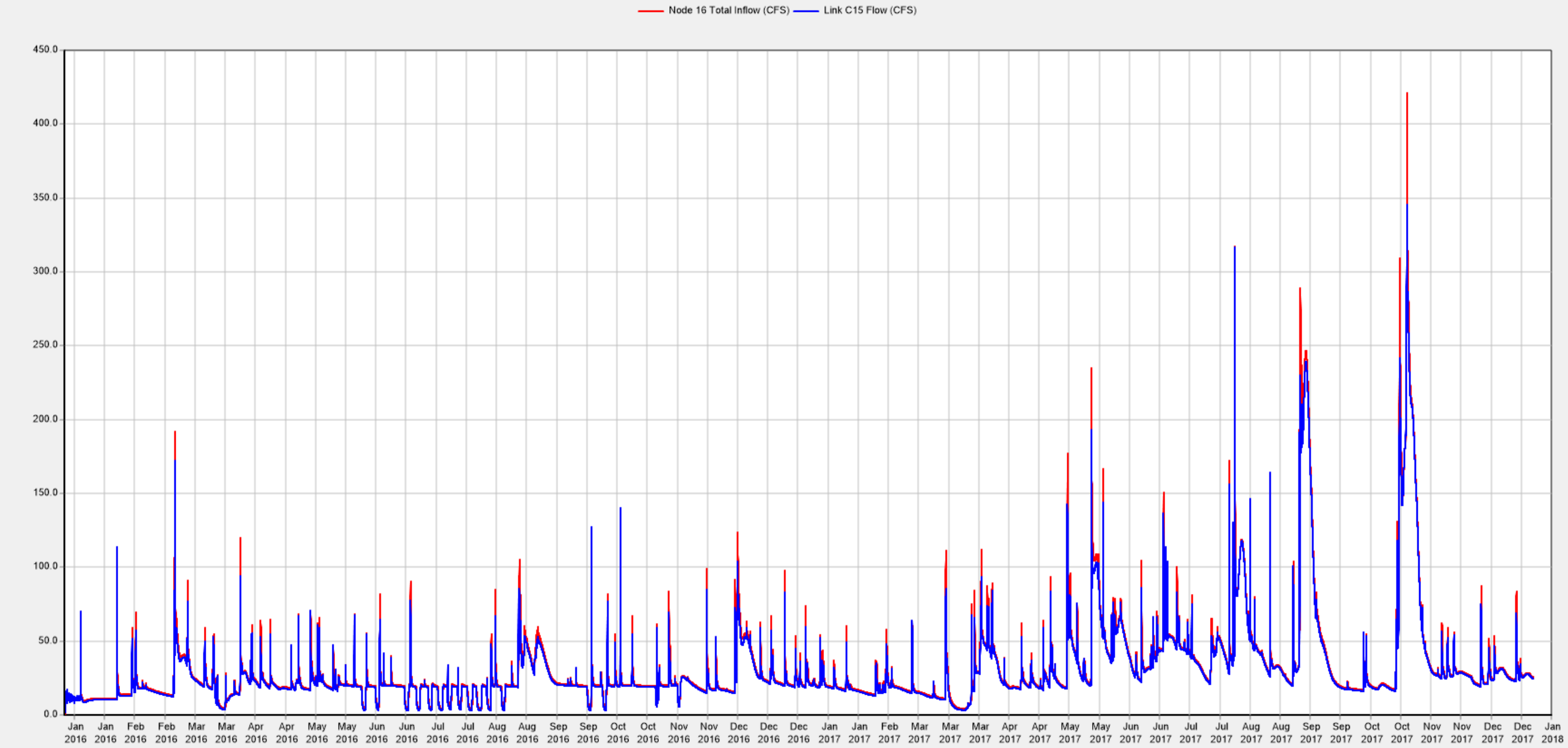


Figure C.18: Iteration 1 – Downstream Streamflow at Depot Dam (Link 16) and Brookside Mills Dam (Node 16)

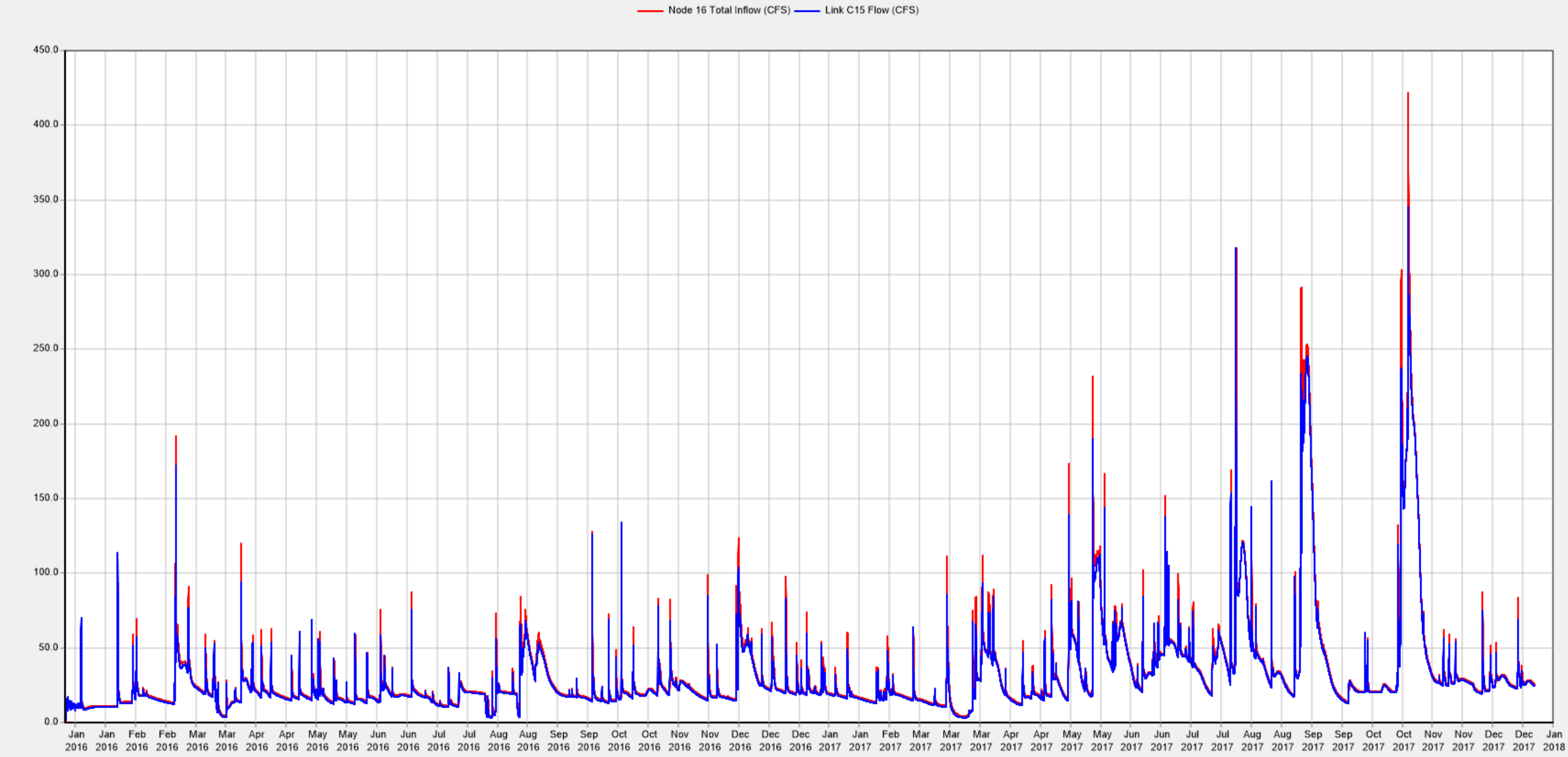


Figure C.19: Iteration 2 – Downstream Streamflow at Depot Dam (Link 16) and Brookside Mills Dam (Node 16)

