### Proposed Analysis of Telemetry and PIT Data for Study Report 3.3.2 Evaluate Upstream and Downstream Passage of Adult American Shad

### Introduction

FirstLight Hydro Generating Company (FirstLight) conducted a study with the goal of identifying the effects of the Turners Falls Project and Northfield Mountain Project operations on adult shad migration. Field studies were conducted during the fish passage season in the spring and early summer of 2015. Substantial data was collected during the field studies. FirstLight is currently in the process of data review to assure quality of the data. The next step is to analyze that data to meet the objectives of the study which are as follows:

- Describe the effectiveness of the Cabot fish ladder;
- Evaluate attraction, entrance efficiency and internal efficiency of the gatehouse ladder;
- Identify migration delays resulting from continued operation of the Turners Falls Project;
- Determine route selection and behavior of upstream migrating shad at the Turners Falls Project under various spill flow levels;
- Evaluate attraction, entrance efficiency and internal efficiency of the spillway ladder for shad reaching the dam spillway, under a range of spill conditions;
- Evaluate migration through the Turners Falls Impoundment (TFI);
- Identify impacts of Northfield Mountain, Cabot Station and Station No. 1 operations on upstream and downstream adult shad migration, including delays, entrainment, behavioral changes and migration direction shifts.
- Determine downstream passage route selection, timing/delay, and survival at Turners Falls Dam; and
- Determine passage rates and routes taken by shad migrating downstream through the canal, and evaluate Cabot Station fish bypass effectiveness.

FirstLight intends to conduct the analysis with input from stakeholders. As such, a workshop will be held on March 8 2016 at the Conte Lab to present and discuss the approach. The following summarizes the data collected during the field effort, the specific objectives and how the analysis will achieve those objectives. The approach described herein is based on the best available science and, to the best of our understanding, recommendations by stakeholders. Our approach should be considered a framework to the analysis and be informative to the workshop participants prior to the meeting.

### **Field Method**

Beginning in March 2015, FirstLight installed and tested passive and active radio telemetry monitoring equipment within the study area, which extended from the Holyoke Dam in Holyoke, MA to the Vernon Dam in Vernon, VT. Mobile tracking was conducted through the entire study area, whereas stationary monitoring stations were confined to the area between the Route 116 Bridge in Sunderland, MA and the Shearer Farms area located midway in the Turners Falls Impoundment (TFI). The study was coordinated with concurrent study efforts for the upstream TransCanada Projects. Monitoring within the upper TFI and

in the tailwater of the Vernon Dam was conducted by the TransCanada study team and will be a component of their study efforts.

A total of 20 radio telemetry monitoring stations, using 29 receivers, were deployed within the study area. Radio receivers consisted of Orion units manufactured by Sigma Eight, and SRX400 and SRX800 units manufactured by Lotek. Thirteen passive integrated transponder (PIT) monitoring stations were deployed within the three fishways: Cabot, Spillway and Gatehouse Fishways. The half-duplex PIT readers were manufactured by Oregon RFID. Table 1 summarizes the location of the monitoring stations and the equipment used. Figures 1-9 in Appendix B show the monitoring zones.

Adult shad used in the evaluation were collected at the upstream fish passage facilities at the Holyoke Project and within the Cabot Ladder at the Turners Falls Project using the existing fish trapping facilities. Shad tagging at Holyoke consisted of multiple cohorts that were released in the Holyoke fishway exit flume as well as cohorts that were transported upstream for release in the TFI, approximately 1200 ft. upstream of the Turners Falls Dam. Shad tagging at Cabot consisted of multiple cohorts that were tagged and released in the Cabot power canal, immediately upstream of the fishway exit, and within the TFI, approximately 1200 ft. upstream of the Turners Falls Dam. Tagging occurred over the course of 12 days in the months of May and June, 2015 with approximately half of the shad tagged with radio and PIT tags (double tagged) (n=397) and half tagged with PIT only (n=396). A total of 793 adult shad were collected, tagged and released as summarized in Table 2.

A dynamic flow release schedule was maintained throughout the study and was determined in real time with input from the United States Fish and Wildlife Service (USFWS). Figure 10 is the actual flow release schedule.

