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Prioritizing Mitigation of Road-Stream Crossings for Resident Aquatic Organisms by Accounting for Habitat Quantity, Quality, and Accessibility

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Prioritizing Mitigation of Road-Stream Crossings for Resident Aquatic Organisms by Accounting for Habitat Quantity, Quality, and Accessibility

A Project Presented

by

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Introduction

Dams, culverts, and other infrastructure can present barriers to in-stream movement for many types of aquatic organisms, reducing the ability of these organisms to access habitat that would provide food, mates, or refugia. With many species at risk and with millions of dams and culverts blocking passage through streams nationwide, conservation planning requires systematic methods by which to prioritize individual barriers for removal, to ensure that the greatest ecological value is gained for the money spent on conservation projects.

This study applies a systems analysis approach to this problem. Systematic methods based in operations research are proposed for barrier removal prioritization and the impacts of the input factors on the method output are examined in order to gain insight into the behavior or barrier.

The first section of this document details the core research project completed. A new optimization formulation is proposed to maximize the amount of quality- and accessibility-weighted habitat which may support aquatic organisms. The formulation is applied in a case study on the Upper West Branch of the Westfield River in western Massachusetts. The solutions obtained from the formulation are analyzed to determine the driving factors in the model and to gain deeper insights into barrier removal prioritization. This document has been written in the format of a journal article to be submitted to the Journal of Environmental Management.

Appendices A-D describe additional work completed as part of this master's research project. Appendix A describes preliminary results obtained by performing a sensitivity analysis on the dispersal distance, d_i. Appendix B outlines avenues for future research in barrier removal prioritization. Appendix C details the sources of the GIS data used in this project and the processing steps used to analyze that data. Appendix D describes a proposed scoring and

ranking protocol that utilizes major elements of the optimization formulation described in the main body of this work.

Appendix E contains presentations created and delivered by the author on the research project described above and closely related topics.

Appendix F is a report written by undergraduate student Cassandra Fagan for an Independent Study while supervised by Dr. David Ahlfeld and myself.

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Abstract

Road crossings and dams may act as barriers to movement for a wide range of aquatic organisms in lotic freshwater systems. Limited funding constrains the number of barriers that may be mitigated by repair or removal, so systematic methods of prioritization are needed for selecting barriers for mitigation. A new formulation is proposed that links the number of organisms in the watershed to the amount and quality of accessible habitat in order to quantify habitat connectivity of a watershed. The method is applied to a case study performed on the Upper West Branch of the Westfield River in Massachusetts, with multispecies measures of habitat integrity and aquatic barrier passability allowing comparison of stream segments and barriers within the network and their contributions to overall habitat availability. Optimization techniques are used to maximize the amount of high-quality habitat in the network accessible by stream-resident organisms. Results of this study demonstrate that the optimal combination of barriers for mitigation may change dramatically as budgets change, and that foreknowledge of a project's lifetime budget and accurate data regarding mitigation costs for individual barriers are crucial to cost-effective barrier removal planning.

1. Introduction

Globally, longitudinal disconnection of riverine systems by culverts, dams, and other in-stream barriers is well-documented (Dynesius and Nilsson, 1994; Stanford et al., 1996; Gibson et al., 2005). Over 50% of large river systems worldwide are impacted by in-stream barriers (e.g.

dams and culverts) (Nilsson et al., 2005).Fragmentation of fluvial ecosystems may affect a wide range of resident aquatic species, including potamodromous fish, by isolating populations and separating organisms from feeding, spawning, and nursery habitats (Nislow et al., 2011; Warren and Pardew, 1998, Wheeler et al., 2005).

Barrier mitigation is the process of improving aquatic accessibility and passage, whether by retrofitting culverts with more passable culvert structures, converting culverts to bridges, or decommissioning and removing dams and roads. By improving longitudinal connectivity in a stream network, these actions provide greater access to habitat and have the potential to restore fluvial processes that maintain habitat. In addition, benefits are often observed within a short time period following barrier mitigation (Catalano et al., 2007, Kanehl et al., 1997, Burroughs et al., 2010). As a result, barrier mitigation is regarded as a cost-effective method watershed restoration (O'Hanley et al., 2013; Roni et al., 2002; 2008) and has gained significant support from state agencies, conservation organizations, and other stakeholders in riverine health in recent years (Bednarek et al., 2001; Bernhardt et al., 2005; Roni et al., 2002).

A single watershed may contain hundreds or even thousands of road-stream crossings, dams, and other barriers.   The high cost of barrier mitigation projects requires restoration managers to carefully evaluate and select projects to ensure that the most effective projects are implemented. Growing attention has been given to systematic prioritization of projects. Formal prioritization methods can help decision-makers make barrier mitigation decisions that provide the greatest ecological improvements for their investment, based on available data.

While methods such as scoring and ranking (e.g. Taylor and Love, 2003; Kocovsky et al., 2009) and GIS-based methods (McGarigal et al., 2012) have been developed for the prioritization of barrier removals, formal mathematical optimization techniques are

recommended over other methods for their ability to efficiently allocate resources to maximize potential gain (O'Hanley and Tomberlin, 2005; Kemp and O'Hanley, 2010). In determining favorable barrier removal combinations, these methods are able to incorporate all relevant operational and resource constraints on the problem, as well as the spatial relationships between barriers in a network. In addition, such methods require quantifiable objectives to be set. Determination of restoration goals and objectives lends transparency and encourages consistency in the decision-making process (Kemp and O'Hanley, 2010; Beechie et al., 2008).

Most prioritization studies have focused on the migratory needs of diadromous fish. (Kemp and O'Hanley, 2010), but recently attention has been turning toward prioritization of barrier mitigation projects for the benefit of potadromous (a.k.a. "stream-resident" or "nonmigratory") aquatic organisms, which also face significant challenges with the loss of connected habitat. Cote et al. (2009) developed a metric termed the Dendritic Connectivity Index (DCI), which represents a stream network as a dendritic network and quantifies structural connectivity using length of available habitat and the passability of barriers on the network for both anadromous (DCI_d) and potadromous (DCI_p) fish. This metric serves only as a descriptive tool that quantifies connectivity based on barrier locations on a network. To use this metric for prioritization, every permutation of barrier mitigation projects would have to be assessed to determine the optimal solution, a process which is only feasible for up to a few dozen projects. Optimization techniques, on the other hand, can handle large problems with hundreds or even thousands of barriers and provide a solution regarding barrier mitigation decisions. O'Hanley (2011) was the first to propose an optimization model prioritizing barrier removals with a focus on potamodromous fish. The model sought to maximize the size of the single largest uninterrupted stream subnetwork in the watershed using a mixed integer linear program. This

model did not include measures of habitat quality in calculating habitat gains, nor did it account for variability in passability values, which allowed for a linear optimization formulation.

Stream connectivity metrics have more recently been proposed that account for habitat quality and organism dispersal abilities. Diebel et al. (2010) developed the *C* connectivity metric, which accounts for passability both upstream and downstream past a passage barrier; length or area of the stream segment in question; proportion of a desired habitat type within the segment; suitability of that habitat type for the target species; and an inverse distance metric comparing the length of the reach to the typical dispersal distance of the target resident fish species. These values are combined into a weighted value which is then compared to a *C* value calculated for the network without barriers, determining the existing barriers' relative influence on connectivity.

O'Hanley et al. (2013) incorporated the *C* connectivity metric into their budget-constrained optimization model to maximize habitat connectivity within a stream network for potadromous fish. This study allowed for partial passability values, which were multiplied to determine cumulative bidirectional passability. This multiplication introduced nonlinearity into the problem, which the authors reformulated to create a linear formulation that could be solved using exact methods. Despite the greater complexity of the model, the authors demonstrated optimization to be an efficient and more accurate method for prioritization compared to scoring and ranking.

The parameters incorporated into these metrics are often defined differently across different regions and studies. Most definitions of barrier passability focus on some measure of passage efficiency, in which passability is defined at the individual level as being relative to the total number of attempts to pass a barrier before success is achieved. Alternatively, barrier

passability is defined at the population level as the number of successful passes of a structure as a portion of the number of fish attempting to pass (Kemp and O'Hanley, 2010). These definitions are flawed in that they assume that a section of stream was completely passable to all organisms under consideration before the barrier was constructed. In reality, any unimpacted section of stream will be passable only to a portion of organisms at any given time; therefore, the goal in removing a barrier should be to restore the stream to its natural state rather than to state that is perfectly passable for all individuals of all species. In addition, most barrier passability scores calculated for existing culverts tend to be biased toward fish (Kemp and O'Hanley, 2010), and do not consider the ability of a barrier to pass other organisms, particularly those of lesser swimming abilities, or to transport materials and nutrients through a river network.

Similarly, assessments of habitat quality or suitability are often excluded from prioritization studies or are biased toward salmonid species (Kemp and O'Hanley, 2010). However, habitat quality often varies throughout a watershed, so that some barriers may block access to a disproportionate amount of high quality habitat, while others may be located within or adjacent to highly degraded stream reaches. Removing a barrier from the latter group may provide far less ecological benefit than removing a barrier that opens up even a small amount of high-quality or unimpacted habitat. Measures of habitat quality are therefore essential to the prioritization process.

However, most habitat quality and barrier passability scores used in past studies have been relevant only to a single species of concern or to a single taxonomic group (e.g., salmonids). By focusing conservation efforts on a single species, management strategies may ignore the needs of other organisms or even contribute to their decline if an organism's needs conflict with those of the species of interest. Preferably, an alternative method may focus on

scoring habitat quality and passability with regards to their ability to support a diverse assemblage of flora and fauna, so that restoration focuses on preserving and connecting habitats where landscape processes that support multiple species are maintained, and on restoring those processes which are impaired. Use of a multi-species habitat restoration strategy requires performance of detailed watershed analyses, but is more likely to lead to treatment of the causes of ecological degradation than of the symptoms (Beechie et al., 2008).

This paper describes a new habitat connectivity metric that assesses habitat connectivity at the catchment scale for stream resident aquatic species, utilizing multi-species measures of habitat quality and barrier passability as weights on the total habitat value. The new formulation seeks to maximize the value of the connected habitat, considering all species over the entire watershed and accounting for the spatial relationships of barriers in the network. An optimization formulation is used to maximize the improvement of longitudinal habitat connectivity in a watershed through the removal of barriers throughout the watershed. A case study is performed within the Westfield River Watershed in western Massachusetts using a genetic algorithm. The behavior of the model is assessed based on the results of the case study to illustrate sensitive variables and general rules that may help guide future prioritization decisions.

2. Methods

2.1 Formulation of Prioritization Problem

The goal of the proposed optimization formulation is to maximize the total quality- and accessibility-weighted habitat available to aquatic organisms in a stream network by selecting barriers for mitigation. The habitat gain is maximized by selecting barriers for mitigation, subject to a limited budget. The stream network in the watershed is described as a series of

stream segments, which may be branched or unbranched. Each stream segment is bounded upstream by headwaters or by one or more barriers; a segment is bounded on the downstream end by a single barrier. Hence, every portion of the stream network can be uniquely associated with a barrier and every barrier has an associated upstream segment.

It is assumed that for every barrier there exists a bidirectional probability of passage ranging from 0 to 1 where 0 indicates there is no probability of passage for an organism and 1 indicates that the barrier has the maximum probability of passage (i.e. no anthropogenic barrier exists and the stream has a natural or unimpacted level of passability). For the stream segment upstream of the barrier there exists a length as well as a habitat quality score which is scaled 0 to 1 with 1 representing the greatest habitat quality.

The formulation is designed to improve conditions for resident aquatic species. As a result, we consider the availability of habitat for species that originate in any segment of the watershed. Our formulation estimates the ability of the organism to travel to adjoining stream segments, the value of the adjoining segments, and the desirability to the organism of moving to adjoining segments.

First, an individual aquatic organism, i, (e.g. a single brook trout) is considered, initially in a segment s. This organism may have the ability and motivation, limited by barriers and metabolic considerations, to travel to any one of the other segments, t, in the watershed. A metric of the value of habitat in any segment t for the organism is proposed that includes measures of ability and motivation. For the organism, the metric is estimated as:

$$V_{i,s} = \sum_{t \neq s}^{T} L_t H_t D_{i,s,t} \varphi_{i,s,t}$$

Eqn 1

The summation in Equation 1 is over all segments in the watershed (excluding segment s) where T is the number of segments in the watershed (and the number of barriers). Each term in the

summation is the value of habitat in segment t to organism i, originating in segment s. L_t is the

length of segment t, H_t is the habitat quality (scaled 0 to 1) of segment t, $D_{i,s,t}$ is the dispersal

function (scaled 0 to 1) between segment s and t for organism i, and $\varphi_{i,s,t}$ is the cumulative

probability of passage (scaled 0 to 1) between segment s and t for organism i.

The cumulative probability of passage provides a measure of the availability of segment t

to the organism (can the organism get there?); the dispersal function indicates whether or not the

organism is capable of travel from segment s to segment t (would the organism want to go

there?); the product of the segment length and habitat quality provide a measure of the value of

the habitat in segment t (is it nice there?).

Using similar methodology and notation to that used by O'Hanley et al. (2013) and

discussed in Kemp and O'Hanley (2010) the cumulative probability of passage is represented by

calculating the product of passability values between segments s and t.

$$\varphi_{i,s,t} = \prod_{j \in B_{s,t}} p_{i,j} \qquad \text{Eqn 2}$$

where $B_{s,t}$ is the set of all barriers between segments s and t and $p_{i,j}$ is the probability that

organism i can pass barrier j as the organism moves in the upstream or downstream direction. It

is assumed that potadromous aquatic organisms are equally likely to move upstream or

downstream (Warren and Pardew, 1998) and the impact of barriers on passability is the same in

either direction. Equation 2 can be interpreted as the probability that the organism can travel

from segment s to segment t, crossing each barrier between s and t only once.

The dispersal function is calculated using the same form as proposed by Diebel et al.

2010 and used by O'Hanley et al. 2013:

$$D_{i,s,t} = \frac{1}{1 + \left(\frac{d_{s,t}}{d_i}\right)^2} \qquad \text{Eqn 3}$$

where d_i is the expected or average dispersal distance for the organism over relevant timescales and $d_{s,t}$ is the sum of segment lengths between segments s and t (inclusive).

For an individual organism, $V_{i,s}$ can be increased by increasing cumulative passability which is accomplished (via equation 2) by increasing the passage probability at individual barriers. The removal of barriers is modeled in our formulation by increasing their associated passage probability to a value of 1, that is, the road crossing no longer produces any barrier to passage.

The objective is to improve connectivity for all organisms. Passage value for all organisms is measured by summing over N_s, the number of organisms in the segment as

$$V_s = \sum_{i=1}^{N_s} V_{i,s} = \sum_{i=1}^{N_s} \sum_{t \neq s}^{T} L_t H_t D_{i,s,t} \varphi_{i,s,t} \qquad \text{Eqn 4}$$

where V_s is the total passage value for all organisms originating in segment s

This formulation maximizes the average quality and accessibility weighted habitat for all organisms in all segments. The average habitat value can be measured by summing total segment value over all segments:

$$V = \frac{1}{N} \sum_{s=1}^{T} V_s \qquad \text{Eqn 5}$$

where N is the total number of organisms over all segments.