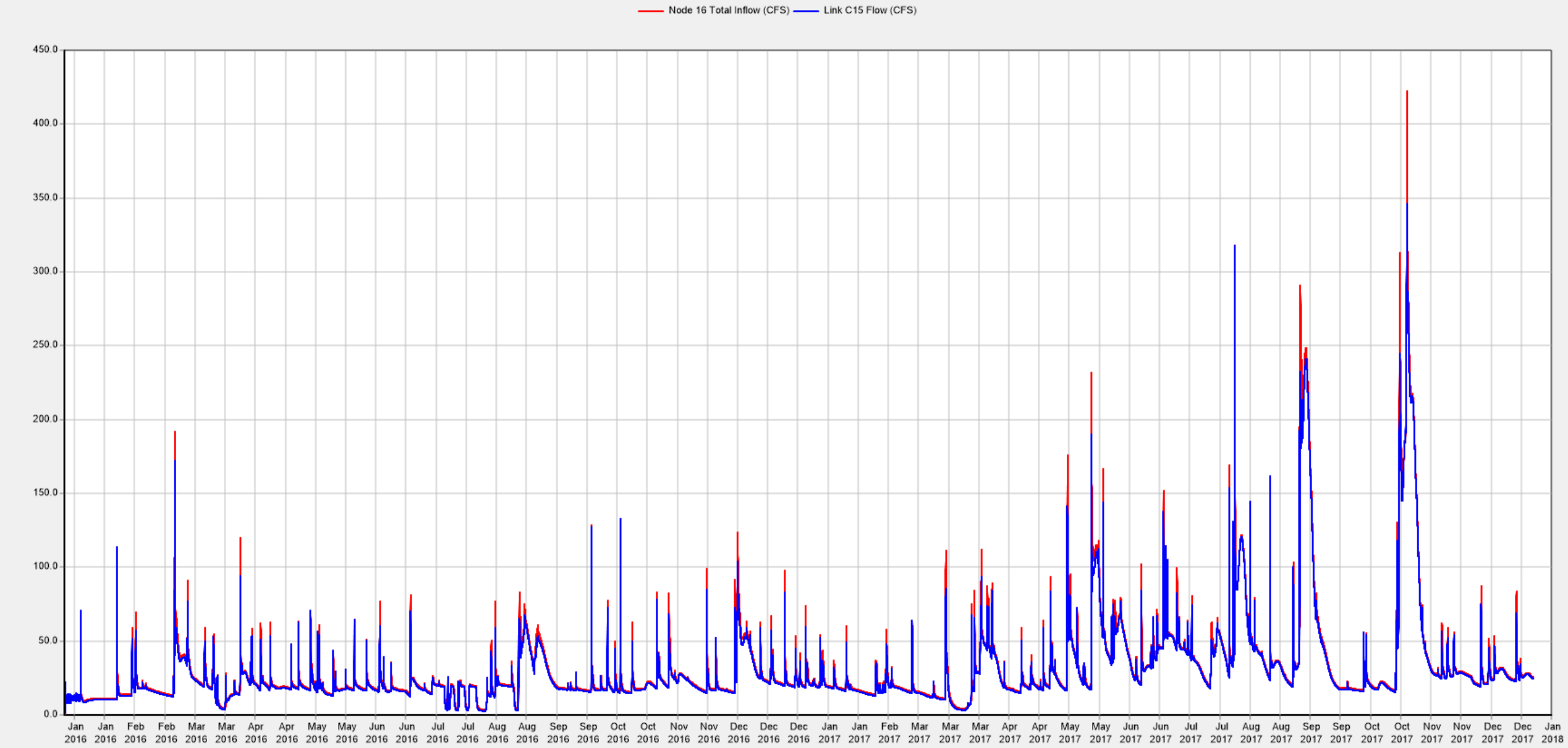


Figure C.20: Iteration 3 – Downstream Streamflow at Depot Dam (Link 16) and Brookside Mills Dam (Node 16)

Appendix D
Data Collection Plans for Streamflow Monitoring Stations

Geosyntec consultants

289 Great Road, Suite 202
Acton, Massachusetts 01750
PH 978.206.5746
FAX 978.263.9594
www.geosyntec.com

Memorandum

Date: June 15, 2018

To: Corey Godfrey, Littleton Water Department

From: David Roman and Taylor Walter, Geosyntec Consultants

Subject: DAM Dashboard: Data Collection Plan for Mill Pond

Appendices:
A. Instrumentation Documentation
B. Inspection/Maintenance Log

This memorandum provides an equipment installation and data collection plan in accordance with Task 3 of the Stony Brook Streamflow Restoration Plan (SRP). The purpose of the SRP was to assess opportunities for improvement of instream flow in the 38-square mile Stony Brook Watershed downstream of a series of surface water impoundments located in the Towns of Littleton and Westford through a coordinated Streamflow Restoration Plan (SRP). Specifically, the SRP evaluates if coordinated releases can be made to improve the timing, magnitude, and duration of downstream flows to mimic natural conditions without compromising other in-lake uses (e.g., significant impacts to water supply, recreation, or ecology).

One component of the SRP was to install streamflow monitoring equipment at Mill Pond and to develop an accompanying web-based decision support dashboard. This memorandum describes the installed monitoring equipment and provides operation and maintenance guidance. Specific sections covered by this plan include:

- Site Information
- Instrumentation Documentation
- Operation and Maintenance Requirements; and
- Reporting and Data Access (DAM Dashboard)

Site Information

Mill Pond is a 25-acre pond located in Littleton, Massachusetts with an approximate watershed area of 5,504 acres. Mill Pond's primary tributaries are Beaver Brook and Reedy Meadow Brook. Mill Pond is impounded by a dam to the east with an ogee style, horseshoe shaped spillway. In addition, there is a concrete headwall with one (1) embedded rectangular sluice gate that appears to be operable via hand wheel. Discharge from Mill Pond flows via Beaver Brook to Forge Pond, approximately three miles to the northeast.

Monitoring instrumentation was installed on May 3, 2018 at the concrete headwall as depicted by **Figure 1**. Coordinates of the monitoring station is listed in **Table 1**. The site is accessible via a Town of Littleton owned parcel at the corner of Pleasant Street and Curtis Street.

Table 1. Monitoring Station Coordinates

Location	Latitude	Longitude
Mill Pond Dam	42.53500	-71.497500



Figure 1. Monitoring Station Location *(Image Courtesy of Google Maps)*

Instrumentation

Instrumentation installed at the monitoring station includes:

- Monitoring probe with water level and temperature sensor
- Communications enclosure with battery and solar power.

Refer to **Table 2** for an instrumentation list including make and model of each component and to **Appendix A** for available manufacturer documentation (i.e., user manuals, cut sheets, specifications, etc.). The solar panel and communications enclosure are attached to a galvanized pipe that is bolted to the concrete headwall of the dam. The monitoring probe is installed inside a perforated rigid PVC conduit.

The monitoring probe can be removed for maintenance by opening the junction box cover above the rigid PVC conduit, detaching the probe from the wire, and coiling up the wire within the junction box. Refer to **Figure 2** for annotated photographs depicting the installed instrumentation configuration.

Table 2. Instrumentation List

Component	Dimensions (inches)	Make	Model	Website
Monitoring Probe	8.5 L x 1 Dia.	In-Situ	Level TROLL 500	Link
Communications Panel[1]	9 L x 7.5 W x 12.5 H	OptiRTC, Inc.	Lightning	Link
30-Watt Solar Panel	25 L x 18 W x 0.2 T	Ameresco Solar	BSP 30-Watt LSS	Link



Figure 2. Instrumentation Configuration (*5/3/2018)*

[1] The communications panel is configured with a cellular modem, a controller (to send readings to the online dashboard), and a 12 Volt, 14-amp hour battery. The solar system is sized to provide up to 10 days of autonomy (i.e. without sunlight).

Operation and Maintenance

Maintenance of the monitoring station will be the responsibility of the Littleton Water Department. It is recommended that **Table 3** be be completed to indicate personnel who will maintain the monitoring station. Maintenance should be performed in accordance with manufacturer recommendations (**Appendix A**); however, general recommended guidelines are provided below.

Table 3. Maintenance Contacts and Roles

Name / Organization	Phone	Role

1. Review Real-Time Data Once Per Week; Evaluate Potential Need for Site Inspection

By providing near real-time data on the DAM Dashboard, indicators of maintenance needs can be observed remotely. It is recommended that real-time data be reviewed once per week for unusual data patterns, anomalies, and other potential issues to determine if a field visit is required. See **Table 4** for a listing of common indicators. A field maintenance visit is recommended if any indicators occur.

Table 4. Dashboard Indicators for Maintenance

Indicator	Possible Cause	Corrective Maintenance
Online Status Reads "0% Online"	Power is disconnected, battery is drained, or internet is down	Check Power and Internet Connection to Communications Panel
Sensor measurements are flat	Sensor is fouled or blocked by debris or malfunctioning	Confirm sensor connection and clean sensor
Sensor measurements continuously fluctuate	Sensor is fouled or blocked by debris or malfunctioning	Confirm sensor connection and clean sensor

2. Perform Site Visit At least Once per Quarter; Complete Site Inspection Form

Maintenance frequency generally is based on the fouling rate of the monitoring probe which, among other factors, varies by hydrologic and environmental conditions, and season. It is recommended that a site-visit be performed to the monitoring station at least once per quarter, or more frequently depending on other potential monitoring disruptions such a equipment malfunction, power disruption, ice, debris, vandalism, or dashboard indicators. Refer to **Table 5** for a list of suggested site inspection tasks. A detailed recommended site inspection form is provided by **Appendix B**.

Table 5. Recommended Site Visit Tasks

Review and implement organization-specific safety procedures and protocols.
Perform detailed equipment inspection.
Remove and clean monitoring probe.
Take on-site water level measurements using a surveyor's rod or measuring tape.
Access online data from Dam Dashboard and verify that on-site measurements match dashboard measurements to ±0.25-inches.
Complete **Appendix B** inspection form.

Detailed troubleshooting procedures (e.g., recalibration of sensors) is outside the scope of this data collection plan. However, detailed procedures and recommendations are provided by [1].

Winterization

Monitoring equipment is installed behind the headwall of the dam and not directly adjacent to the spillway; therefore, water is stagnant and has the potential to freeze during colder winter months. Ice formation will damage the monitoring probe if the stilling well is compromised. It is recommended that the probe be removed prior to ice formation. To remove the probe from the stilling well, open the junction box, lift the probe out of the stilling well, twist off probe at cable connection point, and leave the remaining cable coiled up neatly inside the junction box.

Reporting and Data Analysis

The DAM Dashboard website is hosted by OptiRTC, Inc (www.optirtc.com). OptiRTC is a technology company focused on delivering a cloud-based platform for Continuous Monitoring and Adaptive Control (CMAC) of distributed stormwater infrastructure. Information measured in the field by the monitoring probes is streamed to the Opti-cloud and hosted on DAM Dashboard. The dashboard provides derivative datastreams (i.e., calculated based on in-field sensor measurements) such as calculated discharge rate and pond storage volume statistics. See Reference [2] for a description of data streams and how they were calculated. Refer to **Appendix A** for a detailed user guide which walks users through the log-in process, dashboard navigation, and other available tools. For additional needs, support can be contacted at support@optirtc.com.

