

**Critical Linkages Phase 1:  
Assessing Connectivity Restoration Potential for Culvert  
Replacement, Dam Removal and Construction of Wildlife Passage  
Structures in Massachusetts**

July 13, 2012

Kevin McGarigal, Bradley W. Compton, Scott D. Jackson,  
Ethan Plunkett and Eduard Ene

Landscape Ecology Program  
Department of Environmental Conservation  
University of Massachusetts Amherst

[www.umasscaps.org](http://www.umasscaps.org)



Contacts:

Kevin McGarigal, [megarigalk@eco.umass.edu](mailto:megarigalk@eco.umass.edu)  
Scott Jackson, [sjackson@umext.umass.edu](mailto:sjackson@umext.umass.edu)  
Brad Compton, [bcompton@eco.umass.edu](mailto:bcompton@eco.umass.edu)

# Table of Contents

Introduction.....	2
The Concept of Landscape Connectivity .....	3
The Critical Linkages Project .....	6
Methods.....	6
Connectedness.....	7
Aquatic Connectedness.....	13
Scenario Analysis.....	13
Results.....	15
Dams .....	15
Road-Stream Crossings.....	17
Wildlife Passage Structures .....	19
Availability of Results .....	21
Discussion.....	21
Acknowledgements.....	22
References Cited.....	22
Appendix A: Critical Linkages I results .....	25

Prepared in cooperation with the Massachusetts Department of Transportation Office of Transportation Planning and the United States Department of Transportation, Federal Highway Administration. The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the Massachusetts Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

# **Critical Linkages Phase 1: Assessing Connectivity Restoration Potential for Culvert Replacement, Dam Removal and Construction of Wildlife Passage Structures in Massachusetts**

## **INTRODUCTION**

Connectivity is considered a vital attribute of a landscape (Taylor et al. 1993) and deemed critical to the adaptive capacity (sensu Elmquist et al. 2003) of a landscape in the face of climate change (Czucz et al. 2011). The disruption of landscape connectivity by human land use activities is considered a principal cause of the decline in biodiversity and is increasingly of concern to conservation scientists (Chetkiewicz et al. 2006, Crooks and Sanjayan 2006, Hilty et al. 2006, Beier et al. 2008). There is perhaps no more ubiquitous and insidious anthropogenic influence on landscape connectivity than roads. Roads have both direct (e.g., animal mortality) and indirect (e.g., loss of landscape permeability resulting in fragmentation) effects on terrestrial and aquatic ecosystems (Forman et al. 2003). To a large degree, the placement and construction of roads in large measure determines how permeable the landscape is to the movement of organisms, energy, and matter.

In light of the above and in the face of continued human development and climate change, minimizing the influence of roadways on landscape connectivity is of paramount concern among conservationists and planners. Consequently, the aim of this study was to develop a modern methodology to assess and prioritize where to use mitigation techniques to best facilitate wildlife passage and reduce the risk of animal-vehicle collisions along roadways. Our specific objective was to evaluate and prioritize locations for potential wildlife passage structures and culvert upgrades in Massachusetts, although we extended this to include dam removals as well, even though dams are typically not associated with roadways – dams are otherwise analogous to culverts in impeding movement of aquatic organisms in riverine networks.

Our objective was to employ a "coarse-filter" approach in our assessment of connectivity; i.e., one that did not involve any particular focal species or process but instead holistically considered ecological systems or settings. While there have been many other efforts to develop methods and software tools for similar purposes (e.g., Fuller and Sarkar 2006, Theobald et al. 2006, Roberts et al. 2010) and many proposed measures of connectivity available for use in this context (e.g., Clabrese and Fagan 2004, Fagan and Calabrese 2006, Saura and Pascual-Hortal 2007, Estrada and Bodin 2008, Kindlmann and Burel 2008, Theobald et al. 2011), none of the available approaches make use of resistant kernels (Compton et al. 2007), which we believe provide the most synoptic perspective on landscape connectivity.

Resistant kernels combine two familiar methods: 1) standard kernel density estimation, and 2) least cost path analysis based on resistant surfaces, into a hybrid approach that allows for nonlinear ecological distance relationships and accounts for connectivity between every location

to every other location (as opposed to between a single designated source and destination location). Resistant kernels are described in more detail in the methods section. Consequently, we developed a new approach based on resistant kernels and applied it to potential wildlife passage structures, culvert upgrades and dam removals across Massachusetts.