The optimization formulation consists of a set of decision variables, an objective function and one or more constraints. In the present case, the decision is on the status of each barrier: remove it or make no change to the barrier. In a manner similar to O'Hanley (2011), this decision can be represented with a binary decision variable. For the barrier downstream of segment s (barrier j) define

$$x_j = \begin{cases} 1 \text{ if barrier removed} \\ 0 \text{ if barrier retained} \end{cases} \qquad \text{Eqn 6}$$

Alternative mitigation decisions (e.g. partial removal or improvement) were not considered because of a lack of data regarding potential alternate mitigation actions to full removal. The barrier removal decision is incorporated into the habitat value metric through equation 2 where the passability of a given barrier is defined as:

$$p_{i,j} = \begin{cases} p_{i,j}^0 \text{ if } x_j = 0 \\ 1 \text{ if } x_j = 1 \end{cases} \qquad \text{Eqn 7}$$

Where $p_{i,j}^0$ is the initial barrier passability (before any barrier mitigation occurs). In effect, the formulation assumes that if the barrier is removed, passability for all organisms returns to those present under natural conditions. An extension of the formulation, which is not pursued here, follows the approach of O'Hanley et al. (2013) in which the passability at a given barrier can be incrementally improved based on the degree (and associated cost) of barrier mitigation.

The objective function for our formulation is to maximize the value of the average habitat:

$$\max V(\boldsymbol{x}) \qquad \text{Eqn 8}$$

recognizing that the average habitat connectivity value depends on the choice of barriers to remove. Taken alone, the optimal strategy to maximize habitat for all organisms would be to remove all barriers. In practice, budget limitations typically limit replacement to only a fraction of barriers. A constraint on the budget available for replacement of barriers is added to the formulation and takes the form:

$$\sum_{j=1}^{T} c_j x_j \leq b \qquad \text{Eqn 9}$$

where c_j is the cost of replacing barrier j and b is the total budget available for barrier mitigation.

Taken together, equations 8 and 9 form an optimization problem that can be solved to obtain the set of barriers that should be removed to maximize the average habitat value within a specified budget. Solving this problem requires a cost for the replacement of each barrier, the length of each stream segment and a measure of habitat quality for each segment. As written, the formulation also requires the number of individual organisms in each segment and information about passability and dispersal with respect to that organism.

For many settings it will be impractical to consider all organisms. For these cases, individuals may be grouped by species, by a larger taxonomic group or group of species with similar dispersal tendencies, or may be represented by an "average" target species whose dispersal abilities fall in the middle of a range of expected dispersal tendencies.

Here we use a simplifying approach that starts with the assumption that all organisms have the same passability and dispersal function characteristics so that equation 4 simplifies to:

$$V_s = \sum_{i=1}^{N_s} \sum_{t \neq s}^{T} L_t H_t D_{s,t} \varphi_{s,t} = N_s \sum_{t \neq s}^{T} L_t H_t D_{s,t} \varphi_{s,t} \qquad \text{Eqn 10}$$

The number of organisms in segment s is estimated using the product of length and habitat quality, that is, $N_s = K L_s H_s$ where K is the number of organisms per unit of quality-weighted habitat length. Assuming K takes the same value for all segments and substituting,

$$\max \frac{K}{N} \sum_{s=1}^{T} L_s H_s \sum_{t \neq s}^{T} L_t H_t D_{s,t} \varphi_{s,t} \qquad \text{Eqn 11}$$

Because both *K* and *N* are constant, an equivalent objective function which will produce the same solution can be written as:

$$\max \sum_{s=1}^{T} L_s H_s \sum_{t \neq s}^{T} L_t H_t D_{s,t} \varphi_{s,t} \qquad \text{Eqn 12}$$

By eliminating the constants in Equation 11, equation 12 includes no explicit reference to the number of organisms in the watershed.

Combining equation 12 with equation 9 (with equations 2, 3, 6, and 7 implied) forms a complete formulation for maximizing habitat.

2.2 Case Study

The Westfield River is the longest tributary to the Connecticut River. The watershed, located in the Berkshire Mountains of western Massachusetts in the United States, contains 125.5 km of federally designated National Wild and Scenic River, which is located mainly in the West Branch of the Westfield River. Land use within the watershed is roughly 7 percent agricultural, 12 percent developed, and 82 percent undeveloped, with approximately 27 percent of the watershed permanently protected as open space. The overall population density of the watershed is less than 0.5 persons/acre. The Westfield itself is one of the most intact river systems in southern New England. The lack of development in the watershed and the watershed's natural beauty and recreational opportunities contribute to its importance to both wildlife and the local economy. The area features one of the largest roadless wilderness areas in the Commonwealth of Massachusetts as well as the longest uncontrolled segment of river in the Commonwealth. It is considered an outstanding coldwater fishery and whitewater boating destination, and harbors

many rare and endangered species. Thus, it is considered a high priority for conservation in Massachusetts (Wild and Scenic Westfield River Committee, n.d.)

This case study focuses on the Upper West Branch (UWB) of the Westfield River, a 140 km^2 subwatershed in the headwaters of the Westfield River with a total stream length of approximately 130 km. Available data indicates that the stream network is fragmented by 136 barriers including 10 dams and 126 road-stream crossings (e.g. culverts, bridges) as shown in Figure 1.

Data for this case study were obtained from the Conservation Assessment and Prioritization System (CAPS). CAPS is an ecosystem-based approach for measuring ecological integrity and connectivity, and its purpose is to support decisions regarding conservation of habitat and biodiversity. Here, ecological integrity is defined as the ability of an area to support biodiversity and the ecosystem processes necessary to sustain biodiversity over the long term, and is measured using a metric termed the Index of Ecological Integrity (IEI), which combines various ecological and anthropogenic metrics to predict ecological integrity at the landscape scale. This multimetric indicator of ecological health can range from 0 to 1 and represents a multispecies measure of habitat quality rather than a measure of quality relevant to one species (McGarigal et al., 2008).

As part of the integrity assessment described above, a statewide inventory of barriers, including dams and road-stream crossings, has been compiled, and aquatic passability scores have been determined for road-stream crossings throughout Massachusetts. More than 1000 barriers in the state have been surveyed by volunteers to directly assess physical characteristics that are presumed to influence the ability of aquatic organisms to pass these barriers. Thousands of additional barriers have been assigned an aquatic passability score using a statistical model

based on the field assessment data (McGarigal et al., 2012). Within the dataset, 54 of the 126 road-stream crossings (43%) were surveyed to determine aquatic passability while the remaining 72 crossings were modeled. These passability values represent the similarity of the condition of the stream crossing to its ideal or unimpacted state. It is assumed that an unimpacted stream condition will provide maximum natural aquatic passability for all aquatic organisms attempting passage, while any deviation from the stream's natural state (e.g. a perched culvert outlet or a flow regime quicker or more turbulent than the natural state) will limit passage. Passability scores are scaled from 0 to 1, with 1 representing full or natural bidirectional "passability" (McGarigal et al., 2012). As with the IEI, the passability value is taken as a measure based on a range of physical characteristics representing the overall condition of the stream, and therefore can be considered a multispecies metric (Jackson, personal communication). The passability value derived from CAPS was used as $p_{i,j}$ in the formulation.

CAPS data were provided in the form ArcGRIDS and ArcGIS shapefiles. Locations and aquatic passability ($p_{i,j}$) scores were provided for each barrier. Among the 136 barriers in the watershed, the average aquatic passability value for all dams and stream crossings was 0.760, while the average passability for the 126 road-stream crossings alone was 0.819. The length of habitat between barriers, L_t, was obtained by splitting the stream network into discreet segments with endpoints at barrier locations, providing contiguous reaches of stream bounded by two or more barriers. L_t was calculated as the contiguous length of the stream centerline. The average value of L_t, was 0.976 km.

IEI data were obtained from CAPS in the form of a GIS raster layer scaled to the Westfield River watershed and were used as the measure of habitat quality, H_t, in our formulation. This layer was sampled every 10 meters along the streamlines within the

watershed. The sampled values, grouped by the barrier-bound stream segment on which they occurred and averaged across each of these segments, provided a value for H_t score for each contiguous segment.

Figure 2 illustrates the distribution of values for p_{ij} and H_t within the UWB. Barrier passability values tend to be highest along the mainstem and lower for barriers located on tributaries, likely because road-stream crossings tend to be built as bridges on larger streams and as culverts on smaller streams such as exist in the headwaters of the UWB. Alternatively, habitat integrity values are higher for tributary segments than along the mainstem, as more urbanization and habitat degradation has occurred along the mainstem than along the steeper tributaries of the UWB.

Accurate cost estimates and cost distributions for individual barrier mitigation projects in this region were not available, and had to be generated for this case study. Costs were scaled to the budget so that a budget, b, of $1 million would allow the mitigation of approximately 10 barriers. Thus, a cost, c, was assigned to each culvert mitigation project from a normal distribution with an average of $100,000 and a standard deviation of $25,000. While these costs may not fully represent the range of possible barrier mitigation costs, they fall within the low end of the expected range of culvert mitigation costs for the state (MASSDER, unpublished data). In addition, they allow the comparison of budget scenarios where solutions vary by predictable numbers of barriers, so that the impacts of specific barriers and their characteristics on the solution can be more easily assessed.

2.4 Implementation

To simulate a situation in which only road-stream crossings were considered for removal, dams were excluded from consideration for removal by assigning a value of c higher than the
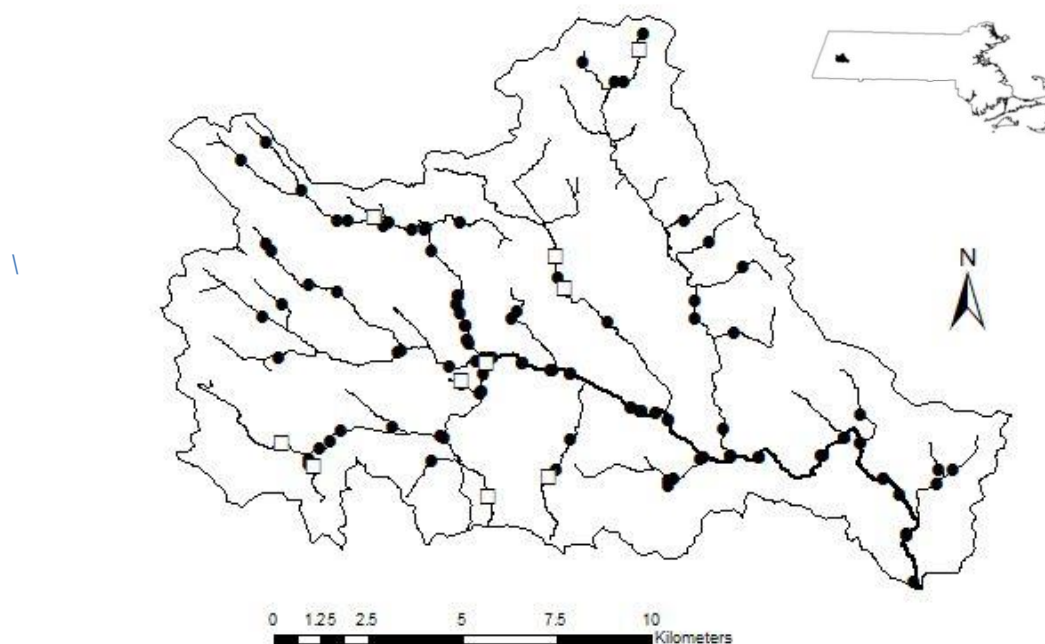
Figure 1: Map of the Upper West Branch (UWB) of the Westfield River. The watershed contains 126 road-stream crossings, indicated by black circles and 10 dams, indicated by white squares. The heavy black line indicates the section of the mainstem of the West Branch of the Westfield River that runs through the UWB.
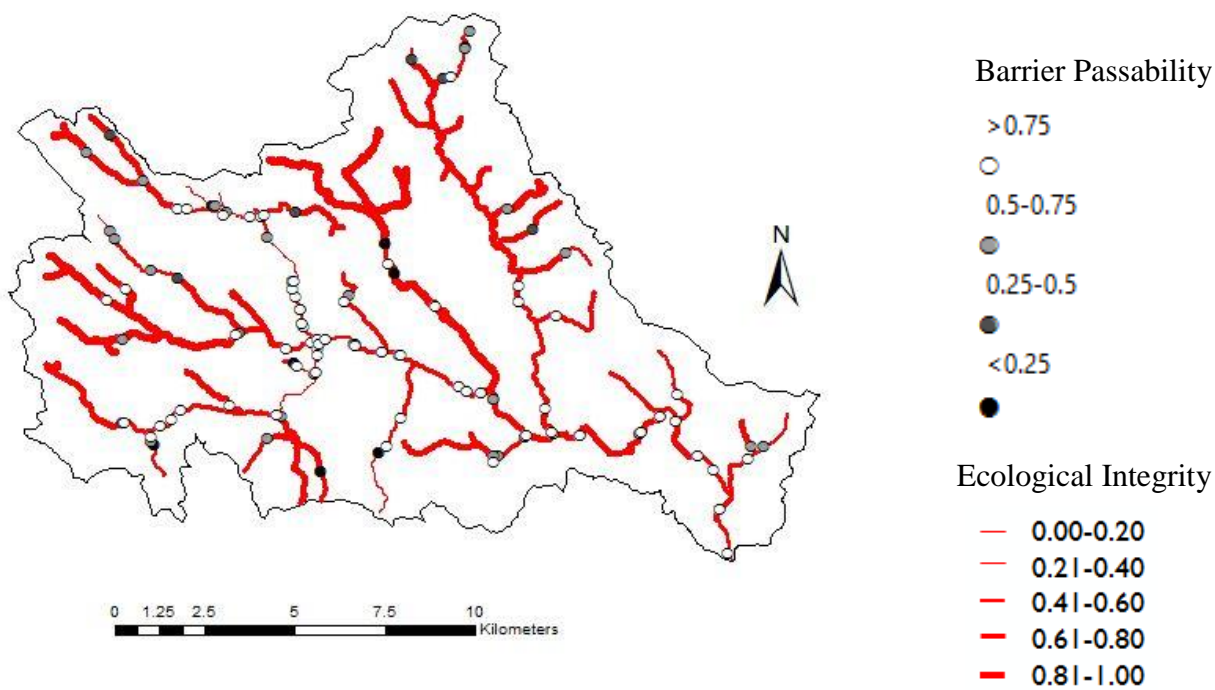

Figure 2: Map of IEI and passability values in the UWB. High-integrity stream reaches are indicated by heavier line weights and tend to be located in the tributaries, or headwaters, of the watershed, while reaches along the mainstem tend to be of lower integrity. Barriers with higher aquatic passability values, indicated as white circles, tend to be located along the mainstem while barriers of lower passability tend to be located at the extremities of the network, on tributaries.

highest budget level, b, assessed. However, the effect of the dams on connectivity was still considered. In this way, dams acted much like natural barriers such as waterfalls, which may block access to sections of riverine habitat and are unlikely to be removed or altered by anthropogenic forces. The impact of natural barriers such as waterfalls or rapids was not considered in this assessment.

A sensitivity analysis was conducted to determine how solutions changed as the budget increased. Budget values increased at $100,000 intervals from a budget of $100,000 up to $1 million, then at $500,000 intervals to $9.5 million. For this analysis, dispersal distance, d_i, was set to 3 km, a value which approximates the dispersal abilities of a small fish. Individual project costs remained constant across all budget levels assessed in the analysis.

To assess the dependency of the results on the generated costs, a randomized cost analysis was performed in which the formulation was solved for two budgets only, using the available barrier data and 100 additional sets of randomized barrier costs generated from the normal distribution described above. Generated costs were inspected to ensure that across the trials each barrier was assigned costs covering the possible range of values in the distribution. Budgets were set to $1 million and $2 million to simulate scenarios in which approximately 10 and approximately 20 barriers would be mitigated in the watershed, as a single round of funding or prioritization effort generally allows the removal of a number of barriers in this range. Following the 100 trials, the set of barriers selected for removal at each budget was assessed for every set of barrier cost data and the frequency of selection of barrier across the 100 trials was determined to assess the impact of cost on the barrier selection choices.

The formulation was solved using a micro-Genetic Algorithm (Nicklow et al., 2010) with the code provided by D.L. Carroll (GA Fortran Driver, Version 1.7a, 2001,

http://www.cuaerospace.com/Technology/GeneticAlgorithm.aspx). The model was run for each

budget three times, with different limits on the number (100,000; 500,000; and 1 million) of

allowed evaluations. The solution that produced the highest objective function value was

selected for the final analysis, irrespective of the number of evaluations allowed in reaching the

solution.