Raw data can be downloaded from DAM Dashboard in the form a comma delimited text file to enable users to perform additional analysis of monitoring data, including quality assurance and corrections. Specific quality and assurance procedures are outside the scope of this data collection plan. However, detailed procedures and recommendations are provided by [1].

References

[1] Wagner, R.J., Boulger, R.W., Jr., Oblinger, C.J., and Smith, B.A., 2006, Guidelines and standard procedures for continuous water-quality monitors—Station operation, record computation, and data reporting: U.S. Geological Survey Techniques and Methods 1–D3, 51 p. + 8 attachments; accessed July 12, 2017, at http://pubs.water.usgs.gov/tm1d3.

[2] Geosyntec Consultants (2018). Stony Brook Flow Restoration Project, Section 4 “Monitoring and Decision Support”, 2018 Water Management Act Grant Project funded by MassDEP.

Geosyntec consultants

DAM DASHBOARD
Dam Assessment and Management Tool

Dam Dashboard Inspection / Maintenance Log

Inspected By:	
Date and Time:	
Weather:	

Task	Completed (Initial)	Comments (Debris Removed, etc.)	
Review and adhere to all organization-specific safety procedures, such as working with a buddy near open-water.			
Inspect equipment for deterioration or any visible signs of wear.			
Inspect conduit and cabling for any signs of damage due to vandalism or signs of deterioration.			
Clear vegetation as feasible from area surrounding communications panel.			
Inspect the color of the desiccant connected to the water level sensor in the Opti Lightning enclosure. The desiccant should be replaced if all beads have turned pink. Replacements can be obtained from In-Situ, at In-Situ.com. (Part Number: 0029140)			
Inspect stilling well and remove any accumulated debris or sediment.			
Remove monitoring probe, clean, rinse thoroughly, and return to stilling well.			
Winter Weather Requirement: Remove monitoring probe prior to ice formation. Ice will potentially damage the probe if the stilling well is compromised. Open junction box, lift off cover, twist off cable connector, and leave the cable coiled up neatly inside the junction box.			
Take on-site water level measurement using surveyor's rod or measuring tape. Access online data from Dam Dashboard and verify that on-site measurements match dashboard measurements to ±0.25-inches.		*On-Site Measurement:* *Date/Time:*	
		Reported Dashboard Value: *Date/Time:*	
		% Difference:	
		Comments:	

Notes / Comments:

Completed By: _____ Signature:_____ Date:_____

Geosyntec consultants

289 Great Road, Suite 202
Acton, Massachusetts 01750
PH 978.206.5746
FAX 978.263.9594
www.geosyntec.com

Memorandum

Date: June 15, 2018

To: Mark Warren, Westford Water Department

From: David Roman and Taylor Walter, Geosyntec Consultants

Subject: DAM Dashboard: Data Collection Plan for Stony Brook Impoundment

Appendices:
A. Instrumentation Documentation
B. Inspection/Maintenance Log

This memorandum provides an equipment installation and data collection plan in accordance with Task 3 of the Stony Brook Streamflow Restoration Project (Project). The purpose of the Project was to assess opportunities for improvement of instream flow in the 38-square mile Stony Brook Watershed downstream of a series of surface water impoundments located in the Towns of Littleton and Westford through a coordinated Streamflow Restoration Plan. Specifically, the SRP evaluates if coordinated releases can be made to improve the timing, magnitude, and duration of downstream flows to mimic natural conditions without compromising other in-lake uses (e.g., significant impacts to water supply, recreation, or ecology).

One component of the SRP was to install streamflow monitoring equipment at the Stony Brook impoundment and to develop an accompanying web-based decision support dashboard. This memorandum describes the installed monitoring equipment and provides operation and maintenance guidance. Specific sections covered by this plan include:

- Site Information
- Instrumentation Documentation
- Operation and Maintenance Requirements; and
- Reporting and Data Access (Dam Dashboard)

Site Information

The Stony Brook Dam impounds an approximate 15-acre waterbody in Westford, Massachusetts with an approximate watershed area of 16,768 acres. The impoundment consists of two primary sub-basins, divided by Bridge Street and connected by a culvert. The Stony Brook Impoundment's primary tributaries are Stony Brook (from Forge Pond) and Boutwell Brook. The impoundment is comprised of an earthen dam with a stone masonry outlet structure with a primary spillway and low-level outlet with two (2) sluice gates. Discharge from the impoundment flows to Depot Street Dam, approximately two miles to the northeast.

Monitoring instrumentation was installed on May 4, 2018 adjacent to Broadway Street on a concrete headwall adjacent to an abandoned inlet (**Figure 1)**. Coordinates of the monitoring station are listed in **Table 1**.

Table 1. Monitoring Station Coordinates

Location	Latitude	Longitude
Upstream	42.5955	-71.4658



Figure 1. Monitoring Station Location *(Image Courtesy of Google Maps)*

Instrumentation

Instrumentation installed at the Stonybrook dam monitoring station includes:

- Monitoring probe with water level and temperature sensor
- Communications enclosure with battery and solar power.

Refer to **Table 2** for an instrumentation list including make and model of each component and to **Appendix A** for available manufacturer documentation (i.e., user manuals, cut sheets, specifications,

etc.). The solar panel and communications enclosure are attached to a galvanized pipe that is bolted to the concrete headwall adjacent to the abandoned inlet. The monitoring probe is installed inside a perforated rigid PVC conduit. The monitoring probe can be removed for maintenance by opening the junction box cover above the rigid PVC conduit, detaching the probe from the wire, and coiling up the wire within the junction box. Refer to **Figure 2** for annotated photographs depicting the installed instrumentation configuration.

Table 2. Instrumentation List

Component	Dimensions (inches)	Make	Model	Website
Monitoring Probe	8.5 L x 1 Dia.	In-Situ	Level TROLL 500	Link
Communications Panel[1]	9 L x 7.5 W x 12.5 H	OptiRTC, Inc.	Lightning	Link
30-Watt Solar Panel	25 L x 18 W x 0.2 T	Ameresco Solar	BSP 30-Watt LSS	Link

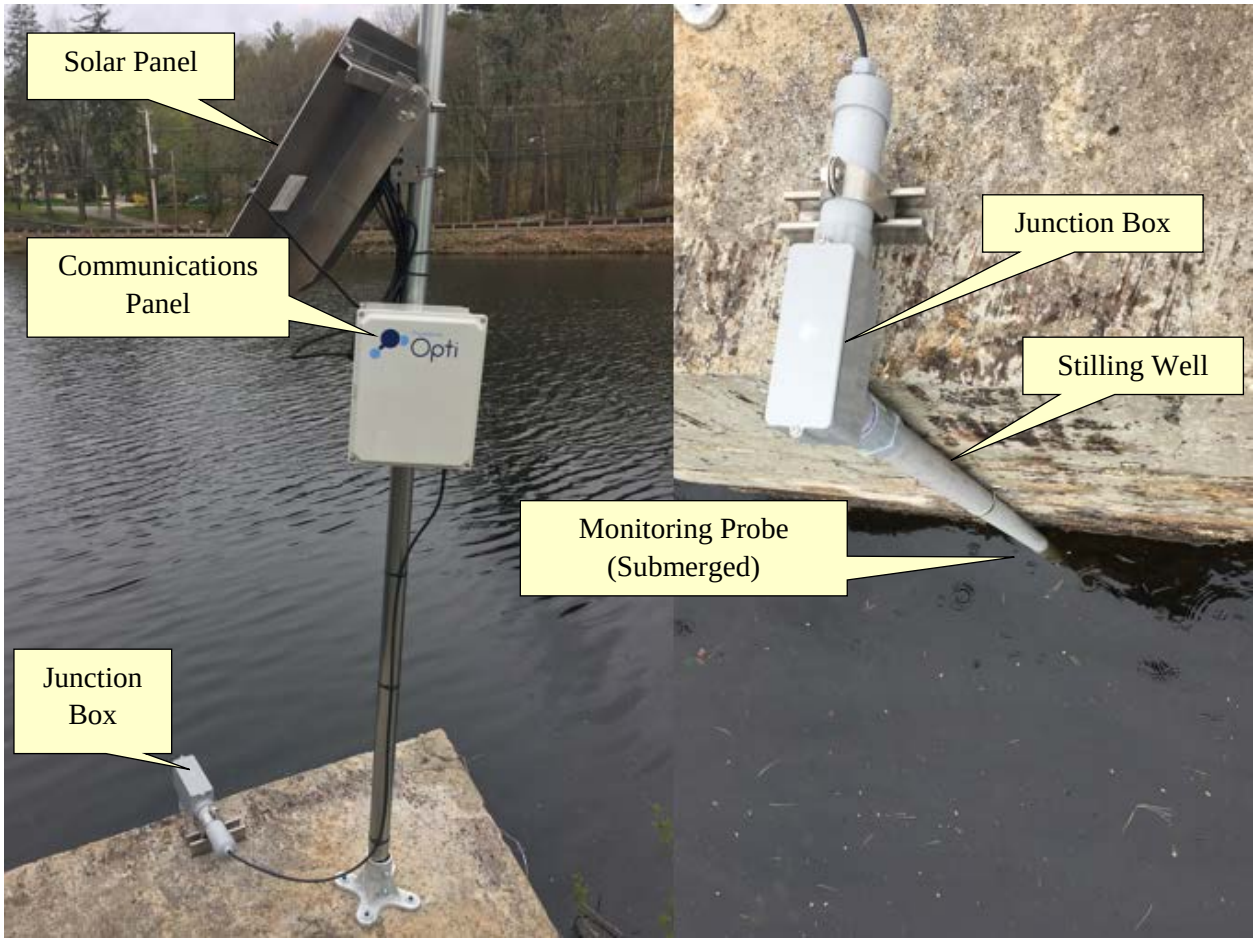


Figure 2. Instrumentation Configuration (*5/4/2018)*

[1] The communications panel is configured with a cellular modem, a controller (to send readings to the online dashboard), and a 12 Volt, 14-amp hour battery. The solar system is sized to provide up to 10 days of autonomy (i.e. without sunlight).