Location	RM	Receiver Station			
Red Cliffe Canoe Club (upstream of Holyoke Dam)*	86.5	A Lotek SRX receiver with yagi antenna monitored the full width of the River.			
Sunderland Route 116 Bridge	111	A Lotek SRX receiver with a double 3 element yagi ant monitored the full width of the River.			
Montague Wastewater	119.5	A Lotek SRX receiver with a double 3 element yagi antenna monitored the full width of the River.			
Deerfield River Confluence	119.5	An Orion receiver with yagi antenna monitored the full width of the Deerfield River upstream of its confluence with the Connecticut River.			
Cabot Station Tailrace	120	<ul> <li>Two radio receivers monitor the tailrace area;</li> <li>1) Lotek SRX with yagi antenna monitored the full river width (far field)</li> <li>2) Orion with yagi antenna monitored attraction to the Cabot Station tailwater (near field).</li> </ul>			
Cabot Station Forebay and Downstream Bypass	120	<ul> <li>Two radio receivers and a PIT receiver monitor the Forebay area;</li> <li>1) An Orion with two yagi antennas monitor the full width of the canal immediately upstream of the Cabot station</li> <li>2) An Orion with dipole antenna and PIT receiver monitored the entrance to the Cabot downstream bypass.</li> </ul>			

Table 1. Adult shad monitoring locations and equipment used.

Location	RM	Receiver Station				
Cabot fish Ladder	120	Two pit tag receivers monitor the entrance (1) and exit (1) to the ladder. Two Orion receivers with dipole antennas were deployed at the fishway entrance and at the exit to the first turning pool.				
Rawson Island	120.5	The North and South channel was monitored an Orion receiver employing antenna switching between two yagi antennas.				
Station 1 Forebay	121	An Orion with yagi antenna monitored the full width of the intake canal.				
Station 1 Tailrace	121	A Lotek SRX with double yagi 3 element antennas monitored the tailrace area. The detection zone extended across the wetted bypass reach area.				
Turners Falls Spillway Ladder	122	<ul> <li>Five PIT tag receivers monitor the ladder;</li> <li>1) Entrance</li> <li>2) Between the ladder entrance and first turn pool</li> <li>3) At the turn pool exit</li> <li>4) Downstream of the counting window</li> <li>5) Exit</li> <li>An Orion receiver was used to monitor the fishway entrance with a dipole antenna.</li> </ul>				
Below Turners Falls Dam	122	Two Orion receivers with yagi antennas monitored the area below the dam, one on either side.				
Gatehouse Ladder	122	<ul> <li>Four PIT receivers monitored the Gatehouse Ladder;</li> <li>1) Entrance (problematic monitoring location)</li> <li>2) First vertical slot</li> <li>3) Last vertical slot</li> <li>4) Upstream of the viewing window</li> <li>An Orion receiver with dipole and yagi antenna monitor the Gatehouse entrance and canal immediately downstreat of the Gatehouse.</li> </ul>				
Lower Canal	122	A Lotek with double yagi antennas monitored full width of the canal in the vicinity of the Conte' intake.				
Upper Canal	122	An Orion with a yagi antenna monitored the full width of the canal at a location downstream of the Gatehouse in the upper canal.				
Turners Falls Impoundment	122	A Lotek with double 3-element yagi antennas monitored the full width of the impoundment.				
NMPS Gill Bank	126.5	A Lotek with double 3-element yagi antennas monitored the full width of the impoundment.				
NMPS Intake	127	An Orion with a yagi and dropper antennas monitored the intake area.				
Upper Reservoir	127	An Orion with double 3-element yagi and dropper antennas monitored the intake area.				
Shearer Farms	127.5	Two Loteks with double 3-element yagi antenna, one on each river bank, monitor the full width of the impoundment.				

					Total Tagged
Date of Collection/Release	Collection Location	Release Location	Number of Double Tagged Shad	Number of PIT only Shad	and Released
5/6/15	Holyoke	Holyoke	72	1	73
5/7/15	Holyoke	Holyoke	0	72	72
5/12/15	Holyoke	Holyoke	48	1	49
5/13/15	Holyoke	Holyoke	0	47	47
	Cabot	Canal	25	25	50
5/15/15	Holyoke	TFI	33	29	62
5/16/15	Cabot	TFI	33	33	66
5/18/15	Cabot	Canal	0	25	25
5/19/15	Holyoke	Holyoke	48	48	96
	Cabot	Canal	25	0	25
5/22/15	Holyoke	Impoundment	33	33	66
5/23/15	Cabot	TFI	33	33	66
5/26/15	Holyoke	Holyoke	24	24	48
6/8/15	Holyoke	Holyoke	23	25	48
	Totals	•	397	396	793

Table 2. Adult shad collection, tagging and release summary.