3. Results

In this analysis a question is proposed: does mitigation cost, existing passability, habitat

quality, or the spatial organization of barriers within the network dominate the solution? The

results of the analysis described above are examined in relation to this question. The discussion

below examines the impact of each factor on the solution.

3.1 Model Behavior

The sensitivity analysis produced objective function values as well as barrier removal

portfolios for each budget level. While the value of the objective function increased with the

total budget (and with the number of barriers removed), Figure 3a shows a pattern of decreasing

marginal improvement in the quality-weighted accessible habitat as the budget increased,

indicating that the combinations of barriers that add the most value to the objective function are

being selected first; barriers that contribute less value are added as more money becomes

available. However, the trend is nearly linear for portions of the curve, which indicates that there

is some homogeneity within the watershed, i.e. many barriers or combinations of barriers in the

network contribute similar quantitative gains in value, as determined by the model, when

removed.

The number of barriers removed increased linearly with the increase in budget, with

approximately 11 additional barriers removed for every $1 million increase in budget, as

illustrated in Figure 3b.   It is important to note that the solutions were not perfectly nested; i.e. the barriers selected at lower budget levels were not always included in the barrier solutions at higher budget levels.   Upon examination of the problem, it is clear that there is no mathematical requirement in the formulation for the solutions to be nested, a phenomenon that has also been demonstrated in prioritization studies using linear programming methods where global optimal solutions are guaranteed (O'Hanley, 2011). This is of concern because it indicates that cases might occur where slight changes in budget could potentially result in significant changes in the barriers selected for mitigation and in the objective function value. Inspection of the results of this case study revealed that though solutions were not perfectly nested, they were remarkably similar across budget levels. High levels of similarity may allow decision makers confidence in their restoration decisions, even if the reality of the situation requires that a barrier in the solution set be replaced with another; within limits, it can be assumed that near-optimal gains will still be achieved. However, restoration solutions will not always be so straightforward, and the level of flexibility available in the solutions will have to be assessed on a case-by-case basis. In watersheds where solutions change dramatically with the budget, knowledge of the total budget that will be available for a project over its lifetime is crucial if one hopes to achieve the greatest possible restoration gains.

3.2 Impact of Barrier Cost

Individual barrier costs generated for the sensitivity analysis ranged from $50,250 to $149,230, with an average barrier mitigation cost of $97,106.

Barriers selected for removal generally were less expensive than the average across all budgets tested in the sensitivity analysis, but especially for budgets less than $2 million. Average costs for selected barriers ranged from $64,381at a budget level of $200,000 to
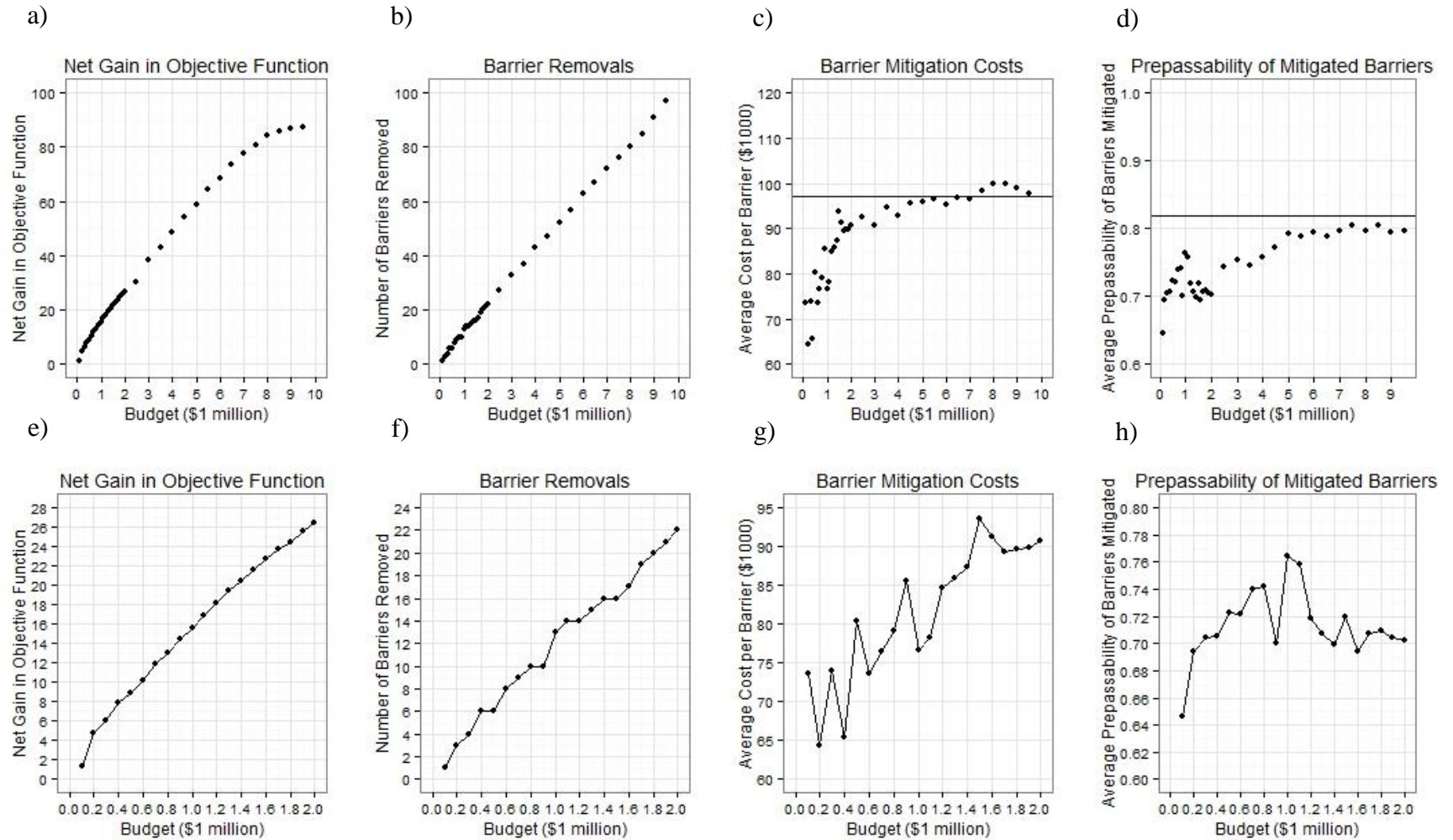
Figure 3: For budgets of $100,000 to $9.5 million, (a) the number of barriers removed; (b) the net gain in quality-weighted habitat; (c) the average cost of mitigation per barrier selected, with the average for all barriers in the dataset marked by the horizontal line; (d) the average pre-mitigation passability of barriers selected for mitigation, with the average for all barriers in the dataset marked by the horizontal line. For a higher-resolution sensitivity analaysis of budgets of $100,000 to $2 million, (e) the number of barriers removed; (f) the net gain in quality-weighted habitat; (g) the average cost of mitigation per barrier selected; (h) the average pre-mitigation passability of barriers selected for mitigation.

$100,000 for a budget of $8.5 million. Figure 3c shows that average costs generally increased with the increase in budget, so that at budgets over $1.5 million, costs for selected barriers were within 10% of the average; at budgets over $3.5 million, average costs for selected barriers were within 5% of the average.

The results of adjusting the budget at a finer resolution are illustrated in Figures 3e-h. When the budget increases from $0.4 million to $0.5 million, Figure 3g indicates that the number of barriers remains the same; at the same time both the objective function and the average cost per barrier rise. This occurs again as the budget increases from $0.8 million to $0.9 million, from $1.1 million to $1.2 million, and from $1.4 million to $1.5 million. This illustrates a threshold effect whereby the formulation switches one barrier out of the solution set and instead selects a different, more expensive barrier for removal in order to provide more habitat value. This is the mechanism which leads to the lack of nestedness mentioned above.

Although individual removal cost has no direct impact on the value of the objective function, it is clear from the formulation's consistent selection of low-cost barriers that individual mitigation costs are an important factor in the formulation. However, results from the randomized cost analysis indicate that the randomly generated costs were not the main driver of the results. Figure 4 illustrates the frequency of selection for each barrier out of 100 runs for budgets of $1 million and $2 million, respectively. Decay in frequency of selection is apparent for both budget levels: a few barriers are selected for nearly 100% of the project cost scenarios regardless of their cost, while some barriers are never selected in any scenario. These results indicate that though cost does play a somewhat significant role in barrier selection, it is not the only deciding factor. If price were the only driver, we would expect to see no decay in Figure 4, since barriers would be selected with approximately equal frequencies. The extreme differences

in the frequency of removal for some barriers indicate that some additional factor(s) is driving these decisions in combination with project price. In fact, some barriers are selected with such frequency it is clear that they have an inordinate impact on stream connectivity through some other factor.
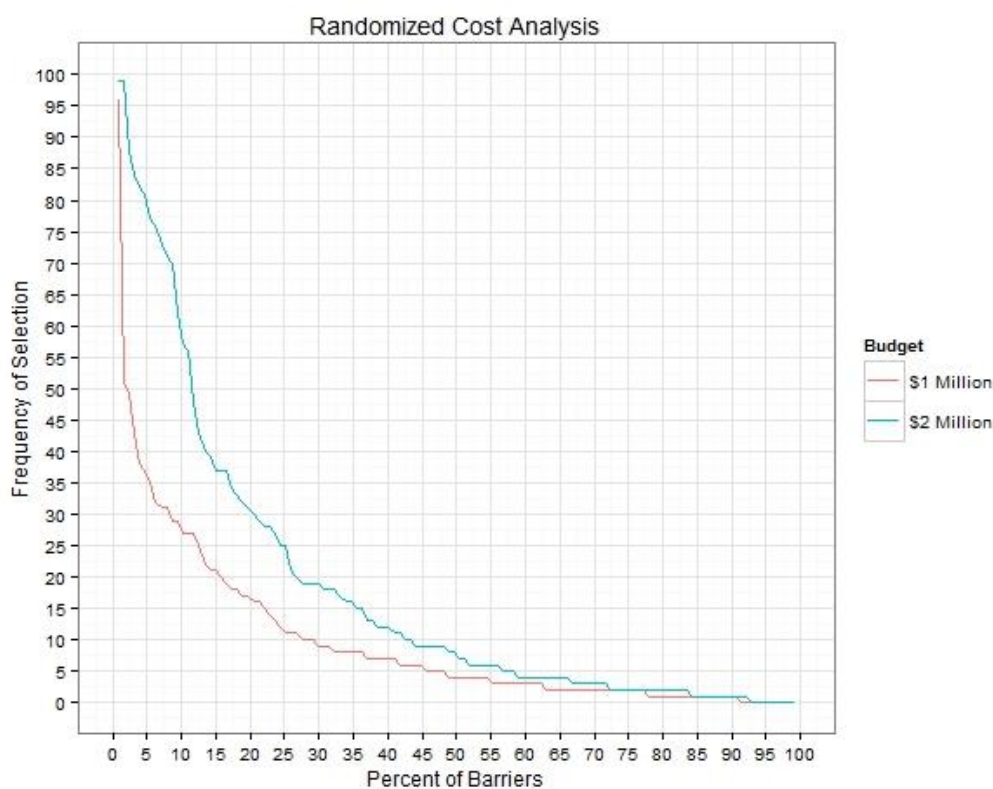

Figure 4: Frequency of removal out of 100 trials for barriers with randomly varied costs. Solutions were generated for 100 sets of randomly generated barrier removal costs, and the frequency with which each barrier was selected among the trials was tallied to determine the impact of cost on the solutions.

3.3 Impact of Initial Barrier Passability

Among barriers selected for removal, average passability generally increased as the budget increased; i.e. the formulation initially prioritized less passable barriers for removal, but selected more passable barriers for mitigation when more money was available. However, this increase is not consistent and the slope of the overall trend shown in Figure 3d decreases as

budget decreases; at higher budgets the average passability for barriers selected for removal is similar to the average barrier passability value for the entire set of barriers.

In the randomized cost analysis, the average passability for barriers selected in over 75% of the trials for budget of $1 million was 0.694 (median =0.694), compared to an average of 0.880 (median = 0.983) for barriers that were never removed. Similarly, for a budget of $2 million, the average passability of barriers selected in 75% of trials or more had an average passability of 0.720 (median = 0.732) while the passability barriers were never selected for removal averaged 0.908 (median =0.98).   The lack of barriers with extreme prepassability values in the solution sets indicates that barrier passability is a factor in determining the frequency of barrier selection in the randomized cost analysis, but not the primary driver in the decision.

3.4 Impact of Habitat Quality

There is no apparentrelationship between barrier selection and habitat quality values, which are associated with stream segments, so habitat values cannot be used independently to predict/determine barrier selection. Instead, the formulation selects barriers that create the most connected path between different high quality segments, maximizing L_sH_s and L_tH_t. Figure 5 illustrates the location of barriers selected for removal at four different budgets in the sensitivity analysis. A comparison with Figure 2 reveals that barriers are frequently removed in stream segments directly connecting two separate segments with extremely high quality.   Connecting these habitat patches maximizes the accessible habitat for aquatic species by providing corridors for migration between them, reducing their isolation and the isolation of any species dependent on such high-quality patches.
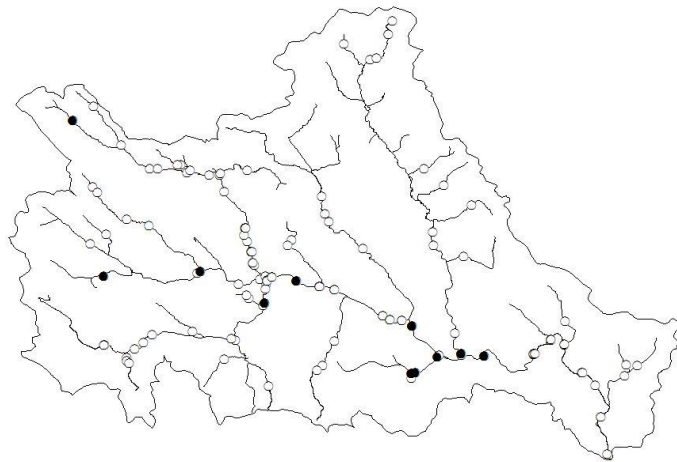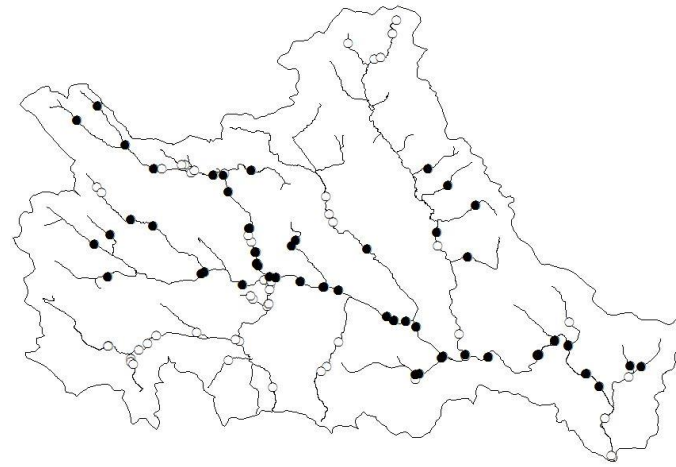
(a)
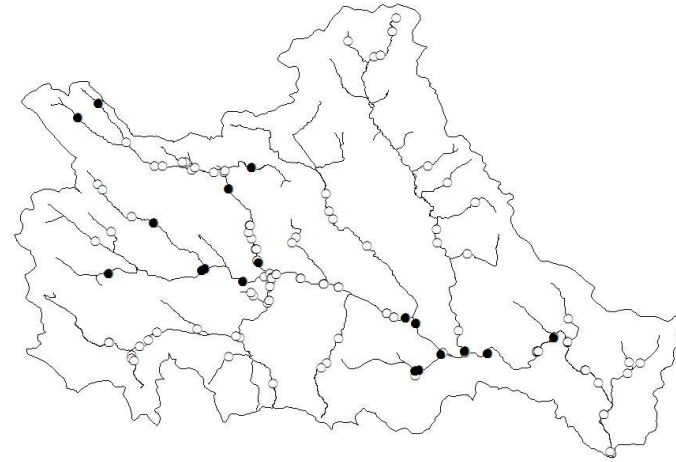
(b)
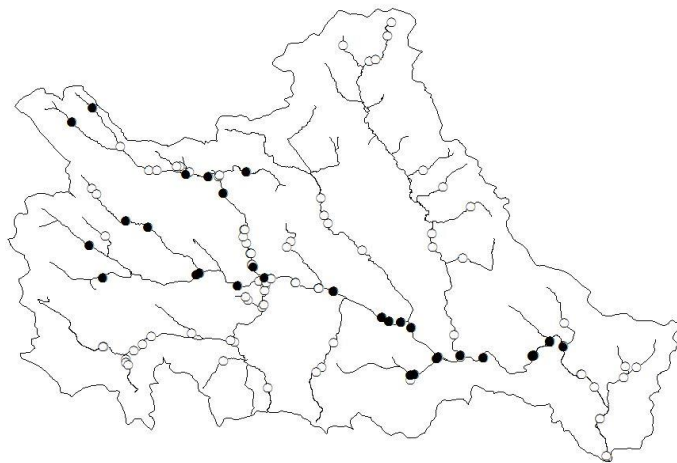
(c)

(d)

Figure 5: Barrier mitigation solutions for the Upper West Branch of the Westfield River. a) Budget =$1 million; b) budget = $2 million; c) budget = $4 million; (d) budget = $8 million. Black circles indicate barriers selected for mitigation. Unmitigated barriers are indicated by white circles.