Operation and Maintenance

Maintenance of the monitoring station will be the responsibility of the Westford Water Department. It is recommended that **Table 3** be be completed to indicate personnel who will maintain the monitoring station. Maintenance should be performed in accordance with manufacturer recommendations (**Appendix A**); however, general recommended guidelines are provided below.

Table 3. Maintenance Contacts and Roles

Name / Organization	Phone	Role

1. Review Real-Time Data Once Per Week; Evaluate Potential Need for Site Inspection

By providing near real-time data on the DAM Dashboard, indicators of maintenance needs can be observed remotely. It is recommended that real-time data be reviewed once per week for unusual data patterns, anomalies, and other potential issues to determine if a field visit is required. See **Table 4** for a listing of common indicators. A field maintenance visit is recommended if any indicators occur.

Table 4. Dashboard Indicators for Maintenance

Indicator	Possible Cause	Corrective Maintenance
Online Status Reads "0% Online"	Power is disconnected, battery is drained, or internet is down	Check Power and Internet Connection to Communications Panel
Sensor measurements are flat	Sensor is fouled or blocked by debris or malfunctioning	Confirm sensor connection and clean sensor
Sensor measurements continuously fluctuate	Sensor is fouled or blocked by debris or malfunctioning	Confirm sensor connection and clean sensor

2. Perform Site Visit At least Once per Quarter; Complete Site Inspection Form

Maintenance frequency generally is based on the fouling rate of sensors which, among other factors, varies by hydrologic and environmental conditions, and season. It is recommended that a site-visit be performed at the monitoring station at least once per quarter, or more frequently depending on other potential monitoring disruptions such a equipment malfunction, power disruption, ice, debris, vandalism, or dashboard indicators. Refer to **Table 5** for a list of suggested site inspection tasks. A detailed recommended site inspection form is provided by **Appendix B**.

Table 5. Recommended Site Visit Tasks

Review and implement organization-specific safety procedures and protocols.
Perform detailed equipment inspection.
Remove and clean monitoring probe.
Take on-site water level measurements using a surveyor's rod or measuring tape.
Access online data from Dam Dashboard and verify that on-site measurements match dashboard measurements to ±0.25-inches.
Complete **Appendix B** inspection form.

Detailed troubleshooting procedures (e.g., recalibration of sensors) is outside the scope of this data collection plan. However, detailed procedures and recommendations are provided by [2].

Winterization

Since the monitoring equipment is not located adjacent to the spillway, water is stagnant and has the potential to freeze during colder winter months. Ice formation will damage the monitoring probe if the stilling well is compromised. It is recommended that the probe be removed prior to ice formation. To remove the probe from the stilling well, open the junction box, lift the probe out of the stilling well, twist off probe at cable connection point, and leave the remaining cable coiled up neatly inside the junction box.

Reporting and Data Analysis

The DAM Dashboard website is hosted by OptiRTC, Inc (www.optirtc.com). OptiRTC is a technology company focused on delivering a cloud-based platform for Continuous Monitoring and Adaptive Control (CMAC) of distributed stormwater infrastructure. Information measured in the field by the monitoring probes is streamed to the Opti-cloud and hosted on DAM Dashboard. The dashboard provides derivative datastreams (i.e., calculated based on in-field sensor measurements) such as calculated discharge rate and pond storage volume statistics. See Reference [2] for a description of data streams and how they were calculated. Refer to **Appendix A** for a detailed user guide which walks users through the log-in process, dashboard navigation, and other available tools. For additional needs, support can be contacted at support@optirtc.com.

Raw data can be downloaded from DAM Dashboard in the form a comma delimited text file to enable users to perform additional analysis of monitoring data, including quality assurance and corrections. Specific quality and assurance procedures are outside the scope of this data collection plan. However, detailed procedures and recommendations are provided by [1].

References

[1] Wagner, R.J., Boulger, R.W., Jr., Oblinger, C.J., and Smith, B.A., 2006, Guidelines and standard procedures for continuous water-quality monitors—Station operation, record computation, and data reporting: U.S. Geological Survey Techniques and Methods 1–D3, 51 p. + 8 attachments; accessed July 12, 2017, at http://pubs.water.usgs.gov/tm1d3.

[2] Geosyntec Consultants (2018). Stony Brook Flow Restoration Project, Section 4 “Monitoring and Decision Support”, 2018 Water Management Act Grant Project funded by MassDEP.

Geosyntec consultants

DAM DASHBOARD
Dam Assessment and Management Tool

Dam Dashboard Inspection / Maintenance Log

Inspected By:	
Date and Time:	
Weather:	

Task	Completed (Initial)	Comments (Debris Removed, etc.)	
Review and adhere to all organization-specific safety procedures, such as working with a buddy near open-water.			
Inspect equipment for deterioration or any visible signs of wear.			
Inspect conduit and cabling for any signs of damage due to vandalism or signs of deterioration.			
Clear vegetation as feasible from area surrounding communications panel.			
Inspect the color of the desiccant connected to the water level sensor in the Opti Lightning enclosure. The desiccant should be replaced if all beads have turned pink. Replacements can be obtained from In-Situ, at In-Situ.com. (Part Number: 0029140)			
Inspect stilling well and remove any accumulated debris or sediment.			
Remove monitoring probe, clean, rinse thoroughly, and return to stilling well.			
Winter Weather Requirement: Remove monitoring probe prior to ice formation. Ice will potentially damage the probe if the stilling well is compromised. Open junction box, lift off cover, twist off cable connector, and leave the cable coiled up neatly inside the junction box.			
Take on-site water level measurement using surveyor's rod or measuring tape. Access online data from Dam Dashboard and verify that on-site measurements match dashboard measurements to ±0.25-inches.		*On-Site Measurement:* *Date/Time:*	
		Reported Dashboard Value: *Date/Time:*	
		% Difference:	
		Comments:	

Notes / Comments:

Completed By: _____ Signature:_____ Date:_____

Geosyntec consultants

289 Great Road, Suite 202
Acton, Massachusetts 01750
PH 978.206.5746
FAX 978.263.9594
www.geosyntec.com

Memorandum

Date: Revised October 5, 2017

To: Jim Barisano, Friends of Forge Pond

Copies to: Jeff Sacknowitz, Friend of Forge Pond

From: Robert Hartzel, David Roman, Hayley O'Grady Geosyntec Consultants

Subject: DAM Dashboard: Equipment Installation and Data Collection Plan

Appendices:
A. Instrumentation Documentation
B. Inspection/Maintenance Log

This memorandum provides an equipment installation and data collection plan in accordance with Task 3 of the Forge Pond Dam Assessment and Management Dashboard (DAM Dashboard) Pilot Project. The purpose of the Pilot Project is to create a network of instrumented water supply reservoirs and other managed surface water impoundments to provide real-time data and decision support tools. Specific sections covered by this plan include:

- Site Information
- Instrumentation Documentation
- Operation and Maintenance Requirements; and
- Reporting and Data Access

Site Information

Forge Pond is a 203-acre pond located in Littleton and Westford, Massachusetts with an approximate watershed area of 15,056-acres [1]. The pond is impounded to the north by a stone dam consisting a series of weirs on its northern side and three sluice gates on its southern side. Discharge from the dam flows into a stone lined rectangular channel through the Abbot Mill property and into Stony Brook.

Monitoring instrumentation is installed in the southern portion of the pond at 59 Matawanakee Trail and downstream of the dam within the Abbot Mill property at the Pump House building, as depicted by **Figure 1**. Coordinates of both monitoring stations are listed by **Table 1**.

Table 1. Monitoring Station Coordinates

Location	Latitude	Longitude
Upstream	42.572560	-71.495826
Downstream	42.580767	-71.484984



Figure 1. Location of Monitoring Stations *(Image Courtesy of Bing Maps)*

Instrumentation Plan

Instrumentation installed at each monitoring station (i.e., upstream and downstream) includes:

- Monitoring probe with water level and temperature sensor
- Communications enclosure with battery and solar power.

Refer to **Table 2** for an instrumentation list including make and model of each component and to **Appendix A** for available manufacturer documentation (i.e., user manuals, cut sheets, specifications, etc.).

Table 2. Instrumentation List

Component	Dimensions (inches)	Make	Model	Website
Monitoring Probe	8.5 L x 1 Dia.	In-Situ	Level TROLL 500	Link
Communications Panel[1]	9 L x 7.5 W x 12.5 H	OptiRTC, Inc.	Lightning	Link
30-Watt Solar Panel	25 L x 18 W x 0.2 T	Ameresco Solar	BSP 30-Watt LSS	Link

The upstream communications enclosure and solar array was mounted to an existing pole. The upstream monitoring probe was installed approximately 45 feet southeast offshore of the communications enclosure and a depth of 6.5 feet (based on the water surface elevation on 8/18/2017). The monitoring probe was mounted on top of a standard cinder block to minimize the potential for sensor fouling. Cabling running back to the communications enclosure was encased in 1 inch diameter black polyethylene tubing and secured to the pond bottom with a concrete filled lally column. A pull rope was attached to the cinder block and run back to shore to enable retrieval of the monitoring probe for maintenance.