### **The Concept of Landscape Connectivity**

The concept of landscape connectivity (Merriam 1984) provides the broad conceptual underpinning for this study and our approach, and thus it is important to clarify and define the concept as we use it here given the diverse and often confusing uses of the concept in the literature. The concept of landscape connectivity has been defined as the “degree to which the landscape facilitates or impedes movement among resource patches” (Taylor et al. 1993) or as “the functional relationship among habitat patches, owing to the spatial contagion of habitat and the movement responses of organisms to landscape structure” (With et al. 1997). Both of these definitions highlight the functional nature of connectivity, by emphasizing the dependence of movement on landscape structure. Furthermore, while these and other definitions emphasize the movement of organisms, the concept of landscape connectivity can be extended to consider more generally the movement of energy, matter, or information (gene flow) across the landscape. Regardless of which currency is used, the greater the degree of movement or flow across the landscape, the greater the overall connectivity of the landscape.

While the above definitions emphasize the functional nature of connectivity, ecologists often distinguish between functional connectivity (what is generally referred to as simply "connectivity") and structural connectivity (what is sometimes referred to as "continuity") (Crooks and Sanjayan 2006). *Structural connectivity* measures the spatial arrangement of landscape elements (e.g., habitat types or ecological systems) without reference to the likelihood of movement of particular organisms (or energy, matter or information for that matter) through the landscape. In contrast, *functional connectivity* incorporates at least some aspects of the behavioral response of individuals, species, or ecological processes to the physical structure of the landscape (Crooks and Sanjayan 2006). Thus, functional connectivity reflects the interaction of ecological flows (e.g., movement of organisms) with the physical landscape structure (i.e., the composition and spatial configuration of the landscape).

What constitutes functional connectivity clearly depends on the organism or process of interest; for example, patches that are connected for bird dispersal might not be connected for salamander dispersal. Thus, functional connectivity is affected by the structural connectivity of the landscape, but the magnitude and nature of the effect depends on how the organism or process scales and perceives the landscape. A central question in landscape management for the conservation of biodiversity and ecological integrity is, “as the physical continuity of the landscape is disrupted (through development), at what point does landscape connectivity become impaired and adversely impact ecological processes?” In other words, at what point do structural

disconnections impact the functional connectivity of the landscape.

In this study, we evaluate functional connectivity, not just continuity per se, but we do so in a generalized manner because we do not have a single focal organism or process. Instead, we are concerned with how myriad organisms and processes collectively respond to the physical continuity of environments. This approach is implemented in our “resistant kernel” methodology (see below) that combines the physical distribution of land cover types and ecological settings (i.e., continuity) with the concept of permeability or ecological resistance, whereby each location confers a varying degree of resistance to ecological flows (i.e., connectivity).

Functional connectivity can be subdivided further into *potential connectivity*, which uses some basic, indirect knowledge of the potential for movement, and *actual connectivity*, which directly quantifies movement rates based on actual observations (Fagan and Calabrese 2006). The primary difference between potential and actual connectivity lies in the amount of information available on the response of the organism or process to landscape structure. Although assessing the actual connectivity of the landscape might be the goal, we usually do not have sufficient empirical information on how landscape structure influences movement behaviour or other ecological flows across the landscape to permit this level of assessment. Thus, most analyses of landscape connectivity are of the potential connectivity of the landscape. In this study, we evaluate potential connectivity, as we do not have empirical data on movement, nor do we have a single species or process on which to focus estimates of movement rates.

There are myriad ways to measure the functional connectivity of a landscape or of a particular landscape unit (e.g., grid cell) within a landscape. In the context of our approach, the functional connectivity of a landscape unit can be assessed from three different perspectives.

We refer to the connectivity of a focal cell to its ecological neighborhood (i.e., its landscape context) when it is viewed as a target as *connectedness*; in other words, to what extent are ecological flows (e.g., dispersal) to that cell impeded or facilitated by the surrounding landscape. Connectedness is a function of both the similarity of the neighboring cells to the focal cell (i.e., the more similar the more connected) and any impediments to movement from the neighboring cells to the focal cell (i.e. the more impediments the less connected).

The outflow from a focal cell, for example when it is viewed as a source, we refer to as *traversability*. Traversability is a function solely of impediments to movement from the focal cell outward to all neighboring cells; it does not take into account whether or not the destination cells are similar to the focal cell, only whether stuff can get there.