3.5 Impact of Spatial Organization of the Watershed and Barriers

The spatial distribution of barrier solutions for four budget levels is shown in Figure 5. Barriers selected for removal at lower budget levels are located primarily along the mainstem of the UWB. At higher budgets, barriers are selected from the tributaries with increasing frequency, while mainstem barriers still comprise a large portion of barriers selected for mitigation. Barriers selected frequently in the randomized cost analysis are also located on the mainstem of the UWB. Beyond their central position in the network, which leads to a greater impact on overall connectivity as measured here, the most frequently selected barriers occur in reaches along direct paths between the stream segments with the highest habitat quality, as discussed above. Barriers along these reaches are even more likely to be selected if other barriers on the same path are already highly passable; thus, colinearity with other highly passable barriers is accounted for in selecting barriers for removal.

3.6 Use of Genetic Algorithms

Genetic algorithms are widely used for water resources applications (Nicklow et al., 2010; Reed et al., 2013) because of their ability to handle nonlinearities. In addition, genetic algorithms allow for simplicity and convenience in writing a sophisticated optimization formulation.   One challenge with genetic algorithms is computational time. In the work presented here, solving a single problem with the genetic algorithm using 500,000 evaluations could take up to an hour. Alternate solution methods (O'Hanley, 2009) can be more efficient for formulations similar to the one presented here. Problems of similar size to that presented here have been solved in fewer than 5 minutes by O'Hanley et al. (2013) and O'Hanley (2011). A larger-scale problem with more barriers or additional decision variables would require even greater solution times.   Nevertheless, in cases such as this, where projects are resource-intensive

and have considerable ecological, political, and social implications, but are not time-sensitive, computational efficiency is not the highest priority.

4. Conclusion

In this paper a nonlinear optimization formulation is proposed to determine which barriers within a watershed should be selected for removal across a range of budgets. The model includes a new metric for habitat quality-weighted connectivity and incorporates measures of habitat integrity and barrier passability which generalize the model to take a multispecies approach rather than focusing on a single species. The formulation is demonstrated in a case study on the Upper West Branch of the Westfield River in Massachusetts.

It was demonstrated that certain barriers may have an inordinate impact on stream connectivity such that removing these first few barriers can effect large ecological gains within relatively tight budgets, but that the right barriers must be picked to have this effect. For systems in which non-migratory organisms are of concern these barriers tend to be located along central portions of the mainstem, particularly in those reaches that connect one high-quality reach to another. In this, the formulation is in accordance with current ecological theory that it is most beneficial to overall ecological health and native species to preserve high quality habitat patches and the connections between them.

The results of this analysis confirm the findings of O'Hanley (2011) and O'Hanley et al. (2013), who also found that barriers selected for removal tend to be less expensive than the average barrier in the watershed, and that having accurate knowledge of project costs is crucial to the prioritization process if the most efficient solutions are to be selected and implemented. Planning using known project costs allow restoration managers to make more reliable and cost-effective restoration decisions while staying within the limits of a prescribed budget, which can

bolster support for restoration actions. Accurate knowledge of project costs can also allow decision-makers to determine and request budget levels that will allow the implementation of the most efficient combination barrier removal projects based on thresholds in the objective function. These results indicate the importance of knowing accurately the costs of barrier mitigation for all barriers considered for mitigation in a watershed.

However, restoration budgets for multi-year or multi-stage restoration projects are sometimes unknown, while the lack of nested solutions also indicates the importance of knowing accurately the long-term budget for basin-wide barrier mitigation efforts. Since a small increase in budget could potentially lead to a completely different solution (set of barriers) and a marked increase in ecological benefits, decision makers should consider performing a sensitivity analysis across budgets for every watershed barrier removal project. Doing so is a relatively quick process given current modeling capabilities, and while restoration decisions are not particularly time-sensitive, they often have large-scale, long-ranging implications that increasingly demand thorough planning and accountability.

Although ecological connectivity is the goal of this particular model, in reality many other factors influence the decision to mitigate any given barrier. In the Northeast, the risk of the failure of a dam or stream crossing and the severity of the consequences of that failure are of great concern, particularly in the face of climate change and the larger, more frequent floods that are expected to occur. Maintenance schedules, transportation delays, provision of emergency services, public support, and other factors must also be considered before a final decision is made regarding which barriers to mitigate. This formulation provides insight on only one, albeit significant, area of concern and thus should be utilized as a screening tool and its products a starting point in the decision-making process, rather than an ultimatum.

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Appendix A: Sensitivity Analysis across Expected Dispersal Distance

A sensitivity analysis was performed on the expected or average dispersal distance for the organism over relevant timescales, d_i, using data from the Upper West Branch (UWB) of the Westfield River watershed and the randomly generated costs used in the budget sensitivity analysis. Budget constraints of $1 million and $2 million were set to allow the removal of 10 and 20 barriers, respectively. Values of 0.01 km, 0.1 km, 1.0 km, 3.0 km, and 10.0 km were used for d_i and the model was run for 500,000 evaluations.

Figure 6a illustrates the effect of d_i on the value of objective function. Below values of 1km, the value of di appeared to have little influence on the net gain of the objective function value. At values of 1.0 km and greater the net gain in the objective function increases exponentially with d_i. It should be noted that the value of 1 km is also approximately equal to the average hydrologic distance between barriers in the UWB. Figure 6b shows that the net gain as a percentage of the original value also increases with dispersal distance. These results are not surprising, as organisms with greater dispersal abilities will benefit more from barrier removals. On the other hand, low values of d_i force the value of the objective function to a value so low that most solutions will have approximately the same ecological connectivity value. This reflects the fact that barrier removal would be an ineffective conservation strategy for organisms without the ability to disperse farther than the distance between barriers.

Despite the order-of-magnitude changes in d_i, solutions were highly similar in terms of barriers selected for removal across dispersal values (67% or greater similarity in barriers chosen for all trials with a budget of $1 million, and 74% or greater similarity for all trials with a budget of $2 million).

It is possible that the resolution of the habitat quality data used in this case study is too low in terms of spatial resolution or diversity of habitat types to allow changes in model behavior or in the importance of the input variables to be discerned in relation to changes in d_i. Future analysis of the impacts of d_i might incorporate higher resolution habitat quality data, and should include analysis of the impacts of changing d_i on the relative importance of other input factors. Relationships between dispersal distance and spatial characteristics of the watershed should be explored further as well.
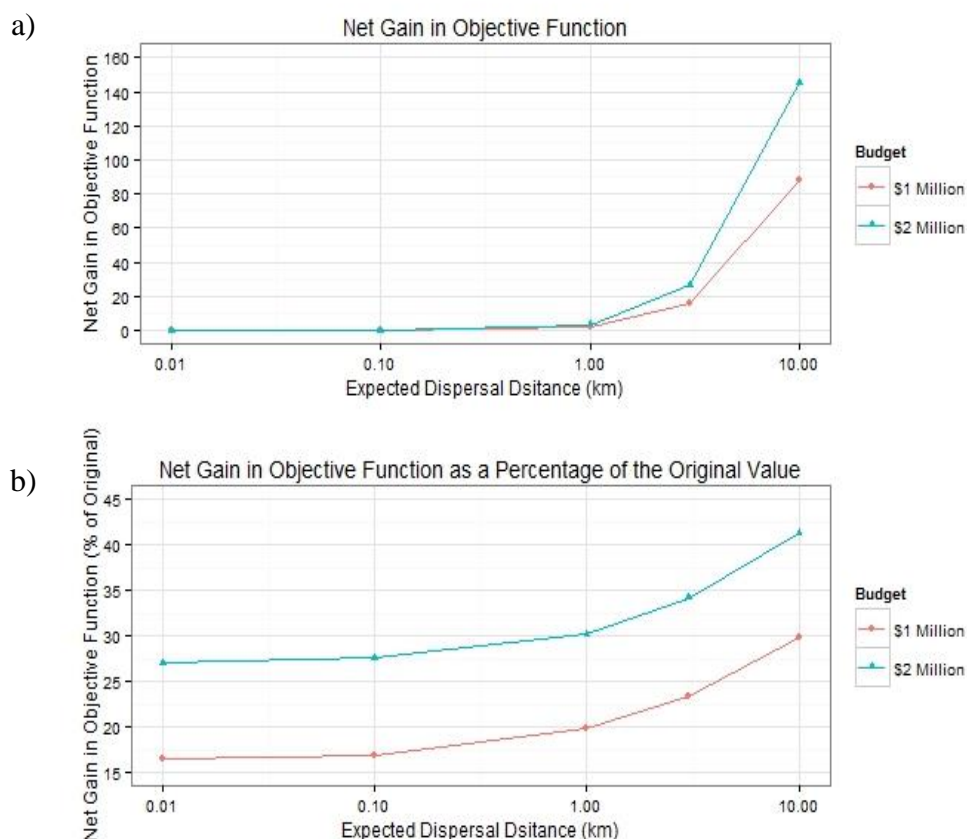
Figure 6: a) The net gain in the objective function, achieved through barrier removal and b) the percent increase in objective function achieved over its original value (before any barriers are removed) vs. the expected dispersal distance, d_i. The objective function increases exponentially with d_i, with major gains seen above d_i=1.0 km. Greater objective function values are achieved for higher budgets due to the ability to remove greater numbers of barriers.

Appendix B: Future Research

In addition to the ideas discussed in the article above, many questions remain in what is a relatively new field of study. Future avenues of research are discussed below.

Further Analysis of the Current Formulation

Preliminary results are presented regarding a sensitivity analysis of dispersal distance, d_i, in Appendix B. Further analysis on this topic is warranted and might reexamine the influence of expected dispersal distance on the objective function using a different range of dispersal distance values. In addition, it is possible that averaging habitat quality data over stream segments of 1 km or longer caused portions of the watershed to appear relatively homogenous in this respect. Among other things, this may have masked any changes in model behavior or in the importance of the input variables in relation to changes in d_i.   Future analysis of the impacts of d_i might incorporate higher resolution habitat quality data, and should include analysis of the impacts of changing d_i on the relative importance of other input factors. Relationships between dispersal distance and spatial characteristics of the watershed should be explored further as well.

Future researchers might consider the loss of optimality associated with limiting the selection of removable barriers to allow mitigation only of dams or only of road-stream crossings as opposed to allowing the removal of any anthropogenic barriers present. It is likely that limiting these choices reduces the efficiency of the solution, especially if omitted barriers are located in or near high-quality habitat patches or near the center or mainstem of the network. Therefore, the results of an analysis such as this are likely to be watershed-specific.

The analysis of the barrier removal solutions discussed in the main article included a qualitative description of spatial characteristics in the barriers selected for removal (as opposed

to those that remained unselected). Quantifying these spatial patterns may reveal important impacts of barrier arrangement and stream network structure on prioritization. Spatial autocorrelation between barriers and/or stream segments should be assessed, as well as any possible links between levels of spatial autocorrelation and the value of d_i.

A Monte Carlo simulation may also provide valuable information. To perform the simulation, the dataset of existing barriers might be randomly sampled to select multiple portfolios of 13 barriers. The characteristics of these barrier portfolios may then be compared to the characteristics of the 13 barriers included in the solution provided by the optimization formulation for a budget of $1 million, in order to determine if spatial characteristics or other parameters differ significantly. The process could be repeated at a budget of $2 million, selecting random sets of 22 barriers for comparison to the solution produced by the optimization formulation.

Specifically, the analysis might be used to compare the spatial arrangement of the barriers (e.g. average distance from the mouth; average number of stream kilometers within one hydrologic kilometer of each barrier; or average distance to adjacent barriers) as well as factors already discussed above (barrier passability and cost of barrier removal).

Informing the Formulation

It has been shown in the results above that accurate *a priori* knowledge of individual barrier mitigation project costs is relatively important, since the solution produced by the formulation tends to select the lowest-cost barriers from the set of barriers available for removal. Currently, cost data is not available for the vast majority of barrier removal projects in Massachusetts, and is particularly lacking for culvert removals.

As part of the Conservation Assessment and Prioritization System (CAPS) project, data regarding physical characteristics of culverts is collected and uploaded to a public database (Jackson et al., 2007). This data could be incorporated into a deterministic model for estimating barrier removal costs, to be used in conjunction with database information.

Model validation would require a significant amount of information regarding the cost of previously completed barrier removals. An online survey such as that created by researchers at the Center for Limnology at the University of Wisconsin (https://docs.google.com/forms/d/1YLxLFkU91HwQoygKlST0P3fInYoZX2VodDFAJvWmAtE /viewform) may be used to collect barrier removal cost data from contractors, landowners, agencies, and NGOs.

Extension of the Current Formulation

The formulation as it is presented above assesses connectivity for only one watershed at a time. However, the formulation is scalable such that the analysis could be extended to account for multiple watersheds with a common outlet or confluence by incorporating all barriers and stream reaches within the watersheds or subwatersheds into a single network. Alternatively, the analysis could be extended to determine connectivity across multiple unconnected watersheds by simply summing connectivity over multiple watersheds, as in O'Hanley et al. (2013).

The formulation proposed here could also be extended to account for the diversity of habitat types which may be present in a stream and which may have different levels of value for different organisms. O'Hanley et al. (2013) accomplished this by including additional variables in their formulation and determining habitat quality from Strahler stream order. Instead, we suggest that habitat diversity and suitability might be determined using metrics (e.g. urbanization, traffic, and land cover class) which have already been calculated within CAPS as

intermediate values in the calculation of the Index of Ecological Integrity (IEI). It will be

important to use the individual metrics in this case rather than simply relying on IEI because the

suite of metrics used to calculate the IEI include connectedness and similarity metrics that reduce

IEI values in the presence of habitat heterogeneity (McGarigal et al., 2008)   .