The downstream communications enclosure and solar array was mounted to the existing fence adjacent to the Abbot Mill Pump House. A rigid 1.5 inch diameter conduit is bolted vertically to the channel's concrete wall. The monitoring probe is located approximately 10 feet into the channel from the bottom of the rigid conduit. The monitoring probe is enclosed in a perforated PVC stilling well which is attached to a concrete brick with hose clamps. The monitoring probe and cabling is entirely buried in river rocks. The monitoring probe can be removed from the stilling well by removing the cap.

Refer to **Figure 2** and **Figure 3** for annotated photographs depicting the installed instrumentation configuration.

[1] The communications panel is configured with a cellular modem, a controller (to send readings to the online dashboard), and a 12 Volt, 14-amp hour battery. The solar system is sized to provide up to 10 days of autonomy (i.e. without sunlight).

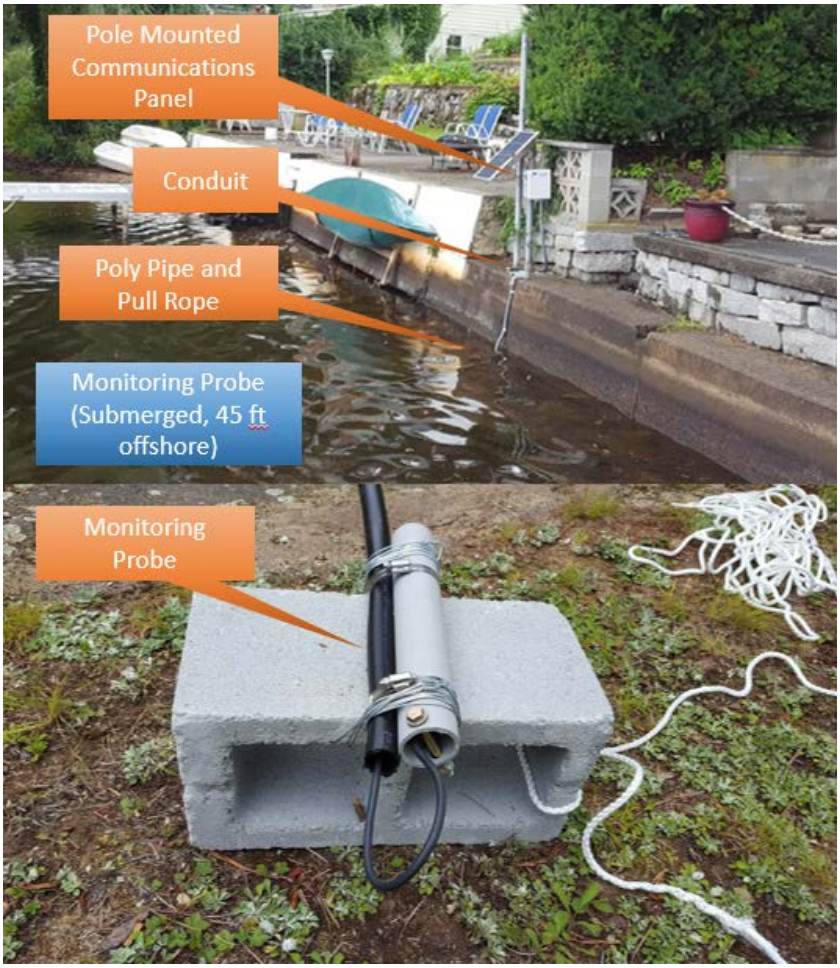


Figure 2. Instrumentation Configuration (Upstream Station) *(8/18/2017)*

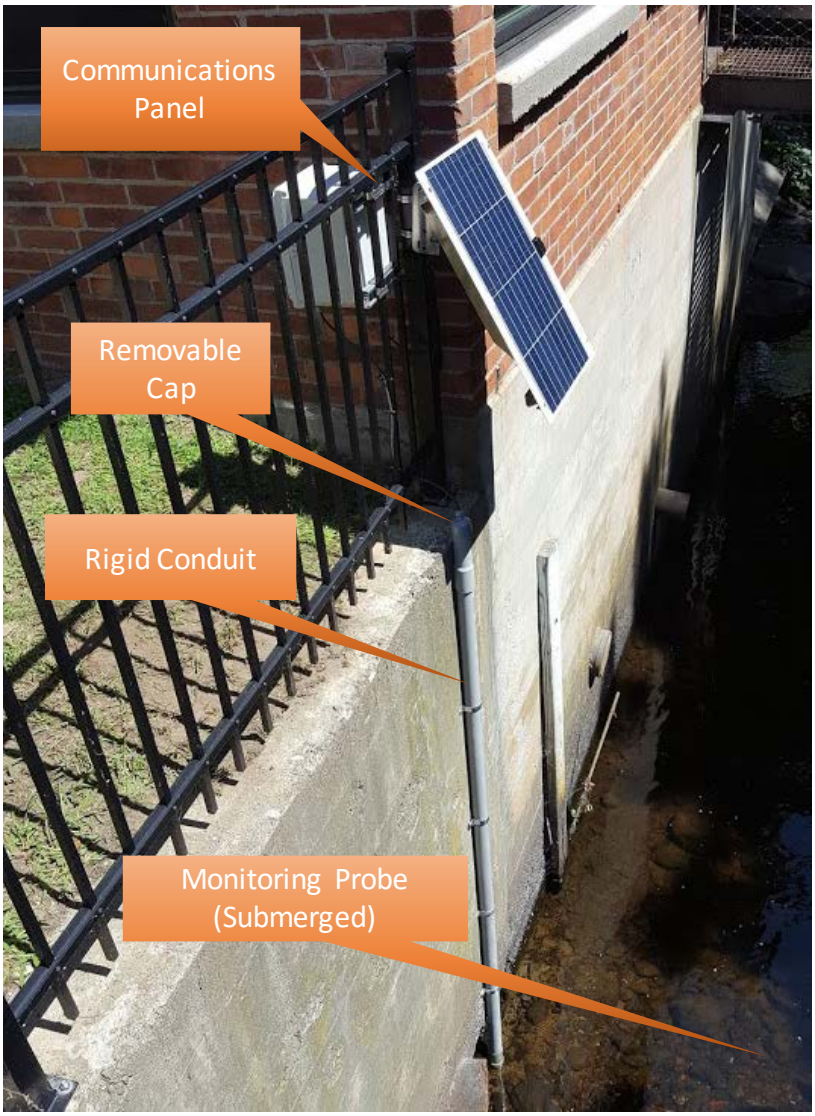


Figure 3. Instrumentation Configuration (Downstream Station) *(8/17/2017)*

Operation and Maintenance

Maintenance of the monitoring stations will be the responsibility of Frends of Forge Pond. It is recommended that **Table 3** be be completed to indicate personnel who will maintain the monitoring stations. Maintenance should be performed in accordance with manufacturer recommendations (**Appendix A**); however, general recommended guidelines are provided below.

Table 3. Maintenance Contacts and Roles

Name / Organization	Phone	Role

1. Review Real-Time Data Once Per Week; Evaluate Potential Need for Site Inspection

By providing near real-time data on the DAM Dashboard, indicators of maintenance needs can be observed remotely. It is recommended that real-time data be reviewed once per week for unusual data patterns, anomalies, and other potential issues to determine if a field visit is required. See **Table 4** for a listing of common indicators. A field maintenance visit is recommended if any indicators occur.

Table 4. Dashboard Indicators for Maintenance

Indicator	Possible Cause	Corrective Maintenance
Online Status Reads "0% Online"	Power is disconnected, battery is drained, or internet is down	Check Power and Internet Connection to Communications Panel
Sensor measurements are flat	Sensor is fouled or blocked by debris or malfunctioning	Confirm sensor connection and clean sensor
Sensor measurements continuously fluctuate	Sensor is fouled or blocked by debris or malfunctioning	Confirm sensor connection and clean sensor

2. Perform Site Visit At least Once per Quarter; Complete Site Inspection Form

Maintenance frequency generally is based on the fouling rate of sensors which, among other factors, varies by hydrologic and environmental conditions, and season. It is recommended that a site-visit be performed to each monitoring station at least once per quarter, or more frequently depending on other potential monitoring disruptions such a equipment malfunction, power disruption, ice, debris, vandalism, or dashboard indicators. Refer to **Table 5** for a list of suggested site inspection tasks. A detailed recommended site inspection form is provided by **Appendix B**.

Table 5. Recommended Site Visit Tasks

Review and implement organization-specific safety procedures and protocols.
Perform detailed equipment inspection.
Remove and clean monitoring probe.
Take on-site water level measurements using a surveyor's rod or measuring tape.
Access online data from Dam Dashboard and verify that on-site measurements match dashboard measurements to ±0.25-inches.
Complete **Appendix B** inspection form.

Detailed troubleshooting procedures (e.g., recalibration of sensors) is outside the scope of this data collection plan. However, detailed procedures and recommendations are provided by [2].