### Figure 10. Flow releases at the Turners Falls Dam during the Adult shad study.

### Specific Goals, Objectives and Data Analysis

The goal of relicensing *Study 3.3.2 Evaluate Upstream and Downstream Passage of Adult American Shad* is to identify the effects of the Turners Falls Project and Northfield Mountain Project operations on adult shad migration. Each study objective is numbered and the proposed analysis for each objective is described below. Within each stakeholder objective, major themes have arisen, including the assessment of fishway

attraction effectiveness, overall passage efficiency, internal fishway efficiency, upstream passage effectiveness and route of passage. Fishway attraction effectiveness is defined as the proportion of fish that enter a fishway to the number of fish deemed available for passage. Upstream fish passage efficiency is the proportion of fish that enter a fishway and pass upstream from those deemed available for passage. Upstream fish passage efficiency is the proportion of fish that enter a fishway and pass upstream from those deemed available for passage. Upstream fish passage efficiency is the proportion of fish that enter a fishway and pass upstream, and remain upstream for a minimum of 48 hours from those deemed available for passage.

- 1. Describe the effectiveness of the Cabot fish ladder;
- An effective fish passage facility provides safe and timely passage. Therefore this analysis is twofold:
  - a. Assess passage facility survival with a MARK model. The fish used for this analysis will be a subset of all fish tagged during the spring 2015 study, and will only include those fish that reached Cabot tailrace and attempted the ladder.
  - b. Timeliness of fish passage will be assessed with graphical methods, and if the data fits the assumptions, will be analyzed for timeliness with the Cox regression model for time to event analysis as explained in (Castro-Santos, 2012).
- 2. Evaluate attraction, entrance efficiency and internal efficiency of the gatehouse ladder;
- Three separate analyses are needed to assess the efficiency of the gatehouse ladder.
  - a. To adequately assess attraction, fish will have to move from one recapture location, or state, to the next. This type of model is commonly referred to as a multi-state model in the literature and it assesses the probability of survival at time, probability of transitioning from one state into another in time, and the probability of recapture in time. To reduce the number of estimable parameters, it is possible to aggregate times or locations (states) in the model. If there is still insufficient data, it is possible to assess attraction with a logistic regression by plotting success/failure of attraction on the y-axis and operational data on the X-axis.
  - b. Entrance efficiency will be assessed with a MARK model that represents a subset of all tagged individuals, and will only include those fish that were present directly downstream of the entrance.
  - c. Efficiency of gatehouse ladder will be assessed with a MARK model that represents a subset of all tagged individuals and will only include those fish that were present directly downstream of the ladder.
- 3. Identify migration delays resulting from continued operation of the Turners Falls Project;
- Migration delay is best assessed with the time to event analysis which incorporates the Cox Regression technique as advised in (Castro-Santos, 2012). As animals are migrating upstream, they encounter multiple operating scenarios which may make some routes more attractive at times than others. The Cox Regression technique is a method capable of understanding these competing risks and will identify flow scenarios that provide favorable routes.
- 4. Determine route selection and behavior of upstream migrating shad at the Turners Falls Project under various spill flow levels;
- Route selection is best determined with a multi-state model that estimates the probability fish will move between recapture stations, survival between recapture stations and recapture, all in time. As previously mentioned, data requirements for this type of analysis are difficult to meet. If data requirements are not met, multinomial logistic regression is an attractive option. Multinomial

regression is a classification method that generalizes logistic regression (probability of true or false) into multiclass problems (probability route A, B or C is chosen). Independent variables in this case can be operations, river flow, etc.