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Appendix C: Data Preparation Using GIS

Data Sources

Vector shapefiles containing dam locations, road-stream crossing locations and streamlines were obtained from the Conservation Assessment and Prioritization System (CAPS) project. The barrier shapefile contained point locations for 25,529 barriers (2189 dams and 23,340 road crossings) in Massachusetts. Barrier attributes for both barrier types are listed in Table 1.

The Streamlines file was a heavily corrected as described in McGarigal et al. (2008). A raster layer containing Index of Ecological Integrity (IEI) values scaled to the Westfield River Watershed was obtained from the same project but was downloaded from (http://www.umasscaps.org/index.html).

A vector shapefile containing the watershed boundary of the West Branch of the Westfield River was downloaded from the National Hydrography Dataset (NHD: http://nhd.usgs.gov/). This watershed is of the smallest selected watershed size/number in the NHD. This feature class shapefile contained information regarding subbasins within the boundary as well as attribute data.   The watershed boundary for the Upper West Branch (UWB) of the Westfield River, a subbasin of the West Branch was then extracted from the subbasins embedded in the West Branch boundary using the *Select (Analysis)* tool using an SQL expression and saved to a new feature class.

Table 1: Attributes Provided for Road-Stream Crossings and Dams

	Road-Stream Crossings	Dams
Attributes	X-coordinate Y-coordinate Aquatic Passability Terrestrial Passability Surveyed (Binary, yes/no)	X-coordinate Y-coordinate Dam (name) River Dam Height Aquatic Passability

Data Processing

Extraction of relevant data for this project required considerable data processing and analysis in ArcMap. All data processing and analysis was performed using ArcGIS 10.2.1 for Desktop (http://www.esri.com/). The XTools Pro 10.1 extension for ArcGIS (http://www.xtoolspro.com/) provided additional tools that were not available in the ArcToolbox.

The first task was to extract the data necessary for this case study from the larger regional ad state-wide datasets provided. To do this, it was necessary to ensure that all barriers located within the watershed of interest were properly located on streamlines within the watershed. Because the barrier data provided consisted of points extracted from a raster file, barriers were not initially located directly on streamlines. The *Snap (Editing)* tool was used to snap each barrier in the dam and crossing datasets to the nearest streamline, within a tolerance of 15 meters.

The *Clip (Analysis)* tool was then used in batch mode to simultaneously clip the dam, crossing, and streamline feature classes to the watershed boundary of interest, creating new feature classes which included the points and streamlines within the UWB boundary. The new barrier feature classes contained 136 barriers (126 crossings and 10 dams)

The stream network provided to us originally consisted of many separate poylines divided in a way which had no bearing on our analysis. The *Dissolve (Data Management)* tool was used to merge all of the streamlines into one streamline. The *Split Line at Point (Data*

Management) tool was then used to divide this network into segments, using barriers as point features and a search radius of 2 m. This tool also divides segments at all line intersections, resulting in a stream network broken both at barriers and at stream junctions. The resulting shapefile was manually edited using the *Editor* toolbar to correct this problem. The *Merge* tool on the *Editor* toolbar was used to merge sections at the stream junctions, so that barriers served as the only breakpoints and so that each branched or unbranched segment between barriers were connected as a single segment. This produced a feature class containing 145 individual branched and unbranched stream segments unbroken by any anthropogenic barriers. Segment lengths could then be determined using the *Identify* tool.

The average IEI score was determined for every individual stream segment by sampling the IEI raster layer at uniform intervals along the network and averaging the IEI sample values across each segment. The dissolved stream network created as the first step in dividing the stream network above was utilized once again. The network was split at 10m intervals using the XTools *Split Polyline* tool.   Points were created at the newly created vertices of the divided stream network using the *Feature Vertices to Points (Data Management)* tool, resulting in the creation of 26,020 points.

IEI values were then determined at these geographic locations using the *Extract Values to Points (Spatial Analyst)* tool. In effect, this tool overlays the IEI raster with the points along the stream network and samples the IEI value at each point. The IEI value within each segment was determined as the mean of the sampled IEI values along each segment, and this value was used as the habitat quality score, *H*, for the segment within the formulation.

Each IEI sample point was then assigned to one of the 145 stream segments produced earlier by using the *Intersect (Analysis)* tool to identify the individual stream segment in which

each sample point was located. This created a point shapefile in which ever IEI sample point was associated with a stream segment ID. The attribute table for this new file was opened and summarized over each stream segment, producing an average IEI value for each stream segment ID. The output was inspected to ascertain that each stream segment had an associate positive IEI value. If a segment was too short to contain even one sample IEI point, the mean of the IEI values of the upstream and downstream segments was used as the IEI value for the segment in question.

Data Storage

All final and intermediate files are stored in a file geodatabase on a personal thumb drive.

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Appendix D: Adaptation of the Formulation into a Scoring and Ranking Process

Theoretical Framework

The optimization formulation described above provides a mathematical programming method for determining optimal solutions to a complex problem. However, optimization methods can be difficult to implement for conservation planners who lack a specialized level of expertise in mathematical and computer programming (Kemp and O'Hanley, 2010), and these methods similarly lack transparency when presented to stakeholders, which may prevent their widespread application to real-world decision-making (Hajkowicz et al., 2009). As conservation planners adopt more systematic methods for prioritization of barrier removal decisions, it will be important to provide prioritization methods that are both accurate and transparent. In turn, these tools may bridge the gap to the use of more sophisticated methods such as optimization in conservation planning.

The following is a scoring and ranking procedure that approximates the optimization formulation described above. In each protocol, habitat quality and dispersal distance are used to determine the value of connectivity between different sections of the network. Whereas the optimization formulation utilizes habitat quality and dispersal distance as weights on the value of connectivity between segments, this protocol assesses these values in comparison to thresholds, in order to screen out sections of the network in which barrier removal will provide little benefit for the organism(s) of concern. By screening out portions of the network, barriers whose removal would provide little value are simultaneously screened out of the available solution set,

Barriers are then ranked according to their passability and their location relative to the network. The results of the UWB case study suggested that barriers located centrally in the network provide greater benefit when removed because improved passage at that location

improves connectivity between multiple sections of the network. Cote et al. (2009) similarly found that barriers located centrally within a river network had a greater impact on potadromous connectivity than barriers located at the extremities of the same network. The path-counting step described in step 4(a) serves as a simple measure of centrality.

Ties are unlikely to occur given the structure of the protocol and the continuous scale across which passability is scored in CAPS. However, should ties occur, they may be broken by considering issues not included in the formulation (e.g. stakeholder support, regulatory barriers, or constructability).

Protocol

1) Divide the stream network into segments that are unblocked by anthropogenic barriers (e.g. barriers or road-stream crossings). Barriers may be branched or unbranched. Assign a score for the habitat quality or integrity of these segments.

2) Determine a threshold (0-1) for stream segment habitat quality, which will be used to select the highest quality segments for connectivity prioritization. The threshold may be

   a) Associated with individual segments, scaled to allow the selection of a predetermined percentage of stream segments or stream length, or may be scaled to the actual range of habitat quality values in the watershed.

   b) Associated with the cumulative habitat quality of each segment pair, determined by multiplying both quality scores to determine a value that may be compared to a threshold.

3) Each segment pair will be connected by a single linear path along the stream network. The path allows bidirectional (upstream and downstream) movement of organisms. between the two segments in the pair.

a) Determine which segment pairs are blocked by a natural, impassable barrier (e.g. a tall waterfall). Eliminate these segment pairs from consideration if this barrier is completely impassable.

b) Determine which paths are long enough to exceed expected dispersal abilities (d_i). Exclude these segment pairs from consideration.

4) The remaining segment pairs and the paths between them form the remaining solution space. These paths may intersect to form larger networks. Select barriers from identified paths, constrained by an available budget.

a) Measure centrality in the network for each barrier by counting the number of paths identified in Step 3 on which a barrier exists.

b) Multiply the centrality value by the passability, p_j^0, for every barrier.

c) Rank barriers by the value determined in Step 4(b). Remove the highest ranked barriers until the budget is exhausted

i. In the event of ties, consider issues not included in the formulation (e.g. stakeholder support, regulatory barriers, or constructability) to break each tie.

Testing the Protocol

The protocol described above is an inexact procedure, and as such, losses in accuracy are expected when solutions are compared to the original optimization formulation. This protocol should be tested against the original formulation to determine the loss of accuracy of the solutions as well as to compare relative ease of use. The GIS data described in Appendix C may be used but would require significant manipulation. It is assumed information regarding barrier passability and habitat quality will be drawn from the Conservation and Prioritization System

(CAPS) as was done in the case study on the Upper West Branch (UWB) in the Westfield River case study, described above. Results of this process could be compared to results from solving the formulation described in the UWB case study, solved using both the genetic algorithm and using an exact process, to assess losses in efficiency in the solution.

Discussion and Application

The procedure described above mimics the behavior of the optimization model in that it determines which stream segments provide the most value in terms of quality-weighted habitat when connected, then determines which barriers along the routes connecting most efficiently improve connectivity when removed, within the limits of a budget. The procedure thus accounts for the underlying spatial network formed by the stream network and the interconnected barriers and focuses on the amount and quality of habitat being connected. Existing scoring and ranking procedures consider barrier removal decisions independently, which leads to a loss of efficiency in the solutions produced (O'Hanley and Tomberlin, 2005). To our knowledge, this is the first scoring and ranking procedure to incorporate the interaction of barrier removal decisions on the overall connectivity of a network.

It is not uncommon for conservation planners to adopt less sophisticated prioritization methods that sacrifice accuracy and technical complexity for transparency and stakeholder acceptance. The main advantage of this procedure is that it is relatively easily explained to and implemented by stakeholders and users who lack a background in formal optimization methods. Despite its basis in an optimization formulation, this procedure does not require specialized knowledge of mathematical or computer programming. As a result, it will likely be more readily received by conservation planners and stakeholders not versed in mathematical programming.

While the procedure is described as a scoring and ranking procedure, the protocol could also be automated as a GIS-based tool that provides visual and tabular data for further use by conservation planners.

Finally, as with the original optimization formulation, this procedure describes a tool that assesses ecological connectivity only, with no assessment as to the costs or benefits associated with existing barrier vulnerability, disruption of emergency services, or other risks associated with barriers and barrier removal. The procedure is thus presented as an initial screening tool which can provide insight into one *step* of the prioritization process.

References

Cote, D., Kehler, D.G., Bourne, C., Wiersma, Y.F., 2009. A new measure of longitudinal connectivity for stream networks. Landscape Ecology 24, 101-113.

Hajkowicz, S., Higgins, A., Miller, C., 2009. Is getting a conservation model used more important than getting it accurate? Biological Conservation 142, 699-700

Kemp, P.S., O'Hanley, J.R., 2010. Evaluation of barriers to fish migration and prioritisation of removal and mitigation projects. Fisheries Management and Ecology 17, 297-322.

O'Hanley, J.R., Tomberlin, D., 2005. Optimizing the removal of small fish passage barriers. Environmental Modeling and Assessment 10, 85-98.

Appendix E: Presentations

The following presentations were delivered in 2014 and cover aspects of the research discussed here as well as general concepts in prioritization of aquatic organism passage.

The first presentation was delivered on June 10, 2014 at the International Conference on Engineering and Ecohydrology for Fish Passage in Madison, WI, and covered preliminary results of the research discussed here.

The second presentation was delivered on August 5, 2014 at the Fish Passage Workshop presented by the United States Fish and Wildlife Service (USFWS) on August 5-6, 2014. The workshop was a two-day training course for professionals involved in the design, operation, and oversight of fish passage projects. This half-hour presentation discussed prioritization methods within a framework of ecological concerns and practical limitations.

The third presentation covered the same topic as the first presentation and was delivered to staff and students in the Civil and Environmental Engineering program at the University of Massachusetts Amherst on December 5, 2014.

The presentations contain some preliminary data that have since been updated. However, the concepts and conclusions covered in the presentations have not changed. Authoritative results have been provided in the report above.

Barrier Removal Prioritization on the Westfield River in Massachusetts

A Case Study on Optimizing Barrier Removal for Stream Resident Species

International Conference on Engineering and Ecohydrology for Fish Passage
June 2014
Rachael Weiter, David Ahlfeld, Cassandra Fagan
University of Massachusetts Amherst
Department of Civil and Environmental Engineering

Barrier Removal Prioritization

- Approaching barrier removal at a large spatial scale
- Desire the highest possible return on investment
- Optimization fits the bill!
    - Systematic
    - Can consider multiple constraints and objectives
- The expected result?
    - Greater habitat gains
    - More efficient use of funding

Before:

After:

Upper West Branch of the Westfield River

- 140 km^2
- 136 barriers
  - 126 road-stream crossings
  - 10 dams

- 🔴 Dams

- 🔵 Road-stream crossings

- ⭐ Cities

0   2.5   5   10 Kilometers

Chester, MA
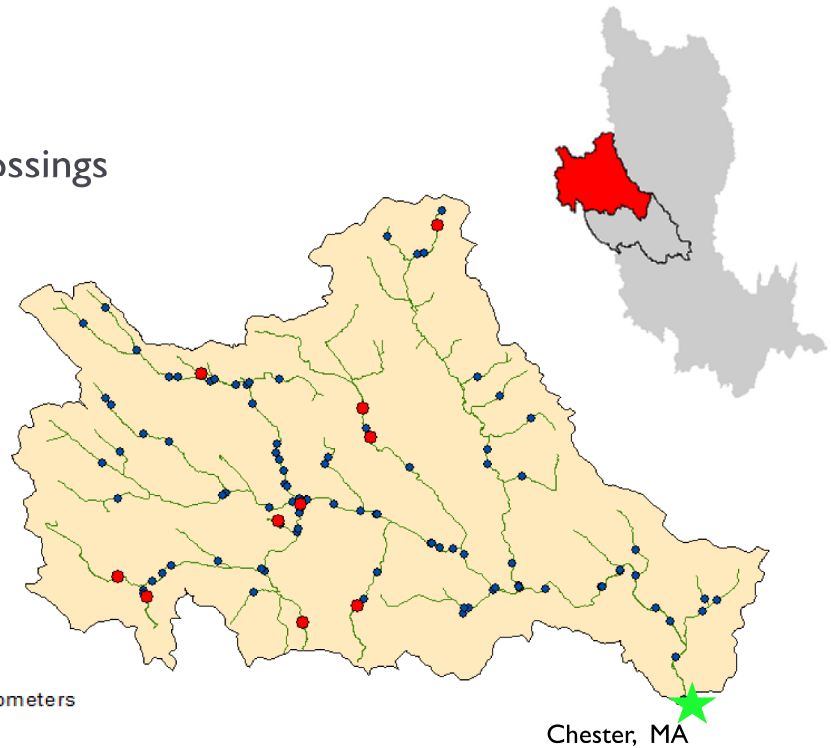
What's the Problem?

- **Goal:**
  - *Maximize* the amount of accessible, quality-weighted habitat for "resident" aquatic species.

- **Constraint:**
  - Limited budget

- **Decision:**
  - Which barriers do we remove?

Problem Formulation

▸ Calculate overall value of a network

 ▸ determining the value of the connection from every stream segment to every other stream segment in the network.