IMPORTANT: UPSTREAM AND DOWNSTREAM MONITORING LOCATIONS ARE SUSCESTIBLE TO ICE DAMAGE, PARTICULARLY DURING ICE-OUT. IT IS RECOMMENDED THAT SENSORS BE MONITORED CAREFULLY IN THE WINTER AND REMOVED IF NECESSARY.

Reporting and Data Analysis

The DAM Dashboard website is hosted by OptiRTC, Inc (www.optirtc.com). OptiRTC is a technology company focused on delivering a cloud-based platform for Continuous Monitoring and Adaptive Control (CMAC) of distributed stormwater infrastructure. Information measured in the field by the monitoring probes is streamed to the Opti-cloud and hosted on DAM Dashboard. The dashboard provides derivative datastreams (i.e., calculated based on in-field sensor measurements) such as calculated discharge rate and pond storage volume statistics. A description of calculation procedures for these derivative datastreams is

provided by [3]. Refer to **Appendix A** for a detailed user guide which walks users through the log-in process, dashboard navigation, and other available tools. For additional needs, support can be contacted at support@optirtc.com.

Raw data can be downloaded from DAM Dashboard in the form a comma delimited text file to enable users to perform additional analysis of monitoring data, including quality assurance and corrections. Specific quality and assurance procedures are outside the scope of this data collection plan. However, detailed procedures and recommendations are provided by [2].

References

[1] Geosyntec Consultants, 2016 Massachusetts Watershed-Based Plans, Lakes & Ponds Module, Element A, for Spectacle Pond in Littleton, accessed July 12, 2017, at http://prj.geosyntec.com/MassDEPWBP.

[2] Wagner, R.J., Boulger, R.W., Jr., Oblinger, C.J., and Smith, B.A., 2006, Guidelines and standard procedures for continuous water-quality monitors—Station operation, record computation, and data reporting: U.S. Geological Survey Techniques and Methods 1–D3, 51 p. + 8 attachments; accessed July 12, 2017, at http://pubs.water.usgs.gov/tm1d3.

[3] Geosyntec Consultants, 2017, Modeling Memorandum, "Task 2. Desktop Analysis and Modeling – Forge Pond", 8/2017.

Geosyntec consultants

DAM DASHBOARD
Dam Assessment and Management Tool

Dam Dashboard Inspection / Maintenance Log

Inspected By:		
Date and Time:		
Weather:		
Location (Circle One):	Upstream	Downstream

Task	Completed (Initial)	Comments (Debris Removed, etc.)	
Review and adhere to all organization-specific safety procedures, such as working with a buddy near open-water.			
Inspect equipment for deterioration or any visible signs of wear.			
Inspect for any signs of damage due to vandalism.			
Clear vegetation as feasible from area surrounding communications panel.			
Inspect conduit/cabling for signs of deterioration.			
Inspect the color of the desiccant connected to the water level sensor in the Opti Lightning enclosure. The desiccant should be replaced if all beads have turned pink. Replacements can be obtained from In-Situ (Part Number: 0029140) at in-situ.com.			
Inspect stilling well and remove any accumulated debris or sediment.			
Remove monitoring probe, clean, rinse thoroughly, and return to stilling well.			
Take on-site water level measurement using surveyor's rod or measuring tape. Access online data from Dam Dashboard and verify that on-site measurements match dashboard measurements to ±0.25-inches.		*On-Site Measurement:* *Date/Time:*	
		Reported Dashboard Value: *Date/Time:*	
		% Difference:	
		Comments:	

Notes / Comments:

Completed By: _____ Signature:_____ Date:_____

289 Great Road, Suite 202
Acton, Massachusetts 01750
PH 978.206.5746
FAX 978.263.9594
www.geosyntec.com

Memorandum

Date: Revised September 22, 2017

To: Corey Godfrey, Littleton Water Department

Copies to: Leon Weaver, Littleton Clean Lakes Committee

From: Robert Hartzel, David Roman, Hayley O'Grady Geosyntec Consultants

Subject: DAM Dashboard: Equipment Installation and Data Collection Plan

Appendices:
A. Instrumentation Documentation
B. Inspection/Maintenance Log

This memorandum provides an equipment installation and data collection plan in accordance with Task 3 of the Spectacle Pond Dam Assessment and Management Dashboard (DAM Dashboard) Pilot Project. The purpose of the Pilot Project is to create a network of instrumented water supply reservoirs and other managed surface water impoundments to provide real-time data and decision support tools. Specific sections covered by this plan include:

- Site Information
- Instrumentation Documentation
- Operation and Maintenance Requirements; and
- Reporting and Data Access

Site Information

Spectacle Pond is a 79-acre pond located in Littleton, Massachusetts with an approximate watershed area of 4,690-acres [1]. The pond's outlet control structure consists of two stop log-type weirs that discharge to a dual 48-inch concrete culvert under Great Road. Discharge from the pond flows to Gilson Brook which flows into Forge Pond approximately 0.5-miles to the northeast.

Monitoring instrumentation was installed on 8/15/2017 upstream of the outlet control structure and downstream of the culvert, within Gilson Brook, as depicted by **Figure 1**. Coordinates of both monitoring stations are listed by **Table 1**.

Table 1. Monitoring Station Coordinates

Location	Latitude	Longitude
Upstream	42.566598	-71.508888
Downstream	42.566588	-71.508272



Figure 1. Location of Proposed Monitoring Stations *(Image Courtesy of Bing Maps)*

Instrumentation Plan

Instrumentation installed at each monitoring station (i.e., upstream and downstream) includes:

- Monitoring probe with water level and temperature sensor
- Communications enclosure with battery and solar power.

Refer to **Table 2** for an instrumentation list including make and model of each component and to **Appendix A** for available manufacturer documentation (i.e., user manuals, cut sheets, specifications, etc.). Each communications enclosure is pole mounted while monitoring probes are installed inside perforated PVC pipe stilling wells within the upstream and downstream channels. PVC stilling wells are anchored to the channel banks with steel posts. Refer to **Figure 2** and **Figure 3** for annotated photographs depicting the installed instrumentation configuration.

Table 2. Anticipated Instrumentation List

Component	Dimensions (inches)	Make	Model	Website
Monitoring Probe	8.5 L x 1 Dia.	In-Situ	Level TROLL 500	Link
Communications Panel[1]	9 L x 7.5 W x 12.5 H	OptiRTC, Inc.	Lightning	Link
30-Watt Solar Panel	25 L x 18 W x 0.2 T	Ameresco Solar	BSP 30-Watt LSS	Link



Figure 2. Instrumentation Configuration (Upstream Station) *(8/15/2017)*

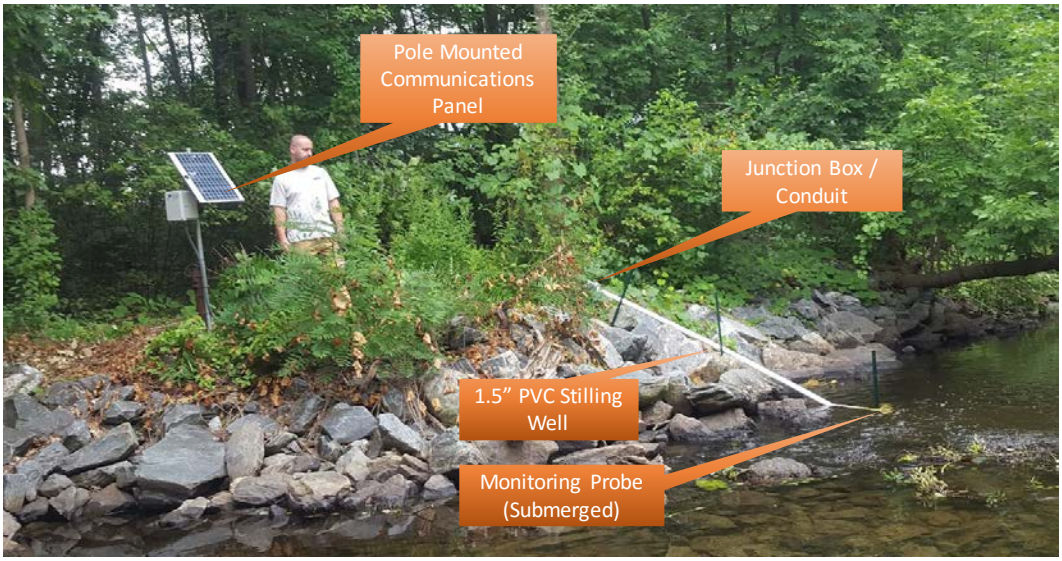


Figure 3. Instrumentation Configuration (Downstream Station) *(8/15/2017)*

[1] The communications panel is configured with a cellular modem, a controller (to send readings to the online dashboard), and a 12 Volt, 14-amp hour battery. The solar system is sized to provide up to 10 days of autonomy (i.e. without sunlight).

Operation and Maintenance

Maintenance of the monitoring stations will be the responsibility of Littleton Electric Light and Water Department. It is recommended that **Table 3** be be completed to indicate personnel who will maintain the monitoring stations. Maintenance should be performed in accordance with manufacturer recommendations (**Appendix A**); however, general recommended guidelines are provided below.

Table 3. Maintenance Contacts and Roles

Name / Organization	Phone	Role

1. Review Real-Time Data Once Per Week; Evaluate Potential Need for Site Inspection

By providing near real-time data on the DAM Dashboard, indicators of maintenance needs can be observed remotely. It is recommended that real-time data be reviewed once per week for unusual data patterns, anomalies, and other potential issues to determine if a field visit is required. See **Table 4** for a listing of common indicators. A field maintenance visit is recommended if any indicators occur.