Lastly, we refer to the rate of flow through a focal cell (i.e. when it is viewed as a conduit) as *conductance*. Conductance refers to how much stuff moves through a focal cell when all neighboring cells are treated as sources, and it is a function of the focal cell's permeability (or resistance) to ecological flows as well as its strategic position in the landscape between other

cells. For example, a wildlife passage structure on an expressway may be quite permeable to wildlife crossings, but if it is not located along an important movement route between sites A and B, it will not function to promote the linkage of A and B. Thus, conductance deals with the role of each location in conferring connectivity to the broader landscape.

From a conceptual standpoint, all three components of connectivity (i.e., connectedness, traversability and conductance) are relevant to this study. However, after preliminary examination of the results we limited our analyses to the use of connectedness. Thus, in this study, we are principally concerned with the effect of roads, culverts and dams on the connectedness of the surrounding landscape.

What ultimately influences the functional connectivity of the landscape is the scale and pattern of movement relative to the physical structure of the landscape (With 1999). Thus, functional connectivity is a scale-dependent concept and there is no one right scale for assessing it. In the context of this study, because we are dealing with biodiversity in its broadest sense (i.e. approaching it using a coarse filter), it is impossible to define a single scale for assessing connectivity that will be meaningful for all organisms and processes of concern. Yet at the same time it is impractical to examine connectivity at every relevant scale. As a practical compromise, we distinguish two important scales for assessing connectivity, which we refer to as local and regional scales.

The distinction between these two scales is best illustrated from the perspective of movement of organisms (rather than energy or matter). In this context, *local connectivity* refers to the spatial scale at which the dominant organisms interact directly with the landscape via demographic processes such as dispersal and home range movements. This is the landscape context that an individual organism might experience during their lifetime.

*Regional connectivity* refers to the spatial scale exceeding that in which organisms directly interact with the landscape. This is the scale at which long-term ecological processes such as range expansion/contraction and gene flow occur. At this scale, individuals generally do not interact with the landscape, but their offspring or their genes might over multiple generations. Consequently, there is no real upper limit on the regional scale; the longer the time frame, the larger the regional scale at which the landscape context matters.

In the first phase of this study reported in this report, we are concerned with local connectivity; regional connectivity will be addressed in the next phase of this study. Of course, even this does not constrain the range of suitable scales for assessing connectivity, since even the dominant organisms in a community may have ecological neighborhoods that vary in scale by orders of magnitude. Thus, in choosing the spatial scale(s) for the local connectivity assessment (using the resistant kernel estimator), we incorporated two important considerations. First, we focussed on vertebrates, largely because their life history and habitat use patterns are better understood than many plants and invertebrates and because they are more often the focus of conservation

concerns. Second, we focussed on the average maximum movement distances of a suite of organisms; in other words, we did not use the maximum movement distance of a single “indicator” species nor did we choose to bias the result towards the most or least vagile organism.

In summary, connectivity is a complex and multi-faceted concept with many different constructs depending on the application. In this study, we are interested in evaluating and prioritizing locations for potential wildlife passage structures, culvert upgrades and dam removals based on an assessment of how these mitigation measures influence functional, potential, local connectivity as measured from the perspective of connectedness.

### **The Critical Linkages Project**

The University of Massachusetts (UMass) in collaboration with The Nature Conservancy (TNC) integrated data related to landscape connectivity and human development, and developed a comprehensive analysis of areas in Massachusetts where connections must be protected or restored to support biodiversity and minimize vehicle-wildlife collisions. The Critical Linkages project built on the existing Conservation Assessment and Prioritization System (CAPS) through a statewide landscape connectivity study. Phase 1 of the project involved scenario analysis using CAPS to assess the potential for restoring functional connectivity via dam removal, culvert/bridge replacement and use of wildlife passage structures on roads and highways.

### **METHODS**

The Conservation Assessment and Prioritization System (CAPS) is a computer software program and an ecosystem-based (coarse-filter) approach for assessing the ecological integrity of various ecological communities (e.g., forest, shrub swamp, headwater stream) and subsequently identifying and prioritizing land for habitat and biodiversity conservation within an area.

The first step in the CAPS approach is the characterization of both the developed and undeveloped elements of the landscape. Developed land uses are grouped into categories such as various classes of roads and highways, high-intensity urban, low-density residential, agriculture, and other elements of the human-dominated landscape. Undeveloped (“natural”) land is mapped based on an ecological community classification (e.g., swamp, marsh, bog, pond).