▸ Consider three factors:

 ▸ Can they get there?   (Aquatic passability)

 ▸ Is it nice?   (Habitat integrity/quality)

 ▸ Are they likely to go that far?   (Dispersal distance)

▸ In this way we account for:

 ▸ Spatial relationship of barriers

 ▸ Interactive effects of barrier removals on the network

 ▸ Biological limitations on movement

▸

Data Source: CAPS Project
(Conservation Assessment and Prioritization System)

▸ Goal: Guide conservation & restoration efforts

▸ Ecosystem-based approach to assess ecological <u>integrity</u>

 ▸ "Ability of an area to support biodiversity over the long term"

▸ GIS-based tools for use in reconnecting habitat

▸ **Index of Ecological Integrity (IEI)**

 ☐ Weighted combination of many metrics

 ☐ Metric categories:

  ☐ Development and roads

  ☐ Pollution

  ☐ Biotic alterations

  ☐ Hydrological alterations

  ☐ Resiliency metrics

McGarigal et al., 2008
www.umasscaps.org

▸

Data Source: River and Stream Continuity Project

Aquatic Passability

▸ Weighted score based on multiple metrics

▸ Assesses a "deviation from the ideal" stream condition

▸ Scaled 0-1

  ▸ 1 = full passability

  ▸ 0 = no passability

▸ Barriers with higher passability values are considered more similar to the original stream

Stream Crossings Data
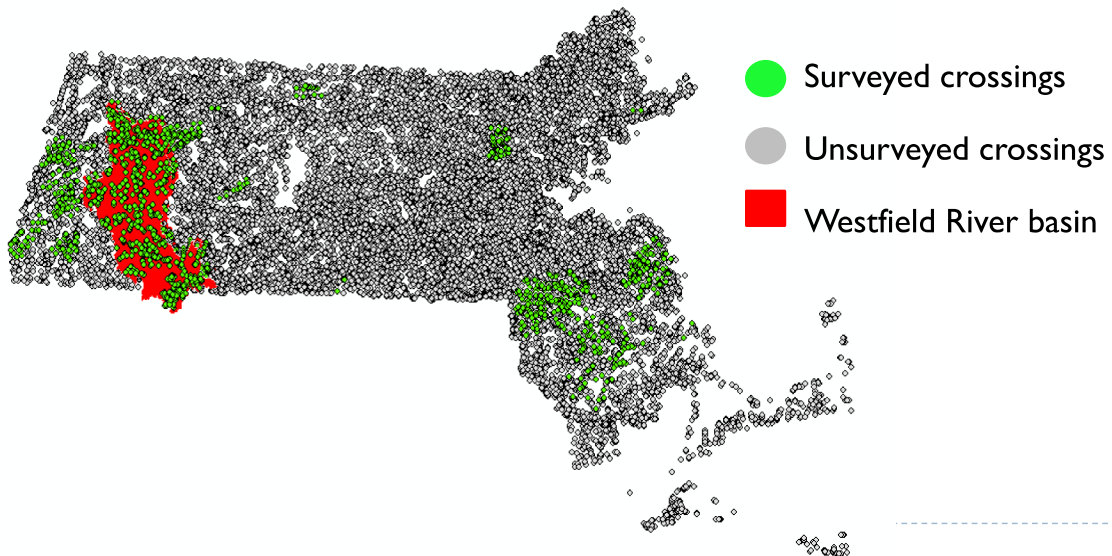
▸ >23,000 stream crossings in MA

  ▸ 1000 crossings surveyed

  ▸ Most are modeled

www.streamcontinuity.org

● Surveyed crossings

● Unsurveyed crossings

■ Westfield River basin

Stream Crossings Data

- **>23, 000 stream crossings in MA**
  - 1000 crossings surveyed
  - Most are modeled

NEW ENGLAND ROAD STREAM CROSSING
Inventory Database

Search Crossings | Login | LogOut

www.streamcontinuity.org

- 🟢 Surveyed crossings
- ⚪ Unsurveyed crossings
- 🟥 Westfield River basin

Barrier Passability in the Upper West Branch

High
passability

> 0.75

0.5-0.75

0.25-0.5

< 0.25

Low
passability

0   2.5   5   10 Kilometers

Habitat Quality in the Upper West Branch

IEI
- 0.00-0.20
- 0.21-0.40
- 0.41-0.60
- 0.61-0.80
- 0.81-1.00

Improving habitat integrity

0   2.5   5   10 Kilometers

Six Major Formulation Inputs

Upstream Segment
- Length
- IEI

Barrier
- Passability
- Removal Cost

▸ **Consider**
  ▸ Length
  ▸ Can they get there?
  ▸ Is it nice?
  ▸ Are they likely to go that far?

▸ **Project logistics**
  ▸ Individual project cost
  ▸ Overall budget

Six Major Formulation Inputs

Expected dispersal
distance

$$

Project Budget

- **Consider**
  - Length
  - Can they get there?
  - Is it nice?
  - Are they likely to go that far?

- **Project logistics**
  - Individual project cost
  - Overall budget

▸

Project Costs

- **Barrier mitigation costs**
  - Randomly generated for preliminary investigations
  - Range: $50,000 - $150,000
  - Average ≈ $100,000
  - Dams are priced above the project budget

- **Budget**
  - Varies from $1 million to $9 million

▸

Solution

- Genetic Algorithm
- Evaluate many solutions, keep the best solution found
- Multiple scenarios can be solved in a few hours on a standard laptop

Results

- Number of barriers removed increases linearly
- Objective Function Value not linear with increasing budget, but close
- No clear trend in IEI, upstream length, or passability

What's the price?

The formulation is selecting the least expensive barriers for removal.

Why?

Results

▸ **Barrier sets are not perfectly nested**

  ▸ Mainstem barriers are consistently removed

  ▸ Barriers at the edges of the network are selected with less consistency

Budget = $3 million

Budget = $5 million

● Barriers selected for removal

● Barriers left in place

Results

- Barrier sets are not perfectly nested
  - Mainstem barriers are consistently removed
  - Barriers at the edges of the network are selected with less consistency

Budget = $7 million

Budget = $9 million

- ● Barriers selected for removal
- ● Barriers left in place

Results

- Barrier sets are not perfectly nested
  - Mainstem barriers are consistently removed
  - Barriers at the edges of the network are selected with less consistency

Budget = $7 million

Budget = $9 million

- ● Barriers selected for removal
- ● Barriers left in place

Why choose cheaper fixes first?

- Three barriers to choose from:

Barrier	Cost	Habitat opened
1	$60,000	5 miles
2	$40,000	4 miles
3	$30,000	3 miles

- Scenario 1: Budget = $60,000.
- Scenario 2: Budget = $70,000
- You would choose the two cheaper barriers, **as long as** they result in greater open habitat than the single, more expensive barrier.
- The solutions are not nested.

The Takeaway

To make the best possible use of funding…

- Accurate cost estimates matter!
  - The formulation seems to favor less expensive projects
- Know your long-term project budget
  - Lack of nestedness implies need for proper prior planning

Next Steps

▸ Perform analysis with accurate barrier removal costs

  ▸ Estimate using survey data from the River and Stream Continuity Project

  ▸ Work around data gaps in the road stream crossing database

▸ Recommend additional crossing survey parameters

▸ Sensitivity analysis WRT different target species, with expected dispersal distance as a proxy

▸

Acknowledgements

▸

Questions?

Prioritization of Fish Passage Projects

Fish Passage Workshop, August 5-6, 2014
Rachael Weiter, Masters Student/Graduate Research Assistant,
University of Massachusetts Amherst

Topics

- Reasons for prioritization
- Prioritization at different scales
- Factors considered in prioritizing projects
- Prioritization methods
- Lessons learned

What is Prioritization?

- Selecting projects for implementation that best meet your goals and criteria
- Strategic approach to a complicated problem

● Dams

● Road-stream crossings

0   2.5   5   10 Kilometers

Why Prioritize?

- Limited funds are available for restoration
    - Justify projects when applying for funds
    - Use funds effectively
- Not all barriers are created equal
    - Ensure effective habitat restoration by getting the worst barriers first
- Inconsistent decisions may harm restoration efforts
    - Provide clear and consistent recommendations

Prioritization Scales

Nation/Region   State   Watershed

Prioritization Scales

Regional Prioritization

- Who cares?
  - Federal agencies
  - National conservation organizations

- Prioritization of barriers across separate watersheds
- Requirement for strategic decisions is pushing these groups toward a watershed-based approach

Prioritization at the State Level

- Who cares?
  - State agencies
    - DER/DEC/DNR
    - DOT

- Consider state-specific priorities

Prioritization within a Watershed

- Who cares?
  - Landowning public agencies
  - Watershed protection associations & partnerships

- Consider an entire stream network with multiple barriers
  - Spatial relationships of barriers matter!
- Political boundaries present challenges

Anadromous vs. Resident vs. Invasive Species

Anadromous Species   Resident Species   Invasive species

Prioritization Criteria

- This depends on your goals

- Common categories
  - Environmental
  - Economic
  - Sociopolitical

Common Factors Considered

- Current available passage
- Project cost
- Available budget
- Location with regard to other projects
- Estimated benefits
  - Length and quality of stream made available
  - Species affected
  - Recreational opportunities and costs

Additional Items to Consider

- Biological limitations
  - Can the organism reach or use the habitat?
- Transportation impacts
  - E.g. transportation delays, maintenance needs
- Risk
  - Changing stormflows due to climate change
- Other socioeconomic factors
  - Stakeholder support & concerns

Prioritization Methods

- Scoring and Ranking
- GIS-Based Analysis
- Optimization Methods
- Expert Opinion

Scoring and Ranking

- Method
  - Barriers are scored based on attributes of concern
  - Benefit-cost ratios are often used
    - E.g. Habitat gain divided by project costs
  - Barriers are ranked by descending score

Scoring and Ranking

- Benefits
  - Simple and straightforward to implement
  - Decisions are easy to explain
- Problems
  - Removal decisions are considered independently of each other
    - spatial relationships of barriers are not considered
- Not well-suited to a watershed-based approach

GIS-Based Analysis

- GIS data may be used raw or in the form of calculated metrics
- Data and metrics can be used to filter projects
- Efforts often result in either
  - A ranked list of projects
  - Project bins

Results of culvert/bridge replacement scenario analyses for a portion of Massachusetts. The darker the circles the greater the improvement in aquatic connectedness. http://www.umasscaps.org/about/applications.html

---

GIS-Based Analysis

- Benefits
  - Visual representation of results
  - Scaling of results is relatively easy
  - Easy handling of many data layers

- Weaknesses
  - Sometimes limited to systems with small numbers of barriers
  - May have heavy knowledge and computational requirements

Optimization Methods

- Systems analysis techniques
- Problem statement is set up with:
  - Objective function   *What do I want?*
  - Decision variables   *What can I change?*
  - Constraints   *What is required?*
- Solution is an unranked portfolio of barriers to be removed

---

Optimization Methods

- Benefits
  - Ability to account for spatial relationships throughout a watershed
  - Clearly stated criteria
  - Ability to balance multiple and often competing goals
- Weaknesses
  - Method requires a specialised level of expertise
  - Explanations can be difficult

$$\text{Maximize} \quad \sum_{s=1}^{T} L_s H_s V_s$$

Such that:

$$V_s = N_s \sum_{t \neq s}^{T} L_t H_t D_{s,t} \varphi_{s,t}$$

$$D_{s,t} = \frac{1}{1 + \left(\frac{d_{s,t}}{d_i}\right)^2}$$

$$\varphi_{s,t} = \prod_{j \in B_{s,t}} p_j$$

Expert Opinion

- Benefits
  - Ability to consider factors we rarely model
  - Take advantage of personal knowledge
- Weaknesses
  - Subjectivity and bias
  - Harder to justify to the powers that be (funders)

- All model results are subject to final review

Lessons Learned

- Role of opportunism
  - Modeled answers don't always hold up to reality
- Problem approach
  - Know your assumptions
  - Prioritizing only one type of barrier may limit restoration effectiveness
- Solutions are not always "nested"
  - The barriers selected for removal at a lower budget level may not be recommended for removal at higher budget levels

Lessons Learned

- Prioritization requires lots of data!
  - Barrier characteristics
  - Stream and habitat characteristics
  - Project cost and budget data

Prioritization Data

- Common Data Sources
  - Barrier inventories
  - GIS data
  - Records of previous projects
- Large data gaps exist
  - Many efforts are underway to change that
- Project costs and budget
  - Research shows that having accurate cost data is crucial

Questions?

Barrier Removal Prioritization on the Westfield River in Massachusetts

Optimizing Barrier Removal for Passage of Stream Resident Species

EWRE Seminar

December 5, 2014

Rachael Weiter, David Ahlfeld

University of Massachusetts Amherst

Department of Civil and Environmental Engineering

What are Barriers to Fish Passage?

- Dams
  - >80,000 in the National Inventory of Dams (NID)
  - 3,000 in Massachusetts
- Road-Stream Crossings
  - Bridges and culverts
  - ~2 million culverts in the U.S. (USFWS)
    - ~23,000 in Massachusetts
- These structures prevent organisms' physical movement through a stream network

Wapping Road Dam, Kingston, MA

Before Removal

After Removal

http://www.mass.gov/eea/agencies/dfg/der/aquatic-habitat-restoration/river-restoration/dam-removal.html

Why is this a Problem for Resident Fish?

▸ Resident aquatic organisms need access to habitat for

  ▸ Foraging
  ▸ Reproduction
  ▸ Refuge

▸ Lack of access to habitat threatens survival

Anadromous Species   *Resident Species*

Barrier Removal Prioritization

▸ Prioritization:

  ▸ Selecting projects for implementation that best meet your goals and criteria

▸ A watershed may contain many barriers (thousands!)

  ▸ Which do we choose?

▸ Goal: the highest possible return on restoration funding

Before Mitigation:

Moose Run Crossing
Nason Creek
Rochester, VT

After:

Optimization Methods for Prioritization

▸ Formal optimization methods:
  ▸ Require explicit goals and objectives to be set
  ▸ Systematically consider multiple constraints
  ▸ Able to solve large, complex problems
▸ The expected result?
  ▸ Greater habitat restoration gains
  ▸ More efficient use of funding

▸

What's the Problem?

▸ **Goal:**
  ▸ By removing barriers, *maximize* the amount of accessible, quality-weighted habitat for "resident" aquatic species.

▸ **Constraint:**
  ▸ Limited budget

▸ **Decision:**
  ▸ Which barriers do we remove?
    ▸ Binary decision variable: Yes/No decision for each barrier

▸

Problem Formulation

▸ Approach the problem at the watershed scale

▸ Determine the value of the connection from every stream segment s to every other stream segment t in the network.

▸ Consider three factors in determining the value of the connection between segments s and t:
  ▸ Can they get there?　　　　　　　　(Aquatic passability, $\varphi_{s,t}$)
  ▸ Is it nice?　　　　　　　　　　　　(Habitat integrity/quality, H_t)
  ▸ Are they likely to go that far?　　　(Dispersal distance, $D_{s,t}$)

▸ In this way we account for:
  ▸ Spatial relationship of barriers
  ▸ Interactive effects of barrier removals on the network
  ▸ Biological limitations on movement

▸

Formulation

Maximize $\quad \sum_{s=1}^{T} L_s H_s V_s$　　　　　Maximize total passage value- and quality-weighted habitat accessible from every segment

Such that:

$V_s = N_s \sum_{t \neq s}^{T} L_t H_t D_{s,t} \varphi_{s,t}$　　　　Total value of passage from segment s

$D_{s,t} = \dfrac{1}{1 + \left(\frac{d_{s,t}}{d_i}\right)^2}$　　　　Inverse distance weighting factor

$\varphi_{s,t} = \prod_{j \in B_{s,t}} p_j$　　　　Cumulative bidirectional passability from s to t

$\sum_{j=1}^{T} c_j x_j \leq b$　　　　Budget constraint

$x_j \in \{0,1\} \quad \forall j \in B_{s,t}$　　　　Each barrier j between s and t is or is not removed

$p_j = \begin{cases} p_{j,0} & if \ x_j = 0 \\ 1 & if \ x_j = 1 \end{cases}$　　　　Barrier removal results in full passability p_j.