- 5. Evaluate attraction, entrance efficiency and internal efficiency of the spillway ladder for shad reaching the dam spillway, under a range of spill conditions;
- Please see Objective 2 above on Gatehouse entry and ladder. A similar analysis will be used.
- 6. Evaluate migration through the Turners Falls Impoundment;
- Migration through TFI will be assessed with MARK and time to event analysis. The classic Cormack Jolly Seber method will assess survival, while passage delay will be assessed with the Cox Regression as outlined in (Castro-Santos, 2012).
- 7. Identify impacts of Northfield Mountain, Cabot Station and No. 1 Station operations on upstream and downstream adult shad migration, including delays, entrainment, behavioral changes and migration direction shifts.
- Separate models for Northfield Mountain, Cabot Station and Station No. 1 will be constructed to ensure estimates are produced with sufficient precision. Further, specific logic is required to parse out the upstream component of a migration from the downstream portion. A script will be constructed to identify the furthest upstream station attained by a fish, once fall back occurs the animal is assumed to have ended upstream migration and begins migrating back downstream through the project towards Holyoke. A simple binary operator will be attributed to each recapture record (PIT or telemetry detection) identifying whether or not the fish is migrating upstream. A map will be constructed showing the location of all migration direction changes for fish that migrated up to the Montague wastewater facility. Hotspot analysis will identify reaches where fish change their direction, and these hotspots will identify the maximum upstream and downstream models will be constructed. A multi-state mark recapture model will understand route of passage and survival through each telemetered reach, while time-to-event analysis will quantify delay.
- 8. Determine downstream passage route selection, timing/delay, and survival at Turners Falls Dam;
- Delay and route of passage will be assessed in the same manner as described for Objective 7.
- 9. Determine passage rates and routes taken by shad migrating downstream through the canal, and evaluate Cabot Station fish bypass effectiveness.
- Delay and route of passage will be assessed in the same manner as described for Objective 7.

### APPENDIX A

Mark Recapture Theory

### Mark Recapture Theory

Effective fish passage requires that animals are passed in a timely and safe manner. In other words, the goal of a fish passage facility should be to pass animals with minimal delay and maximum survivability. In the literature, survival (safe and effective) and movement (attractiveness and route selection) are analyzed with mark-recapture theory, while delay (timely passage) is assessed with survival analysis.

In a perfect world, the recapture rates of all tagged animals present within a detection zone would be 100% and an adequate assessment of survival or delay would be straightforward. Survival, in this case, is the number of fish that successfully passed the structure divided by the number of fish that attempted the structure. However, neither the perfect technology nor the perfect world exists, and some fish will pass through undetected. Therefore, analytical methods that account for this and other sources of uncertainty, like bias from false positive detections, are required. Failure to incorporate uncertainty could lead to bias in the estimate and may underestimate survival in the case of imperfect detections, or overestimate delay with the inclusion of false positives.

Mark-recapture theory provides the researcher with an analytical framework that can estimate demographic parameters of interest (survival and movement) that are unbiased with respect to imperfect detection (Perry, Castro-Santos, Holbrook, & Sandford, 2012). The data analyzed as part of this mark-recapture assessment are representative of an open population. An open population is one that can, and is expected, to change during the course of a study because of any combination of birth, deaths, immigration or emigration (Armstrup, McDonald, & Manly, 2010). While births or immigration will not occur within the Northfield Mountain Relicensing telemetry projects, fish will die or emigrate from the study area by falling back to Holyoke or escaping from the system through one of the many tributaries between Holyoke and Vernon Dam. Further, an animal that has not been observed for some time may have survived and escaped recapture by chance or for biological reasons its recapture might occur if the study were to continue (Lebreton, Burnham, Clobert, & Anderson, 1992). With this binary state of nature in mind, the presence and absence of animals at each location is encoded with a string of 1s or 0s denoting presence and absence, respectively. These input data strings are referred to as detection histories and models have been developed to estimate survival and movement from them.

The Cormack-Jolly-Seber (CJS) model has been the foundation of mark-recapture analysis with open populations for decades (Perry, Castro-Santos, Holbrook, & Sandford, 2012). The CJS model estimates two types of parameters,  $\phi$  or the probability of surviving from telemetry station *i* to station *i* + 1, and *p* the probability of being detected at station *i* conditional on surviving to station *i* (Perry, Castro-Santos, Holbrook, & Sandford, 2012). Under the assumption of independence of fates and identity of individuals, the observed detection history strings (presence/absence at all receivers) are an observation from a multinomial probability distribution (Lebreton, Burnham, Clobert, & Anderson, 1992). The method of maximum likelihood estimation (MLE) will be used to estimate the parameters in the model (Lebreton, Burnham, Clobert, & Anderson, 1992). The statistical likelihood is the product of the probability of observing a particular detection history given release over those capture histories actually observed (Lebreton, Burnham, Clobert, & Anderson, 1992). More than one animal may have the same recapture history, therefore the number observed in each recapture history appears as an exponent in its corresponding probability likelihood statement (Lebreton, Burnham, Clobert, & Anderson, 1992). MARK, the preferred software for analyzing mark-recapture data, uses the profile likelihood estimation of variance to construct the confidence intervals (Cooch & White, 2006). Consequently, the shape of the log-likelihood function estimated by the MLE procedure provides information on the precision of the estimators (Lebreton, Burnham, Clobert, & Anderson, 1992). Profile likelihood intervals have better coverage with small samples because the parameter space has boundaries on the interval [0,1], and the distribution of estimators are often very non-normal (Lebreton, Burnham, Clobert, & Anderson, 1992). With the basics of mark-recapture

theory and the estimation of the survival of marked animals with a CJS model down, the estimation of movement (attraction and route passage) is next.