Table 4. Dashboard Indicators for Maintenance

Indicator	Possible Cause	Corrective Maintenance
Online Status Reads "0% Online"	Power is disconnected, battery is drained, or internet is down	Check Power and Internet Connection to Communications Panel
Sensor measurements are flat	Sensor is fouled or blocked by debris or malfunctioning	Confirm sensor connection and clean sensor
Sensor measurements continuously fluctuate	Sensor is fouled or blocked by debris or malfunctioning	Confirm sensor connection and clean sensor

2. Perform Site Visit At least Once per Quarter; Complete Site Inspection Form

Maintenance frequency generally is based on the fouling rate of sensors which, among other factors, varies by hydrologic and environmental conditions, and season. It is recommended that a site-visit be performed to each monitoring station at least once per quarter, or more frequently depending on other potential monitoring disruptions such a equipment malfunction, power disruption, ice, debris, vandalism, or dashboard indicators. Refer to **Table 5** for a list of suggested site inspection tasks. A detailed recommended site inspection form is provided by **Appendix B**.

Table 5. Recommended Site Visit Tasks

Review and implement organization-specific safety procedures and protocols.
Perform detailed equipment inspection.
Remove and clean monitoring probe.
Take on-site water level measurements using a surveyor's rod or measuring tape.
Access online data from Dam Dashboard and verify that on-site measurements match dashboard measurements to ±0.25-inches.
Complete **Appendix B** inspection form.

Detailed troubleshooting procedures (e.g., recalibration of sensors) is outside the scope of this data collection plan. However, detailed procedures and recommendations are provided by [2].

Reporting and Data Analysis

The DAM Dashboard website is hosted by OptiRTC, Inc (www.optirtc.com). OptiRTC is a technology company focused on delivering a cloud-based platform for Continuous Monitoring and Adaptive Control (CMAC) of distributed stormwater infrastructure. Information measured in the field by the monitoring probes is streamed to the Opti-cloud and hosted on DAM Dashboard. The dashboard provides derivative datastreams (i.e., calculated based on in-field sensor measurements) such as calculated discharge rate and pond storage volume statistics. A description of calculation procedures for these derivative datastreams is provided by [3]. Refer to **Appendix A** for a detailed user guide which walks users through the log-in process, dashboard navigation, and other available tools. For additional needs, support can be contacted at support@optirtc.com.

Raw data can be downloaded from DAM Dashboard in the form a comma delimited text file to enable users to perform additional analysis of monitoring data, including quality assurance and corrections. Specific quality and assurance procedures are outside the scope of this data collection plan. However, detailed procedures and recommendations are provided by [2].

References

[1] Geosyntec Consultants, 2016 Massachusetts Watershed-Based Plans, Lakes & Ponds Module, Element A, for Spectacle Pond in Littleton, accessed July 12, 2017, at http://prj.geosyntec.com/MassDEPWBP.

[2] Wagner, R.J., Boulger, R.W., Jr., Oblinger, C.J., and Smith, B.A., 2006, Guidelines and standard procedures for continuous water-quality monitors—Station operation, record computation, and data reporting: U.S. Geological Survey Techniques and Methods 1–D3, 51 p. + 8 attachments; accessed July 12, 2017, at http://pubs.water.usgs.gov/tm1d3.

[3] Geosyntec Consultants, 2017, Modeling Memorandum, “Task 2. Desktop Analysis and Modeling – Spectacle Pond”, 8/2017.

Geosyntec consultants

DAM DASHBOARD
Dam Assessment and Management Tool

Dam Dashboard Inspection / Maintenance Log

Inspected By:		
Date and Time:		
Weather:		
Location (Circle One):	Upstream	Downstream

Task	Completed (Initial)	Comments (Debris Removed, etc.)	
Review and adhere to all organization-specific safety procedures, such as working with a buddy near open-water.			
Inspect equipment for deterioration or any visible signs of wear.			
Inspect for any signs of damage due to vandalism.			
Clear vegetation as feasible from area surrounding communications panels and monitoring equipment.			
Inspect conduit/cabling for signs of deterioration.			
Inspect the color of the desiccant connected to the water level sensor in the Opti Lightning enclosure. The desiccant should be replaced if all beads have turned pink. Replacements can be obtained from In-Situ (Part Number: 0029140) at in-situ.com.			
Inspect stilling well and remove any accumulated debris or sediment. Confirm secure mounting to channel bank.			
Remove monitoring probe, clean, rinse thoroughly, and return to stilling well.			
Take on-site water level measurement using surveyor's rod or measuring tape. Access online data from Dam Dashboard and verify that on-site measurements match dashboard measurements to ±0.25-inches.		*On-Site Measurement:* *Date/Time:*	
		Reported Dashboard Value: *Date/Time:*	
		% Difference:	
		Comments:	

Notes / Comments:

Completed By: _____ Signature:_____ Date:_____

Appendix E
Decision Support Dashboard Lookup Tables

Dashboard Data and Lookup Table Summary

The below sections describe the lookup tables that were used to develop dashboard datastreams at Mill Pond Dam and the Stony Brook Impoundment. For a detailed explanation of monitoring stations, model inputs, model results, and operational goals, see the Stony Brook Streamflow Restoration Plan (Geosyntec Consultants, 2018). For backup data and lookup tables related to the Spectacle Pond and Forge Pond monitoring stations, refer to (Geosyntec Consultants, 2017).

1. Reference Values

Reference values were used to translate sensor measurements of water depth into elevations relative to impoundment bathymetry. These reference values were then used as a basis for stage storage curves and stage discharge curves.

2. Estimated Inflow

Expected inflow to the impoundments was calculated using a derivative of the Rational Method as follows:

$$V = CPA$$

Where, V = estimated inflow volume
C = composite runoff coefficient;
P = total forecasted precipitation; and
A = total watershed area.

Watershed areas, including areas for each land use type, were estimated and used to calculate composite runoff coefficients. This computation assumes that all runoff will be captured by the impoundment and does not consider transient conditions (i.e. outflow caused by precipitation or capture by upstream impoundments). The dashboard will compute expected inflow volume based on 7-day national weather service precipitation forecasts with a probability of precipitation of greater than 20%.

3. Stage-Storage

Stage-Storage curves were developed from available bathymetry data for each impoundment. These data were input into the model to generate tabulated stage-storage (i.e. volume) curves. Water depths measured by the sensor are then referenced to pond volumes associated with that water level. The current pond volume is compared to the maximum pond volume to determine the percent that the pond is full.

4. Stage-Discharge

Stage-Discharge results are estimated discharge rates associated with measured water depths relative to the elevation of each impoundment's spillway. Discharge estimates were obtained from the regional hydrologic and hydraulic model (H&H) based on drawdown simulations.

References

Geosyntec Consultants (2017). DAM Dashboard: Desktop Analysis and Modeling Summary for Forge Pond and Spectacle Pond, technical memorandum, last revised August 25, 2017.

Geosyntec Consultants (2018). Stony Brook Flow Restoration Project, Streamflow Restoration Plan, last revised June 2018.

Mill Pond

1. Mill Pond Reference Values

Parameter	Value
Water Depth from Sensor Inv. (ft)[1]	1.580
Spillway Elevation (NAVD88, ft)[2]	215.000
Maximum Pond Elevation (NAVD88, ft)[2]	217
Pond Invert Elevation (NAVD88, ft)[3]	207
Water Depth over Spillway (ft)[1]	0.292
Water Elevation (NAVD88, ft)	215.292
Sensor Elevation (NAVD88, ft)	213.712

1. Based on field measurements on 5/4/2018
2. Mill Pond Restoration Project, ESS Group, December 29, 2000
3. Mill Pond Diagnostic Feasibility Study, ESS Group, 1999

2. Estimated Inflow

Coefficient, C:	0.29
Area, A (acres):	5448.45

1. Area included subcatchments draining to mill pond (S4, 6, 7)
2. Area weighted composite runoff coefficient calculated from Land Use data

7-day Precipitation, P (inch)	Exp. Inflow (ac-ft)
0.25	33.33
0.5	66.67
1	133.33
1.5	200.00
2	266.66
3	399.99
4	533.32
5	666.65
6	799.98
7	933.31
8	1066.64
9	1199.97
10	1333.30
11	1466.63
12	1599.96
13	1733.29
14	1866.62
15	1999.96
16	2133.29
17	2266.62
18	2399.95
19	2533.28
20	2666.61