▸

Formulation Inputs

Origin Segment, s
- L_s
- H_s

Destination Segment, t
- Length, L_t
- Habitat Quality, H_t

Barrier
- Passability, p_j
- Removal Cost, c_j

- Consider
  - Length, L_t
  - Is it nice? (H_t)
  - Can they get there? ($\varphi_{s,t}$)
  - Are they likely to go that far? ($D_{s,t}$)

Expected dispersal distance

Upper West Branch of the Westfield River

- 140 km^2
- 136 barriers
  - 126 road-stream crossings
  - 10 dams

- Dams
- Road-stream crossings
- Cities

N

0   2.5   5   10 Kilometers

Chester, MA

Data Source: CAPS Project
(Conservation Assessment and Prioritization System)

- ▸ Goal: Guide conservation & restoration efforts
- ▸ Ecosystem-based approach to assess ecological <u>integrity</u>
  - ▸ "Ability of an area to support biodiversity over the long term"
- ▸ GIS-based tools for use in reconnecting habitat
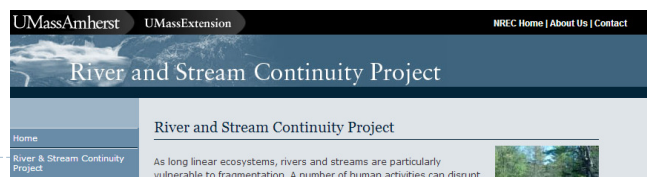
- ▸ **Index of Ecological Integrity (IEI)**
  - ▢ Weighted combination of many metrics
  - ▢ Metric categories:
    - ▢ Development and roads
    - ▢ Pollution
    - ▢ Biotic alterations
    - ▢ Hydrological alterations
    - ▢ Resiliency metrics

The CAPS Analysis

GIS data → Land cover map → Integrity metrics → Index of Ecological Integrity

McGarigal et al., 2008
www.umasscaps.org

▸

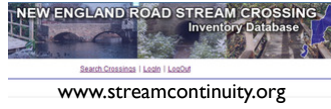## Data Source: River and Stream Continuity Project

Aquatic Passability

- ▸ Weighted score based on multiple metrics
- ▸ Assesses a "deviation from the ideal" stream condition
- ▸ Scaled 0-1
  - ▸ 1 = full passability
  - ▸ 0 = no passability
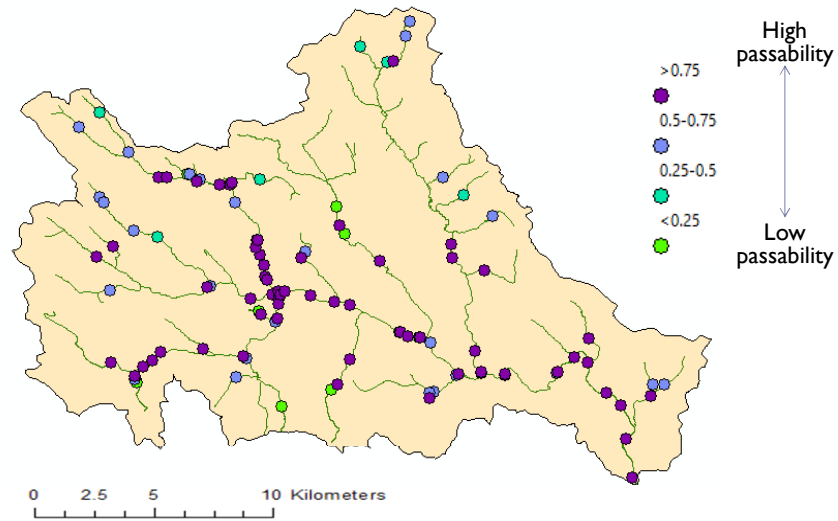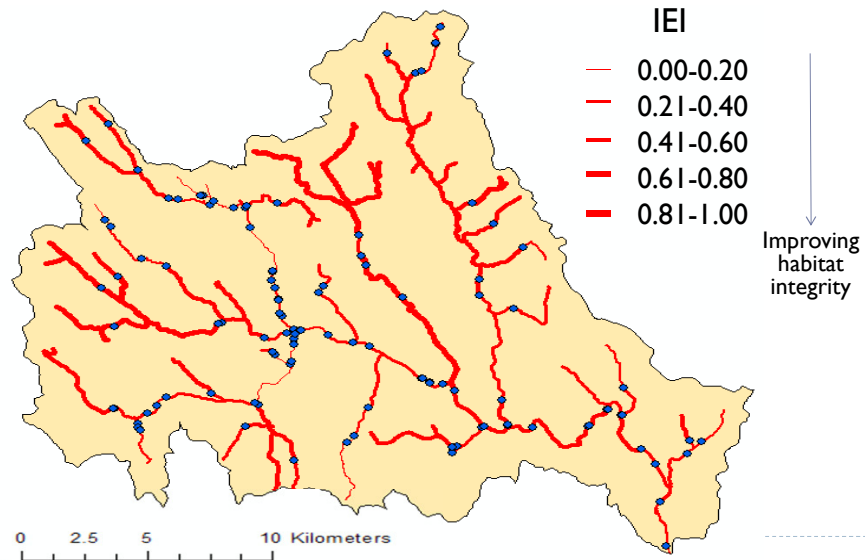- ▸ Barriers considered more similar to the original stream are given higher passability values

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River and Stream Continuity Project

Home
River & Stream Continuity Project

River and Stream Continuity Project

As long linear ecosystems, rivers and streams are particularly vulnerable to fragmentation. A number of human activities can disrupt

▸

Stream Crossings Data

- **>23,000 stream crossings in MA**
  - 1000 crossings surveyed
  - Most are modeled

NEW ENGLAND ROAD STREAM CROSSING
Inventory Database

Search Crossings | Login | Logout

www.streamcontinuity.org

- 🟢 Surveyed crossings
- ⚪ Unsurveyed crossings
- 🟥 Westfield River basin

Barrier Passability in the Upper West Branch

High passability

- >0.75
- 0.5-0.75
- 0.25-0.5
- <0.25

Low passability

0   2.5   5   10 Kilometers

Habitat Quality in the Upper West Branch

IEI
— 0.00-0.20
— 0.21-0.40
— 0.41-0.60
— 0.61-0.80
— 0.81-1.00

Improving habitat integrity

0   2.5   5   10 Kilometers

Project Inputs

▸ Segment length
  ▸ Determined in GIS
▸ Dispersal Distance, d_i
  ▸ Set to 3km
▸ Barrier mitigation costs, c_j
  ▸ Randomly generated for preliminary investigations
  ▸ Range: $50,000 - $150,000
  ▸ Average ≈ $100,000
  ▸ Dams are priced above the project budget
▸ Budget, b
  ▸ Varies from $0.1 million to $1 million at $0.1 million intervals
  ▸ Varies from $1 million to $9 million at $1 million intervals

▸

Implementation

▸ Solve using genetic algorithm

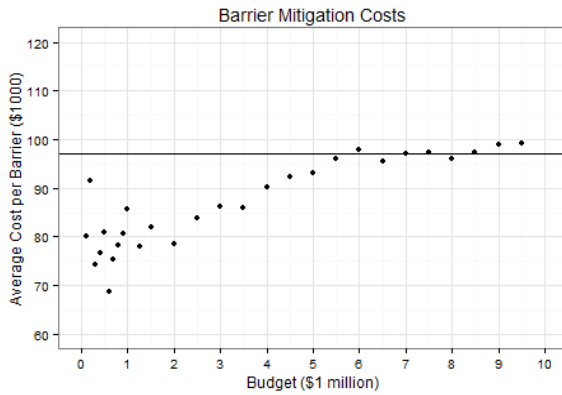▸ Evaluate many solutions, keep the best solution found

---

Results

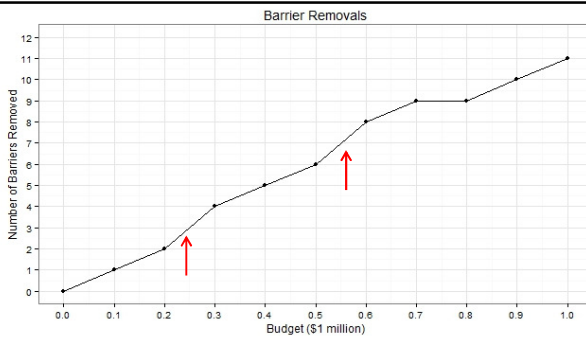▸ The number of barriers removed increases nearly linearly with the budget

▸ The objective function value displays a decreasing marginal gain as budget increases
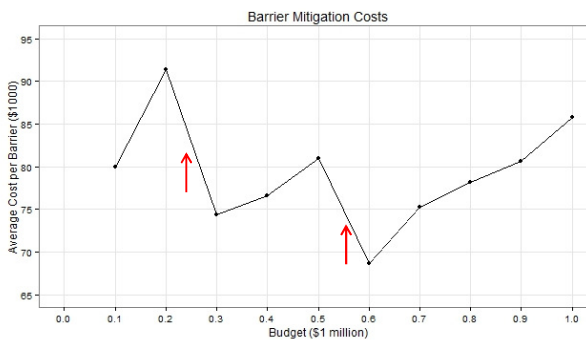
What's the price?

Barrier Mitigation Costs

Average mitigation cost for all road-stream crossings ($97,116)

The formulation is selecting low-cost mitigation projects first.

Barrier Removals

Barrier Mitigation Costs

Threshold Effect:

Drops in average barrier mitigation cost are accompanied by an increase in the rate of barrier removal…

Threshold Effect:

Drops in average barrier mitigation cost are accompanied by an increase in the rate of barrier removal **and** in the rate of gain in the objective function
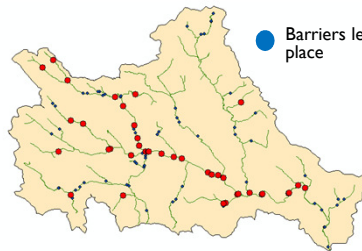

Results

‣ Barrier sets are not perfectly nested
  ‣ Mainstem barriers are consistently removed
  ‣ Barriers at the edges of the network are selected with less consistency
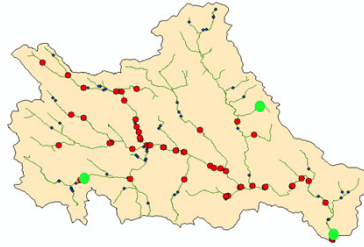
Budget = $3 million

Budget = $5 million

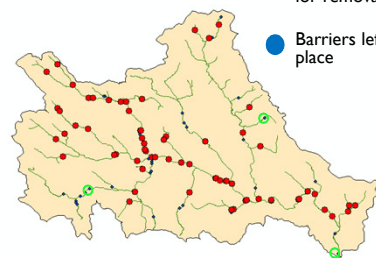● Barriers selected for removal

● Barriers left in place

Results

- Barrier sets are not perfectly nested
  - Mainstem barriers are consistently removed
  - Barriers at the edges of the network are selected with less consistency
- The mainstem forms a "backbone" which connects large sections of the network

Budget = $7 million

Budget = $9 million

- Barriers selected for removal
- Barriers left in place

Why choose cheaper fixes first?

- Three barriers to choose from:

Barrier	Cost	Habitat opened
1	$60,000	5 miles
2	$40,000	4 miles
3	$30,000	3 miles

- Scenario 1: Budget = $60,000.
- Scenario 2: Budget = $70,000
- You would choose the two cheaper barriers, **as long as** they result in greater open habitat than the single, more expensive barrier.
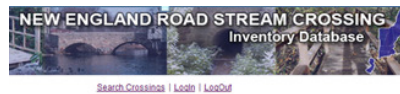- The solutions are not nested.

The Takeaway

To make the best possible use of funding…

▸ Accurate cost estimates matter!
  ▸ The formulation seems to favor less expensive projects
▸ Lack of nestedness implies need for proper prior planning
  ▸ Know your long-term project budget
  ▸ Run model for multiple budget scenarios

▸

Future Work

▸ Continued spatial analysis to determine influence of watershed characteristics

▸ Perform analysis with accurate barrier removal costs
  ▸ Develop cost estimation method using survey parameters

▸ Develop method to deal with the lack of nestedness

▸

Acknowledgements

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- Mass DER: Beth Lambert, Carrie Banks
- Work supported by
  - US Fish and Wildlife Service Coop Agreement #50150-A-J
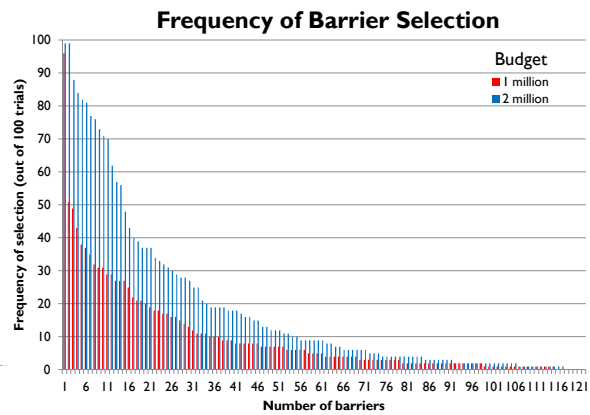 - The Fish Passage Conference Student Fellowship

Questions?

Is Price the Only Important Factor?

- Barriers were assigned new sets of random costs, 100 times.
- The model was run using each new set of costs assuming two budgets
- Decay indicates that factor(s) other than barrier cost affect barrier removal

Frequency of Barrier Selection

Genetic Algorithm

Index of Ecological Integrity: Metrics

- Development and Roads
  - Habitat loss
  - Wetland buffer insults
  - Road traffic intensity
  - Microclimate alterations
- Pollution
  - Road salt intensity
  - Road sediment intensity
  - Fertilizer intensity
  - Point-source pollution

- Biotic Alterations
  - Domestic predators
  - Edge predators
  - Non-native invasive plants
  - Non-native invasive earthworms
- Hydrological Alterations
  - Imperviousness
  - Percent impounded
  - Upstream road crossings
  - Dam intensity
- Resiliency Metrics
  - Connectedness
  - Similarity

Aquatic Passability: Metrics

Parameters
- Outlet drop
- Physical barriers
- Water velocity
- Water depth
- Inlet drop
- Crossing span
- Crossing substrate
- Crossing embedment
- Openness
- Scour pool
- Tailwater armoring
- Height

Method
- A score is assigned for each parameter
- The score is multiplied by a parameter-specific weight
- The weighted scores are added to arrive at an aquatic passage score

Appendix F: Barrier Removal Cost Estimation on the Westfield River in Western Massachusetts

The following is a report written by Cassandra Fagan for an Independent Study in 2014, supervised by Dr. David Ahlfeld and myself. The report details a simple deterministic model for the estimation of the cost of culvert mitigation (removal and replacement) for aquatic organism passage. It is included to document preliminary work in project cost estimation, in the event that the project is pursued as described in Appendix C. Personal contributions included input on ideas and technical operations.

The Excel spreadsheet tool described in Section 5.0 is available from the authors upon request.

Barrier Removal Cost Estimation on the Westfield River in Western Massachusetts

Presented by:

Cassandra Fagan

Table of Contents

1.0 Motivation

Massachusetts has a multitude of lakes, rivers, and streams throughout the state suitable for aquatic life, however many of these systems are disconnected due to poorly performing culverts at road crossings. These poorly performing culverts cause shallow water, increased stream velocities, and other difficulties for aquatic life in the stream.

The goal of culvert replacements is to improve fish passage, river/stream continuity and wildlife passage in streams. This goal is achieved by replacing poorly performing culverts with adequately sized culverts based on stream bankfull width. The objective of this study was to create an efficient method of estimating the cost of removing and replacing barriers on the West Branch of the Westfield River to optimize funds for culvert replacements.

2.0 Project Information

The Westfield River, located in western Massachusetts is a major tributary river of the Connecticut River. The Westfield River flows for a total of 78.1 miles and has a watershed encompassing 517 square miles (Westfield River Committee). The Westfield River was designated as a state and locally initiated National Wild and Scenic River, and the West Branch remains the longest uncontrolled river in Massachusetts (Curtis and Miller, 13-14). This study focuses on 13 barriers on the West Branch of the Westfield River consisting of Shaker Mill Brook, Depot Brook, and Watson Brook. Many of the crossings on these streams were surveyed prior this study. The information collected for the crossings are available on the New England Road Stream Crossing Inventory Database.