Estimating the attraction of marked animals towards fish passage facilities or route of passage is typically analyzed with an extension of the CJS live recapture model, often referred to as the multi-state model. The same software used for the analysis of survival, MARK, is appropriate for building a multi-state model as well (White, Kendall, & Barker, 2006). Aside from traditional parameter estimates of survival and recapture, multi-state models estimate the transition probability that a marked animal will move from one state (location) into another as well as the state specific survival probabilities (Perry, Castro-Santos, Holbrook, & Sandford, 2012). Attraction towards a fish passage structure is assessed with a transition probability, in other words the probability that a fish moves (transitions) from one location (downstream) to another (passage structure). It is possible to assess attraction or route of passage under different operating scenarios. Operating scenarios can either be time varying covariates (continuous measures of discharge) or factors (high/low). When all states are sampled at every occasion, and all animals move among all states at all operating levels, all of the parameters (survival, recapture and transition) in the model are estimable except for the final interval (Perry, Castro-Santos, Holbrook, & Sandford, 2012). This means that marked fish must be present and must move between states at all time intervals assessed to meet sufficient data requirements. Therefore, under certain conditions it will not be possible to estimate some model parameters, especially if data requirements are not met. Mark recapture theory allows the researcher to collapse/aggregate sampling occasions and locations until sufficient data requirements are met. With assessments for basic passage survival and attraction (effectiveness) described, our attention now turns to delay.

Estimating passage delay is a separate analysis from survival and movement altogether. Concerns over the delays incurred at dams have led agencies to call for operational changes at hydroelectric facilities to minimize this effect (Castro-Santos & Haro, 2003). In a seminal paper on the subject, Castro-Santos and Haro (2003) identified survival analysis, common to biomedical research, as an appropriate method to describe the timing of events and incorporate data from individuals that are censored (still remaining in the population that has not passed after the study concludes). Castro-Santos and Haro (2003) also state that the moniker, "survival analysis," is misleading. The intent of applying survival analysis to fish passage is to quantify passage rate with no direct inference on survival, therefore Castro-Santos and Haro (2003) refer to the analysis as event-time analysis. Time to event analysis attributes a binary variable to an individual's passage time, denoting 1 if an animal's passage time was known and 0 if it is not (Castro-Santos & Haro, 2003). The only limitation to the use of censored data is that it must not be informative, i.e. covariate effects should be the same for censored and uncensored observations (Castro-Santos & Haro, 2003). Time to event analysis allows for more complete investigations of passage configurations and can help diagnose fishway delay problems.

### **Visualizations**

In most circumstances, the visual interpretation of study data will provide the researchers and stakeholders with concise and readily interpretable results. When assessing survival metrics through a fishway or passage route, mark recapture results will be plotted by station along the x-axis with 95% CI bars around each station survival estimate on the y-axis. Route of passage will be visualized with network interpretations of study reaches. The width of each connecting edge (route between telemetry receivers) represents the relative proportion of fish that passed via that route during a time step. Delay will be visualized with the Kaplan-Meier (K-M) survival curve. The K-M curve shows the proportion of fish remaining within a population that have not passed or fallen back after a certain amount of time *t*. These three visualizations will suffice for most study goals with the exception of Cox-Regression that is able to

understand delay effects associated with operations scenarios. The specific analysis methodology is explained in the following section.

Analysis by Study Goals and Objectives

The goal of this study is to identify the effects of the Turners Falls and Northfield Mountain Projects on adult shad migration. Appendix B includes maps denoting the locations of the telemetry and PIT receivers and the mobile tracking zones. Appendix C is the schematic of the receiver stations.