1. Inflow computed from rational method derivative (Inflow = P*C*A)
2. Vol = Precip*A

3. Stage-Storage

Water Elevation (NAVD88, ft)	Water Depth Measured by Sensor (ft)	Storage Volume (ft3)	Storage Volume (ac-ft)	Percent Full (%)
213.63	0.00	5,701,951	130.90	25.68%
213.72	0.01	5,966,762	136.98	26.88%
213.81	0.10	6,236,863	143.18	28.09%
213.90	0.19	6,511,963	149.49	29.33%
213.99	0.28	6,791,799	155.92	30.59%
214.08	0.37	7,076,132	162.45	31.87%
214.17	0.46	7,364,735	169.07	33.17%
214.26	0.55	7,657,404	175.79	34.49%
214.34	0.63	7,953,958	182.60	35.83%
214.43	0.72	8,254,232	189.49	37.18%
214.51	0.80	8,558,086	196.47	38.55%
214.59	0.88	8,865,400	203.52	39.93%
214.68	0.97	9,176,074	210.65	41.33%
214.76	1.05	9,490,032	217.86	42.75%
214.84	1.13	9,807,217	225.14	44.18%
214.92	1.21	10,127,590	232.50	45.62%
215.00	1.29	10,451,150	239.93	47.08%
215.15	1.44	11,107,750	255.00	50.03%
215.23	1.52	11,440,760	262.64	51.53%
215.30	1.59	11,776,900	270.36	53.05%
215.38	1.67	12,116,210	278.15	54.58%
215.45	1.74	12,458,730	286.01	56.12%
215.52	1.81	12,804,500	293.95	57.68%
215.59	1.88	13,153,600	301.97	59.25%
215.72	2.01	13,862,000	318.23	62.44%
215.85	2.14	14,584,260	334.81	65.69%
215.92	2.21	14,950,630	343.22	67.35%
215.98	2.27	15,320,470	351.71	69.01%
216.05	2.34	15,693,760	360.28	70.69%
216.11	2.40	16,070,450	368.93	72.39%
216.23	2.52	16,833,710	386.45	75.83%
216.30	2.59	17,220,110	395.32	77.57%
216.42	2.71	18,001,510	413.26	81.09%
216.54	2.83	18,791,300	431.39	84.65%
216.59	2.88	19,188,020	440.50	86.43%
216.71	3.00	19,984,130	458.77	90.02%
216.82	3.11	20,792,960	477.34	93.66%
216.94	3.23	21,650,930	497.04	97.53%
217.00	3.29	22,200,000	509.64	100.00%

1. Measured Depth of 0' corresponds to a sensor invert of 213.63 NAVD88 ft
2. See Table A-3 (Geosyntec Consultants, 2018) for stage-storage input data and source information

4. Stage-Discharge

Water Elevation (NAVD88, ft)	Water Depth over Weir (ft)	Water Depth Measured by Sensor (ft)	Discharge (cfs)
215.00	0.000	1.288	0.00
215.10	0.100	1.388	1.56
215.20	0.200	1.488	4.55
215.30	0.300	1.588	8.49
215.40	0.400	1.688	13.54
215.50	0.500	1.788	18.54
215.60	0.600	1.888	24.33
215.70	0.700	1.988	30.99
215.81	0.810	2.098	38.07
215.90	0.900	2.188	44.91
216.11	1.110	2.398	61.67
216.21	1.210	2.498	69.91
216.32	1.320	2.608	79.39
216.41	1.410	2.698	87.99
216.51	1.510	2.798	97.60
216.62	1.620	2.908	108.35
216.71	1.710	2.998	117.24
216.80	1.800	3.088	126.90
216.90	1.900	3.188	137.39
216.96	1.960	3.248	144.88

1. Measured Depth of 0' corresponds to Bottom of Channel Elevation of 215.00 NAVD88 ft

Stony Brook Impoundment

1. Stony Brook Dam Reference Values

Parameter	Value
Water Depth from Sensor Inv. (ft)[1]	2.930
Spillway Elevation (NAVD88, ft)[2]	182.360
Maximum Pond Elevation (NAVD88, ft)[2]	186
Pond Invert Elevation (NAVD88, ft)[3]	167.36
Water Depth over Spillway (ft)[1]	0.900
Water Elevation (NAVD88, ft)	183.260
Sensor Elevation (NAVD88, ft)	180.330

1. Based on field measurements on 5/4/2018
2. Based on analysis of GIS LiDAR Data
3. Stonybrook Dam Phase I Inspection Report, Weston & Sampson, December 8, 2011

2. Estimated Inflow

Coefficient, C:	0.29
Area, A (acres):	16381.65

1. Area included subcatchments draining to Stonybrook
2. Area weighted composite runoff coefficient calculated from Land Use data

7-day Precipitation, P (inch)	Exp. Inflow (ac-ft)
0.25	100.01
0.5	200.02
1	400.04
1.5	600.05
2	800.07
3	1200.11
4	1600.14
5	2000.18
6	2400.21
7	2800.25
8	3200.29
9	3600.32
10	4000.36
11	4400.39
12	4800.43
13	5200.47
14	5600.50
15	6000.54
16	6400.57
17	6800.61
18	7200.64
19	7600.68
20	8000.72

1. Inflow computed from rational method derivative (Inflow = P*C*A)
2. Vol = Precip*A

3. Stage-Storage

Water Elevation (NAVD88, ft)	Water Depth Measured by Sensor (ft)	Storage Volume (ft3)	Storage Volume (ac-ft)	Percent Full (%)
180.33	0.00	3,060,377	70.26	14.29%
180.43	0.10	3,182,994	73.07	14.86%
180.52	0.19	3,316,971	76.15	15.48%
180.62	0.29	3,463,327	79.51	16.17%
180.72	0.39	3,623,143	83.18	16.91%
180.83	0.50	3,797,581	87.18	17.73%
180.95	0.62	3,988,284	91.56	18.62%
181.01	0.68	4,090,250	93.90	19.09%
181.14	0.81	4,308,336	98.91	20.11%
181.20	0.87	4,424,860	101.58	20.65%
181.34	1.01	4,673,938	107.30	21.82%
181.49	1.16	4,945,884	113.54	23.09%
181.65	1.32	5,242,597	120.35	24.47%
181.73	1.40	5,400,863	123.99	25.21%
181.81	1.48	5,566,081	127.78	25.98%
181.89	1.56	5,738,521	131.74	26.79%
181.98	1.65	5,918,456	135.87	27.63%
182.16	1.83	6,301,951	144.67	29.42%
182.26	1.93	6,506,094	149.36	30.37%
182.35	2.02	6,718,902	154.25	31.36%
182.45	2.12	6,940,684	159.34	32.40%
182.55	2.22	7,171,756	164.64	33.48%
182.65	2.32	7,412,424	170.17	34.60%
182.76	2.43	7,662,512	175.91	35.77%
182.86	2.53	7,906,048	181.50	36.90%
182.95	2.62	8,135,502	186.77	37.97%
183.04	2.71	8,357,912	191.87	39.01%
183.13	2.80	8,578,355	196.93	40.04%
183.22	2.89	8,801,576	202.06	41.08%
183.30	2.97	9,030,152	207.30	42.15%
183.39	3.06	9,264,459	212.68	43.24%
183.48	3.15	9,504,545	218.19	44.36%
183.57	3.24	9,749,920	223.83	45.51%
183.66	3.33	10,000,440	229.58	46.68%
183.76	3.43	10,259,740	235.53	47.89%
183.85	3.52	10,532,250	241.79	49.16%
183.95	3.62	10,817,690	248.34	50.49%
184.05	3.72	11,114,910	255.16	51.88%
184.16	3.83	11,420,980	262.19	53.31%
184.26	3.93	11,735,590	269.41	54.78%
184.37	4.04	12,058,660	276.83	56.29%
184.48	4.15	12,390,110	284.44	57.83%
184.58	4.25	12,729,870	292.24	59.42%
184.69	4.36	13,077,940	300.23	61.04%
184.80	4.47	13,434,350	308.41	62.71%
184.92	4.59	13,799,330	316.79	64.41%
185.03	4.70	14,173,530	325.38	66.16%
185.14	4.81	14,558,750	334.22	67.96%
185.26	4.93	14,960,730	343.45	69.83%
185.40	5.07	15,418,700	353.97	71.97%
185.62	5.29	16,199,870	371.90	75.62%
185.90	5.57	17,226,620	395.47	80.41%
186.23	5.90	18,458,830	423.76	86.16%
186.59	6.26	19,864,610	456.03	92.72%
186.97	6.64	21,423,530	491.82	100.00%

1. Measured Depth of 0' corresponds toa sensor invert of 180.33 NAVD88 ft
2. See Table A-6 (Geosyntec Consultants, 2018) for stage-storage input data and source information

4. Stage-Discharge

Water Elevation (NAVD88, ft)	Water Depth over Weir (ft)	Water Depth Measured by Sensor (ft)	Discharge (cfs)
182.36	0.00	2.03	0.00
182.46	0.10	2.13	5.00
182.56	0.20	2.23	7.00
182.66	0.30	2.33	11.22
182.76	0.40	2.43	16.55
182.86	0.50	2.53	23.21
182.96	0.60	2.63	30.61
183.00	0.64	2.67	34.06
183.10	0.74	2.77	42.29
183.20	0.84	2.87	51.24
183.30	0.94	2.97	60.47
183.40	1.04	3.07	70.69
183.50	1.14	3.17	80.64
183.60	1.24	3.27	92.33
183.70	1.34	3.37	102.82
183.80	1.44	3.47	114.60
183.90	1.54	3.57	126.89
184.00	1.64	3.67	139.44
184.10	1.74	3.77	152.46
184.20	1.84	3.87	166.58
184.30	1.94	3.97	179.88
184.40	2.04	4.07	194.27
184.51	2.15	4.18	209.96
184.61	2.25	4.28	224.78
184.70	2.34	4.37	237.73
184.81	2.45	4.48	254.84
184.89	2.53	4.56	268.20
185.03	2.67	4.70	290.89
185.19	2.83	4.86	316.30
185.29	2.93	4.96	334.52
185.40	3.04	5.07	353.62
185.52	3.16	5.19	373.51
185.64	3.28	5.31	395.84
185.76	3.40	5.43	418.28
185.94	3.58	5.61	450.71
186.16	3.80	5.83	492.73

1. Measured Depth of 0' corresponds to Bottom of Channel Elevation of 182.36 NAVD88 ft

We are
engineers, scientists
and innovators.

Offices in Principal Cities of the United States
and Select International Locations

Geosyntec.com

Geosyntec consultants