With a computer base map depicting the various land cover classes, we then evaluate a variety of landscape metrics for every undeveloped cell in the landscape. A metric may, for example, take into account the microclimatic alterations associated with “edge effects,” intensity of road traffic in the vicinity, nutrient loading in aquatic ecosystems, or the effects of human development on landscape connectivity. Many of these metrics measure the intactness of the focal cell; i.e., the naturalness or freedom from adverse anthropogenic effects. Two of these metrics measure the connectedness of each undeveloped cell; i.e., the degree to which a focal cell is surrounded by

ecologically similar cells and the degree of impedance of ecological flows from similar neighboring cells to the focal cell. One of these metrics (*connectedness*) applies to both terrestrial and aquatic cells and the other metric (*aquatic connectedness*) applies only to aquatic cells, as described below.

Because the landscape metrics are quantitative, they can be used for comparing various land use scenarios. In essence, scenario analysis involves running CAPS separately for each scenario, and comparing results to determine the loss (or gain) in specific metric units. This scenario-testing capability can be used to evaluate and compare the impacts of development projects on habitat conditions as well as the potential benefits of habitat management or environmental restoration.

In Phase 1 of the Critical Linkages project we used the scenario-testing capabilities of CAPS to assess the change in either the *connectedness* or *aquatic connectedness* metrics for three types of ecological restorations designed to promote connectivity: 1) dam removal, 2) culvert/bridge replacement, and 3) the use of wildlife crossing structures on roads and highways (for technical reasons, railroads have not yet been included in the analysis).

### **Connectedness**

The *connectedness* metric is a measure of the degree to which a focal cell is interconnected with other cells in the landscape that can be a source of individuals or materials that contribute to the long-term ecological integrity of the focal cell. *Connectedness* is based on a "resistant kernel", introduced by Compton et al. (2007), which is a hybrid between two existing approaches: the standard kernel estimator and least-cost paths based on resistant surfaces.

The resistant kernel begins by placing a standard kernel over a focal cell. A standard kernel is simply a mathematical function that describes the shape and size of a utilization distribution. Here, we can think of the standard kernel as estimating the shape and size of the ecological neighborhood of a focal cell. Importantly, the kernel can take on any shape and size to reflect the ecological process under consideration. In CAPS, we use a normal (or Gaussian) kernel to reflect the nonlinear strength of ecological interaction between a focal cell and its ecological neighborhood. This is like placing a bell-shaped surface of a specified size over the focal cell, where the height of the surface represents the strength of the interaction with the focal cell -- greatest at the focal cell and then with increasing distance decreasing slowly at first and then rapidly until the strength of the interaction becomes trivial.

Resistant surfaces (also referred to as cost surfaces) are being increasingly used in landscape ecology, replacing the binary habitat/non-habitat classifications of island biogeography and classic metapopulation models with a more nuanced approach that represents variation in habitat quality (e.g., Ricketts 2001). In a resistant surface a cost is assigned to location, typically representing a divisor of the expected rate of ecological flow (e.g., dispersing or migrating animals) through a particular cell. For example, a forest-dependent organism might have a high



rate of flow (and thus low resistance) through forest, but a low rate of flow (and thus high resistance) through high-density development. In this case, the cost assigned to a cell in the resistant surface may represent the willingness of the organism to cross the cell, the physiological cost of moving through the cell, the reduction in survival for the organism moving through the cell, or an integration of all these factors. Empirical data on costs are often lacking, but can be derived from a variety of data sources, including location, movement and/or genetic data for the organism (or process) under consideration, although more often than not expert opinion is used to assign costs.

Traditional least-cost path analysis finds the shortest functional distance between two points based on the resistant surface. The cost distance (or functional distance) between two points along any particular pathway is equal to the cumulative cost of moving through the associated cells. Least-cost path analysis finds the path with the least total cost. This least-cost path approach can be extended to a multidirectional approach that measures the functional distance (or least-cost path distance) from a focal cell to every other cell in the landscape. In the resistant kernel estimator, the complement of least-cost path distance (a.k.a. functional proximity; see below) to each cell from the focal cell is multiplied by a weight reflecting the shape and width of the standard kernel. The result is a resistant kernel that depicts the functional ecological neighborhood of the focal cell. In essence, the standard kernel is an estimate of the fundamental ecological neighborhood and is appropriate when resistance to movement is irrelevant (e.g., highly vagile species), while the resistant kernel is an estimate of the realized ecological neighborhood when resistance to movement is relevant.