### 1. Describe the effectiveness of the Cabot fish ladder;

An effective fish passage facility provides safe and timely passage. Therefore this analysis is twofold, the overall passage efficiency (number of animals passed over the number of animals attempting) and passage delay. The fish used for this analysis will be a subset of all fish tagged during the spring 2015 study, and will only include those fish that reached Cabot Tailrace and attempted the ladder. The release occasion/location for the MARK model will be fish present at T3 with the first recapture station occurring at the T6-T5 combined station, then at the T7, P111, and P112 combined station followed by T29, then P12. Fish are considered to have passed the Cabot Ladder when they are detected/recaptured at T14 or T8. The full MARK model proposed for the Cabot Fish ladder is depicted below (Figure 11). While MARK can estimate the last survival and recapture occasions, it cannot differentiate between those fish not recaptured and fish that did not survive passage.



Figure 11. Graphical schematic of the MARK model to assess fish passage effectiveness at the Cabot Fishway showing estimable parameters. Survival probabilities ( $\phi_i$ ) are assessed between stations while recapture rates ( $p_i$ ) are measured at a station

As fish approach Cabot, they are offered multiple passage routes including the bypass reach, escapement into the Deerfield River, fallback towards Holyoke or upstream passage via the Cabot Fishway (Figure 12). In time to event analysis, survival time is the distance on the time scale between when an animal enters the approach until it ultimately chooses a passage route. Timeliness of fish passage will first be assessed with graphical methods, particularly the Kaplan-Meier survival curves which show the proportion of individuals remaining in the population (those that have no passed) after a certain time (*t*). Analysis of time to passage (or route selection) under time varying covariates will be conducted with the Cox proportional hazards regression model (Castro-Santos T. a., 2012). Passage delay or residence time among competing risks (passage routes) will be assessed at T3 as fish can fall back to T2, escape to the Deerfield River via T33, continue upstream to Turners Falls Dam via T11-T6 or pass via Cabot Fishway at the T7-P111-P112 combined station.



Figure 12. Route of passage schematic in front of Cabot Fishway showing competing routes for Time to Event analysis.

#### 2. Evaluate attraction, entrance efficiency and internal efficiency of the gatehouse ladder;

The analysis for the gatehouse ladder is three fold and will require multiple models. To adequately assess attraction, fish will have to move from one recapture location, or state, to the next. The gatehouse entrance has three locations (states), the canal (C), ladder (L) and upstream (U) (Figure 13). This type of model is commonly referred to as a multi-state model in the literature and it assesses the probability of survival (S) at time, probability of transitioning from one state into another ( $\Psi$ ) in time, and the probability of recapture (p) in time. The transition probabilities (probability of movement) between all stations in a time step must sum to 1. Therefore, transition probabilities represent the relative proportion of animals alive at time *i* either migrating to another location or staying in place. Because multi-state models assess survival, recapture and movement in time, the data requirements for precise estimates are large. To reduce the number of times we will assess, it is possible to aggregate times or locations (states) in the model. If there is still not appropriate data for precise estimates, it is possible to assess attraction with a logistic regression with success/failure of attraction towards a particular location on the y-axis and operational data on the X-axis.



Figure 13.Multi-state mark recapture showing state transitions and estimable parameters in time

Both the entrance and internal efficiency will be assessed with the same MARK model that represents a subset of all tagged individuals, and will only include those fish that were present directly downstream of the entrance (Figure 14). As fish enter the gatehouse ladder, they may face delay from competing risks (fall back or upstream passage) and make multiple passage attempts. Delay will be assessed between each station in Figure 15 with Time to Event analysis. The internal efficiency of the gatehouse ladder is assessed with the following mark recapture model (Figure 14) and will take into account only those marked animals attempting passage with the release point in the canal. An assessment of the internal efficiency of the

gatehouse ladder also requires an accounting of delay between all stations. Each station represents a competing risk as marked animals can pass to an upstream station or fall back. Therefore each marked animal may have a number of attempts at each station with time to passage at each. Assessing delay between stations may help elucidate fishway problems.



Figure 14. Mark recapture model showing estimable parameters that will assess the internal efficiency of the gatehouse ladder.

#### 3. Identify migration delays resulting from continued operation of the Turners Falls Project;

Migration delay is best assessed with the time to event analysis which incorporates the Cox Regression technique as advised in (Castro-Santos, 2012). As animals are migrating upstream, they endure multiple operating scenarios which may make some routes more attractive at times than others. The Cox Regression technique is a method capable of understanding these competing risks and can identify flow scenarios that provide favorable routes. Receiver stations along major portions of each routes will be aggregated (Figure 15) allowing for a more manageable dataset and easier interpretation of results.