3.0 Estimating Width of Replacement Culvert

General standards for replacement culvert structures require the culvert width to be at minimum 1.2 times the bankfull width of the stream (Bent and Waite, 2). Bankfull width is the width of the stream at bankfull stage. It is difficult to obtain an accurate measurement of bankfull width of a stream. For that reason the bankfull width of the stream at each road crossing was estimated using a bankfull width regression equation developed by the USGS (Bent and Waite, 22).

$$B = 15.1988\,[D^{0.4190}]$$

Where B = Bankfull Width (feet)

D = Drainage Area (square miles)

The USGS developed the bankfull width equation for streams in and near Massachusetts (Bent and Waite, 22). To find the bankfull width for the crossings in this study, a drainage area analysis was performed in ArcGIS using a Digital Elevation Model (DEM) of the Westfield River Watershed. A detailed outline of the analysis is found in the Appendix.

4.0 Estimating Replacement Cost of Culvert

Cost estimation is a very important aspect of culvert removal. Due to budget limitations, only a fraction of the culverts on the West Branch of the Westfield River may be replaced. Cost estimation along with information on culvert performance allows for optimization of spending. This study developed an efficient method of estimating culvert replacement cost using channel geometry and lump sum costs for certain aspects of the replacement. This approach is similar to that to that implemented by Diebel et al. for road crossing replacements in Wisconsin. The cost estimation for culvert replacement was separated into two categories: design and engineering, and construction costs.

4.1 Design and Engineering

Design and engineering costs include the following tasks: surveying, geotechnical evaluations, footing design & detailing, design preparation & permitting plans, hydraulic, geotechnical & structural reports, MassDOT Chapter 85 Review, and technical specifications/bidding documents. These items were estimated as lump sums, and based on culvert replacements estimates performed by the Division of Ecological Restoration (DER) using the Massachusetts Department of Transportation (MassDOT) project estimator tool.

4.2 Construction Costs

4.21 Traffic Control

Culvert replacement construction will be taking place on crossings, the crossings in this study being roadways. This construction creates a potentially hazardous situation, and will require the use of temporary traffic controls to protect the work crew as well as those using public roads. Traffic control devices are as traffic control during culvert construction to warn drivers of construction and unusual roadway conditions and will and inform them how to move safely through or around the work area. (Mass Highway 3) Traffic devices used for cost estimates include signs, special lighting units, channelizing devices and warning lights. When used together these devices must provide motorists with sufficient warning of the work area, advise them of the proper travel paths to follow, and provide protection for the motorists and work crew.

There are two main variables affecting the traffic control planning and selection of traffic control devises for culvert replacement construction: the type of crossing over the culvert, and the speed of the traffic travelling on the crossing. For this study the information needed for traffic control estimation is the characteristics of the roadway over the crossing. The road characteristics include the number of lanes on the roadway. The roadway information for the culverts in this study was found using the Stream Continuity Database and Google Earth. The cost estimations for traffic control were based on earlier culvert assessments on the Westfield River that the DER used to estimate cost of culvert replacements on the Westfield River.

4.22 Site Preparation

Site preparation is a critical part of the culvert replacement process consisting of mobilization and control of water. Mobilization includes the cost for transportation of contractor's personnel, equipment, and operating supplies to the site. The cost estimations for mobilization were based on earlier culvert assessments on the Westfield River that the DER uses to the cost of culvert replacements.

Before construction provisions must be in place to control water and use soil erosion and sedimentation controls to prevent from entering the stream during and after construction. For

streams sandbags, silt, and earthen dikes are used to inhibit flow when possible. Often a pump is used to convey water around the excavation/work site, and discharge onto an outlet downstream of construction. The cost estimations for mobilization were based on earlier culvert assessments on the Westfield River that the DER uses to the cost of culvert replacements.

4.23 Channel Excavation and Demolition

In this study demolition consisted of channel excavation. Prior to installing the replacement culvert the existing road surface, bed material, and existing culvert must be removed. Channel excavation includes the removal and disposal of roadway surfaces and bed material. The cost estimation for channel excavation for this study was found using channel geometry to calculate the volume of excavation and multiplying the volume by a channel excavation unit price from MassDOT project estimator. An angle of repose of 34 degrees was assumed for these calculations. The New England Road Stream Crossing Inventory Database provided the length of culverts through the crossings, diameter of existing circular culverts, and road information for the crossings in this study. The earth cover as seen in Figure 1, is measured from the top of the existing culvert structure to the bottom of the road surface. For these volume estimations the fill depth above the replacement culvert was back calculated using the replacement culvert height and a new earth cover, or fill depth seen in Figure 2 of 2 feet. It was assumed that 2 feet on each side of the culvert would be necessary to properly install the replacement arch culvert. For paved road surfaces, it was assumed that the existing conditions would consist of a 0.5 ft. thick subbase of gravel, and a 0.5 ft. thick layer of bituminous for removal. For a paved road the channelexcavation volume may be calculated using Equation 2.
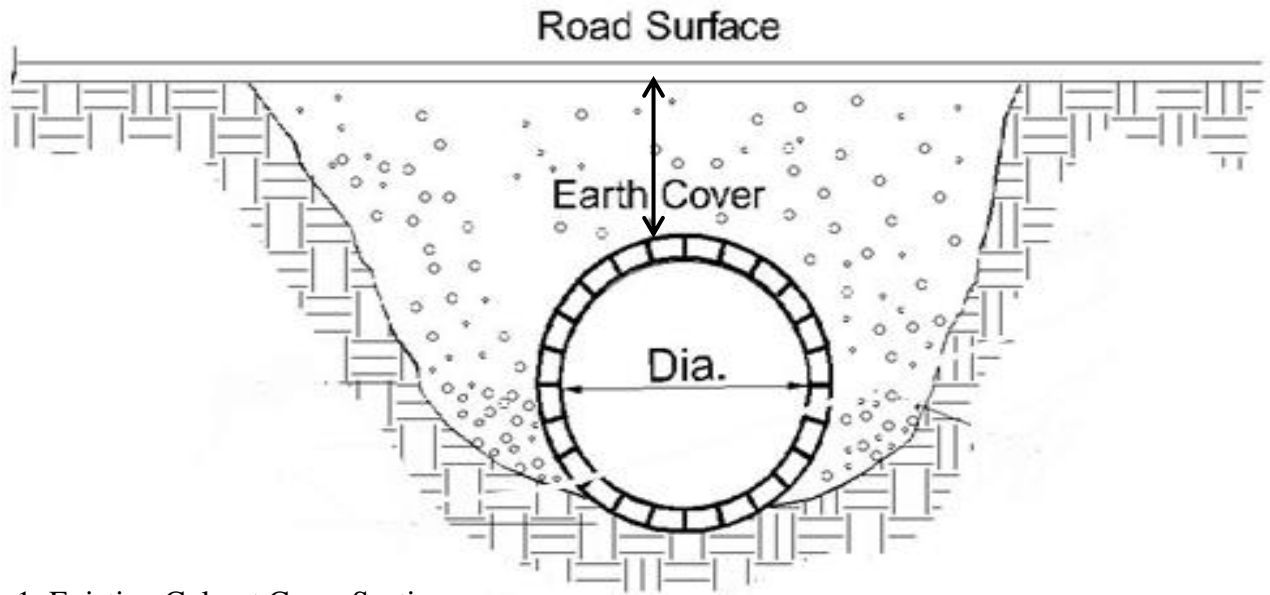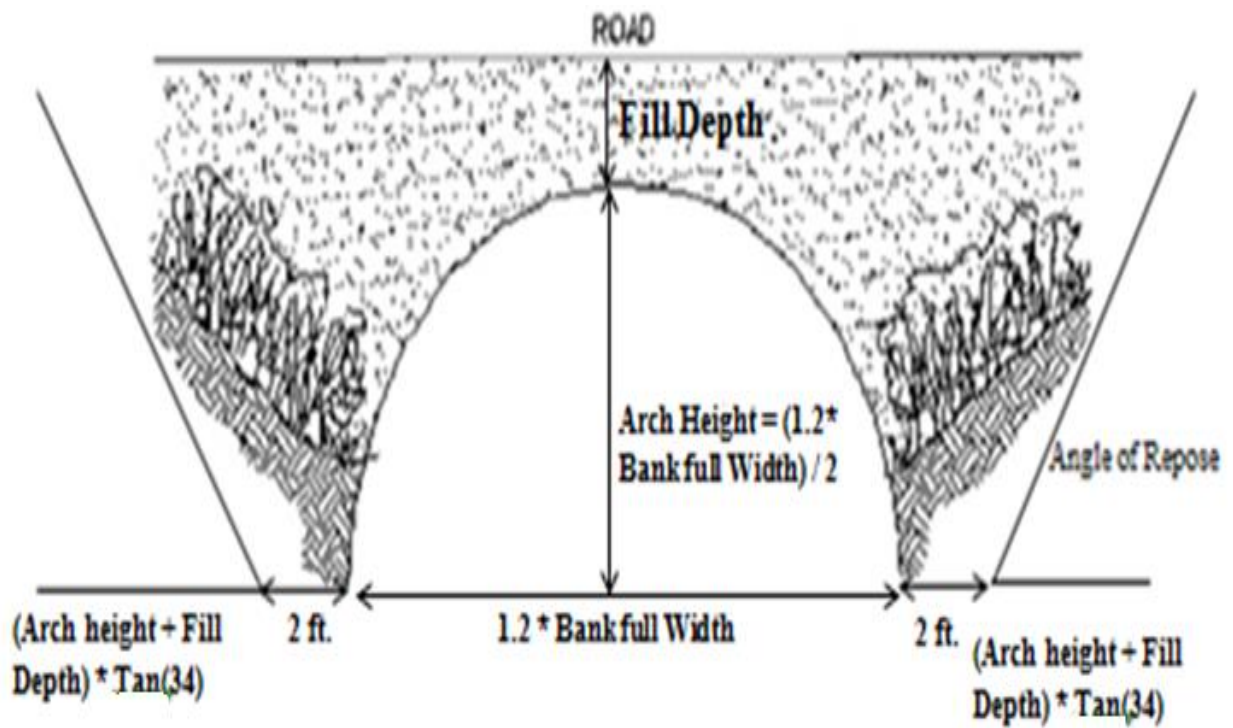
Figure 1: Existing Culvert Cross-Section

Figure 2: Replacement Arch Cross Section

$$EV = [(CD + E + R) * (A + 4 + (A + F + R) * Tan(34))] * L - [(CD)^2 * \left(\frac{\pi}{4}\right) * L]$$

Where EV = Channel Excavation Volume (in cubic feet)

CD = Existing Culvert Diameter (in feet)

E = Existing Earth Cover (in feet)

R= Road Thickness (in feet)

A = Width of Replacement Culvert (in feet)

L = Existing Culvert Length (in feet)

4.24 Culvert Installation

Culvert installation includes placement of the aluminum arch culvert, backfilling borrow, fine grading and compaction, and road surface repair. The cost estimate for the aluminum culvert was estimated as a lump sum range using earlier culvert assessments on the Westfield River that the DER. For volume calculations in this study it was assumed that the arch culvert will be a semi-circle with a width equal to 1.2 times the bankfull width of the stream at the crossing, and the height of the replacement culvert will be ½ times the width of the replacement culvert.

The cost of borrow needed to backfill the arch culvert was estimated using the culvert geometry and a cost per unit volume for borrow from MassDOT project estimator. It was assumed that half of the volume of borrow excavated could be reused for borrow backfill. The volume of borrow required for backfilling was calculated using Equation 3.

(3)

$$BV = \left[(A + F) * (A + 4 + (H + F) * Tan(34^0)) - (A^2) * \left(\frac{\pi}{8}\right) \right] * \frac{L}{2}$$

Where BV = Borrow Volume

F= Fill Depth (in feet)

H =Height of Replacement Arch (in feet)

Fine grading and compaction of the borrow material will be the next phase of the installation process. The cost for grading and compaction for this study was estimated using arch geometry and a cost per unit area for grading and compaction from MassDOT project estimator. The estimate area requiring fine grading and compaction was calculated using equation 4.

(4)

$$FCG = RW * [2 * (2 + A + (H + F + R) * Tan(34^0)]$$

Where FCG = Fine Grading & Compaction Area (in square feet)
RW = Road Width (in feet)

The gravel base is placed after fine grading and compaction of borrow material. The gravel base is a pavement subbase or if the road is unpaved it is used as the top course. The cost of the gravel base was estimated using culvert geometry to calculate the required volume and a cost per unit volume for gravel base from MassDOT project estimator. The gravel base for paved road surfaced was assumed to be 0.5 ft. thick. The estimated gravel base volume may be calculated using equation 5.

(5)

$$G = GT * [RW * (A + 4 + (A + F + R) * Tan(34^0))]$$

Where G = Gravel Volume (in cubic feet)
GT = Gravel Thickness (in feet)

For stream crossing under paved roads, bituminous concrete pavement repair is required. Similar to gravel base, a 0.5 ft. thickness was assumed for the bituminous layer. The estimated volume of bituminous was calculated using equation 5, and to find the required area the bituminous volume was divided by the thickness of the layer.

4.25 Finished Surfaces

The finished surfaces portion of culvert replacements for this study consisted of the removal and replacement of guardrail and the loam, seed and cleanup. The cost for guardrail removal and replacement was only included in the estimates if the stream crossing inventory or another resource indicated there was a guardrail over the crossing. The cost of the guardrail removal and replacement was estimated using arch geometry to find length of affected roadway and a per length unit cost from MassDOT project estimator. The estimated length of guardrail to be removed and replaced was calculated using equation 6.

$$(6)$$

$$G = 2 * [(2 * (A + F + R) * Tan(34^0)) + 4 + A]$$

G = Guardrail Length (in feet)

The loam, seed and cleanup for the disturbed area was estimated using a lump sum value estimated by the DER during culvert estimates on the Westfield River.

5.0 Conclusion

In this study of method of estimating culvert costs was found using channel geometry, crossing information, and previous crossing estimates. An excel file was created to perform these culvert cost estimates using very few input parameters: bankfull width, existing culvert length and diameter, type of road, existing road width, and existence of a guardrail. When these parameters are entered into the spreadsheet, the estimated amounts of each task are calculated using the formulas in this paper.

6.0 Appendix

6.1 Drainage area analysis
The data required to perform the drainage area analysis in ArcGIS for the West Branch of the Westfield River included a DEM of the watershed, barriers locations along the streams, and the streamlines.

DEM Processing

1. Fill DEM

2. Flow Direction

3. Flow Accumulation

Barriers

1. Select Using Polygon

2. Right click on layer in Table of Contents and create new layer from selection

3. Snap pour points using 25m distance (or other appropriate distance)

Watershed:

1. Open watershed tool. Input **Fac** and snapped pour points. Select Value for raster pour points or ObjectID for vector pour points

2. Inspect: Do your watershed boundaries make sense?

3. Convert Watershed raster to polygon (Data Management >> From Raster >> To polygon). The resulting polygons will have an area attribute in map units.

   a. Map units should be in meters or square meters for our work.

   b. If area is not an attribute, create a new field and calculate polygon geometry.

4. Extract all data that makes sense, then adjust distances for snapped pour points and run Watershed again.

7.0 Citations

Bent, G.C., and Waite, A.M., 2013, Equations for estimating bankfull channel geometry and discharge for streams in Massachusetts: U.S. Geological Survey Scientific Investigations Report 2013–5155, 62 p., http://dx.doi.org/10.3133/sir20135155.

Curtis, Christopher, and Catherine Miller. The Westfield River Watershed Open Space and Recreation Plan. Rep. N.p.: Pioneer Valley Planning Commission, 2003. Print.

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