The resistant kernel is derived for a focal cell as follows.

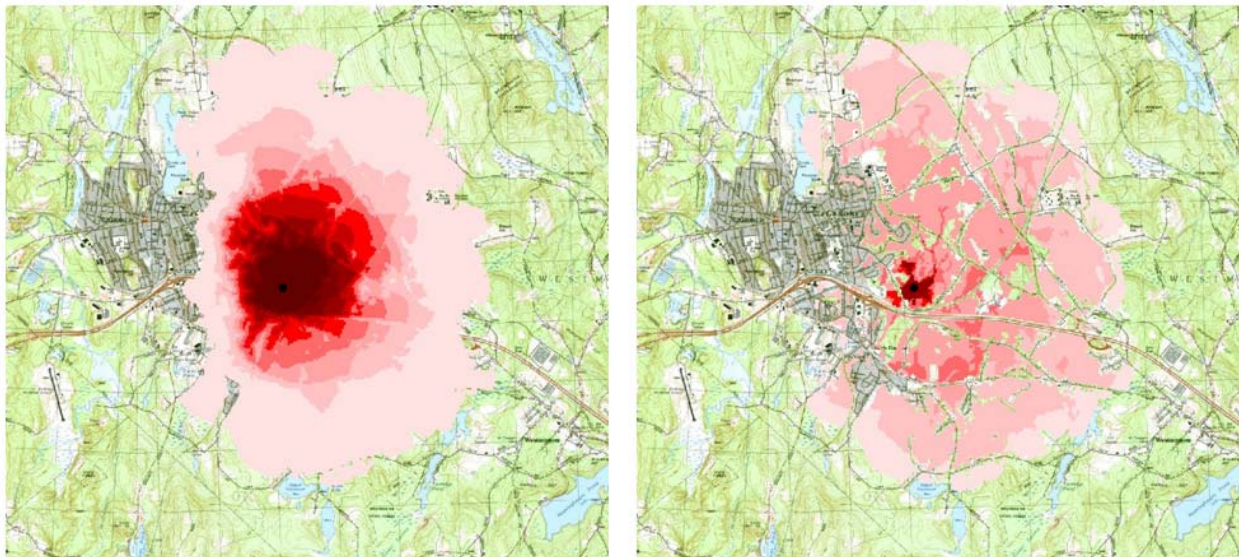
First, we assign a cost (i.e., resistance) to each neighboring cell. In CAPS, we assign cost based on the ecological distance between each cell and the focal cell based on a suite of ecological settings variables (**Table 1**). Most of the settings variables are continuous and thus represent landscape heterogeneity as continuous (e.g., temperature, soil moisture), although some are categorical and thus represent heterogeneity as discrete (e.g., water salinity, developed). The cost for each cell is based on the multivariate weighted Euclidean distance to the focal cell in ecological settings space. Thus, the more similar a cell is to the focal cell in each of the ecological settings, the shorter the multivariate distance and the lower the cost. Note that the cost surface constructed in this manner varies with each focal cell.

Second, we assign to the focal cell a "bank account" based on the specified width of the standard kernel, and allow the kernel to spread outward to adjacent cells iteratively, depleting the bank account at each step by the minimum cost of spreading to each cell. In CAPS, we use a normal (or Gaussian) kernel with a standard deviation of 2 km for connectedness, and 5 km for aquatic connectedness. This process is repeated iteratively, spreading outward in turn from each visited cell, each time finding the lowest cost of getting to that cell from any of its neighbors, until the

balance reaches zero. This produces a functional proximity surface representing the proximity of every cell to the focal cell within a threshold proximity distance (6 km for connectedness, and 15 km for aquatic connectedness).

Lastly, we multiply the cell values in the proximity surface by weights derived from the specified kernel function. The resulting surface is the resistant kernel and its volume is always less than or equal to one (**Fig. 1**).

*Connectedness* is computed in two steps as follows. First, we multiply the resistant kernel by the ecological similarity between each neighboring cell and the focal cell (**Fig. 1**). Ecological similarity is inversely related to ecological distance in ecological settings space (**Table 1**). Specifically, similarity is based on the multivariate weighted Euclidean distance to the focal cell and scaled such that the maximum similarity is 1.0 for a perfectly similar cell and decreases to a minimum of 0 for the most dissimilar cells. In essence, each neighboring cell is weighted by the degree of similarity with the focal cell. Thus, if the neighboring cell has a similarity weight of 1.0, it is given the full value of the resistant kernel. If, on other hand, the neighboring cell has a similarity weight of 0.2, it is given only 20% of the value of the resistant kernel. Lastly, at each focal cell, we sum across the similarity-weighted resistant kernel surfaces derived above from all the neighboring cells.