Figure 15. Aggregated routes that show route of passage as competing risks to be analyzed with time to event analysis.

The following stations on Figure 15 represent aggregated routes: HL, CL, C1, B1, SW, GL, and TFI which may contain more than 1 telemetry/PIT station. Delay in the HL route will be assessed between release at Holyoke and telemetry station T2. Delay within the Cabot Ladder (CL) is assessed between the entrance stations (T7, P111, P112) and the exit station P12. The delay along the first Bypass Route, is assessed between T3 and T16. Delay at the second bypass reach (B1) is assessed between station T16 and the combined spillway ladder entrance consisting of stations T30, P21 and P22. Delay along the Gatehouse Ladder (GL) to TFI route is assessed between station P34 and P33/T23.

## 4. Determine route selection and behavior of upstream migrating shad at the Turners Falls Project under various spill flow levels;

Route selection is best determined with a multi-state model that estimates the probability fish will move between recapture stations (Figure 15), survival between recapture stations and recapture, all in time. As previously mentioned, data requirements for this type of analysis are difficult to meet. If data requirements are not met, multinomial logistic regression is an attractive option. Multinomial regression is a classification method that generalizes logistic regression (probability of true or false) into multiclass problems (probability route A, B or C is chosen). Independent variables in this case can be operations, river flow, etc.

# 5. Evaluate attraction, entrance efficiency and internal efficiency of the spillway ladder for shad reaching the dam spillway, under a range of spill conditions;

See sections on gatehouse entry and ladder for a discussion on modeling techniques. The entrance attraction will be assessed with a multi-state model between aggregated bypass reach stations (B1,Figure 15), the spillway entrance (stations T30, P21 and P22) and the next upstream station (P23SL) (Figure 16).



Figure 16. Multistate model with estimable parameters to assess attraction at the Spillway Ladder entrance

As with the entrance and internal efficiency of the gatehouse ladder, the entrance at the spillway and internal efficiency of the spillway ladder will be assessed with a combination mark recapture and time to event analysis. Figure 17 shows the receiver locations and estimable parameters where the entrance and internal efficiency will be assessed. Time to event analysis will assess delay between stations.



Figure 17. Mark recapture model showing estimable parameters for route of passage. Time to event analysis will assess delay between all reaches.

#### 6. Evaluate migration through the Turners Falls Impoundment;

Migration through TFI will be assessed with MARK and time to event analysis. The classic Cormack Jolly Saber method will assess survival, while passage delay is assessed with the Cox Regression as outlined in (Castro-Santos, 2012) (Figure 18).



Figure 18. Mark recapture model showing estimable parameters to evaluate migration through Turners Falls Impoundment. Time to event analysis will assess delay between each station.

# 7. Identify impacts of Northfield Mountain, Cabot Station and Station No. 1 operations on upstream and downstream adult shad migration, including delays, entrainment, behavioral changes and migration direction shifts.

Separate models for Northfield Mountain, Cabot Station and Station No. 1 will be constructed to ensure estimates are produced with sufficient precision. Further, specific logic is required to parse out the upstream component of a migration from the downstream portion. A script will be constructed that will identify the furthest upstream station attained by a fish, once fall back occurs the animal is assumed to have ended upstream migration and begins migrating back through the project towards Holyoke. A simple binary operator will be attributed to each recapture record (PIT or telemetry detection) identifying whether or not the fish is migrating upstream. A map will be constructed showing the location of all migration direction changes for fish that migrated up to the Montague wastewater facility. Hotspot analysis will identify reaches where fish change their direction, and these hotspots will identify the maximum upstream extents for segments of the migrating population. Following data management, separate upstream and downstream models will be constructed.

Migration in the vicinity of Northfield Mountain will be assessed with a multi-state mark recapture model assessing survival and transition probabilities and time to event analysis to assess delay for both the upstream and downstream component of the migration. Multi-state models allow transition in both directions along each migratory route, therefore a single model is capable of understanding infrastructure impacts in both directions. A flowchart showing estimable multi-state parameters is depicted in Figure 19. Movement can occur in both directions along a migratory route. Variables were created describing each recapture location, where V = Vernon dam and consists of telemetry stations T26 and T27, R is a virtual release located at telemetry station T24 and will only include those animals that migrated up to this station, I is the Northfield Mountain Intake consisting of station T25 and U is the upper impoundment consisting of telemetry station T31. The entrainment rate will be estimated with the transition probability  $\Psi^{IU}$ .



Figure 19 Flow chart of multi-state mark recapture model in the vicinity of Northfield Mountain Intake. Time to event analysis will assess delay along over migration route. Entrainment is assessed via the transition probability  $\Psi^{IU}$ 

Migration for Cabot Station will be assessed in much the same manner as with Northfield Mountain, except there are multiple virtual release locations. During the early stages of the migration, shad are expected to approach Cabot Station via Montague wastewater (T3), however during the latter part of the migration as fish are moving downstream, animals may approach the project from the canal or bypass reach. Therefore, virtual release locations are needed there as well. Figure 20 depicts the estimable parameters in the vicinity of Cabot Station. As with migration in the vicinity of Northfield Mountain, variables were assigned to major receiver stations where, H = Holyoke, M = Montague Wastewater, D = Deerfield River, B = bypass reach, T = Cabot tailrace, L = Cabot ladder, C = canal, F = Cabot Forebay and X = downstream bypass. Delay will be assessed between each station with Time to Event Analysis. Entrainment into Cabot Station will be quantified with the  $\Psi^{FT}$  transition probability.



Figure 20.Flow chart for multi-state mark recapture model in the vicinity of Cabot Station. Time to event analysis will be assessed along migratory reaches while entrainment is given with the transition probability  $\Psi^{FT}$ . Note some routes are 1 and cannot incorporate fallback.

As with Northfield Mountain and Cabot Station, migration in the vicinity of Station No. 1 will also be assessed with a combination of multi-state mark recapture modeling and time to event analysis (Figure 21).



Figure 21 Flow chart for multi-state mark recapture model in the vicinity of Station No. 1. Time to event analysis will be assessed along migratory reaches, while entrainment is given with the transition probability  $\Psi^{FT}$ 

## 8. Determine downstream passage route selection, timing/delay, and survival at Turners Falls Dam; and

Downstream migration at Turners Falls dam will be assessed in the same manner as migration past Northfield Mountain intake, past Cabot Station and past Station No. 1. Route of passage and survival will be assessed with a multi-state mark recapture model (Figure 22) and delay will be assessed with Time to Event along migratory reaches. Variables were created for each major reach including: I = impoundment, Sw = spillway, Sl = spillway ladder, Gl = gatehouse ladder, G = gatehouse, B = bypass reach and C = canal.



Figure 22 Flow chart for the downstream multi-state mark recapture model in the vicinity of Turners Falls Dam. Time to event analysis will be assessed along migratory reaches.

## 9. Determine passage rates and routes taken by shad migrating downstream through the canal, and evaluate Cabot Station fish bypass effectiveness.

As with other facilities, passage rate will be assessed with time to event analysis and route of passage with a multi-state mark recapture model (Figure 23). Reaches and stations will be aggregated to cut down on the number of estimable parameters where: G = gatehouse,  $F_1$  = station 1 forebay,  $T_1$  = station 1 tailrace, B = bypass reach, Re = Rawson Island east channel, Rw = Rawson Island west channel, C = canal,  $F_2$  = Cabot forebay, X = downstream bypass,  $T_c$  = Cabot tailrace, M = Montague wastewater, D = Deerfield River and H = Holyoke reach.



Figure 23 Flow chart for the downstream multi-state mark recapture model through Turners Falls Canal. Time to event analysis will be assessed along migratory reaches, while entrainment into Station No. 1 and Cabot Station is given with the transition probabilities  $\Psi^{F_1T_1}$  and  $\Psi^{F_cT_c}$  respectively. Passage via the downstream bypass is assessed with the transition probability  $\Psi^{XT_c}$ .

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# APPENDIX B Maps of Telemetry Stations



Path: W:\gis\studies\3\_3\_2\TelemetryPitStations\Redcliffe.mxd







Path: W:\gis\studies\3\_3\_2\TelemetryPitStations\CabotAreaPITandDroppers.mxd



Path: W:\gis\studies\3\_3\_2\TelemetryPitStations\AboveCabot.mxd







Path: W:\gis\studies\3\_3\_2\TelemetryPitStations\NorthSites.mxd



Path: W:\gis\studies\3\_3\_2\TelemetryPitStations\UpperRes.mxd

### APPENDIX C

### Route Selection Network