*Figure 1. A resistant kernel for a cell of forest in a heterogeneous landscape (left pane) and the similarity-weighted resistant kernel derived by multiplying the resistant kernel by the ecological similarity (0-1) between each neighboring cell and the focal cell (right pane).*

*Table 1. Ecological settings variables used to calculate ecological distance among cells in the landscape.*

<b>Biophysical attribute</b>	<b>Biophysical variable</b>	<b>Description</b>
Temperature	Growing season degree-days	Degree-days is calculated by taking the sum of daily temperatures above a threshold (10°C). Temperatures above an upper threshold of 30°C are excluded.
	Minimum winter temperature	The minimum temperature (°C) reached in the winter
Solar energy	Incident solar radiation	Solar radiation based on slope, aspect, and topographical shading.
Chemical & physical substrate	Soil pH	Soil pH
	Soil depth	Soil depth (cm)
	Soil texture	Soil texture based on USDA-NRCS classification
	Water salinity	Salinity (ppt) in coastal settings in three broad classes: fresh, brackish, and saltwater
	Substrate mobility	The <i>realized</i> mobility of the physical substrate, due to both substrate composition (i.e., sand) and exposure to forces (wind and water) that transport material
	CaCO <sub>3</sub> content	Calcium carbonate content based on the composition of the soil and underlying bedrock
Physical disturbance	Wind exposure	Wind exposure based on the mean sustained wind speeds at 30 m above ground level using a 200 m resolution model
	Wave exposure	Direct exposure to ocean waves
	Steep slopes	The propensity for gravity-induced physical disturbance
Moisture	Wetness	Soil moisture (in a gradient from xeric to hydric) based on a topographic wetness index
Hydrology	Flow gradient	Gradient (percent slope) of a stream approximated by categories such as step-pool, riffle, run, cascade and flat water
	Flow volume (watershed size)	The absolute size of a stream or river
	Tidal regime	In coastal areas, degree of tidal influence
Vegetation	Vegetative structure	Coarse vegetative structure, from unvegetated through shrubland through closed canopy forest
Development	Developed	Whether a cell can be considered largely developed or undeveloped
	Hard Development	Whether a cell can be considered “hard” development; areas such as commercial, industrial, and higher-density residential.

<b>Biophysical attribute</b>	<b>Biophysical variable</b>	<b>Description</b>
	Traffic rate	A scaled measure of traffic volume on roads and highways
	Impervious	Percent of impervious surfaces
	Terrestrial barriers	Degree to which a cell constitutes a barrier to terrestrial organisms
	Aquatic barriers	Degree to which a cell constitutes a barrier to aquatic organisms

*Connectedness* represents the amount of ecological flow to the focal cell from neighboring cells weighted by their ecological distance (as represented by the kernel shape and width) and their ecological similarity (as represented by the similarity weights). Note, underlying this metric is the assumption that ecological flows from similar ecological communities is more important to long-term integrity than those from dissimilar communities.

The *connectedness* metric applies to all ecological communities including aquatic communities (e.g., lakes, rivers, streams). In order to characterize the ecological distances and ultimately the resistant surface for developed land classes we included several anthropogenic attributes among the settings variables, including aquatic barriers, terrestrial barriers, traffic rate, imperviousness, and developed, and parameterized them as follows:

Dams generally have traffic rates of zero. However, dams that have a road that runs along their surfaces will have non-zero traffic rates. Dams have a terrestrial barrier score of zero unless a road goes over the dam, in which case it gets the road's terrestrial barrier score. The aquatic barrier scores are a function of dam height.

To assign aquatic barrier scores for road-stream crossings we used an assessment protocol and scoring system developed by the River and Stream Continuity Partnership (2010, [www.streamcontinuity.org](http://www.streamcontinuity.org)). The protocols were developed for implementation by trained volunteers or technicians and rely on information that can be readily collected in the field without surveying equipment or extensive site work. The Partnership also created an algorithm for scoring crossing structures according to the degree of obstruction they pose to aquatic organisms. We used data and crossing scores from over 1,000 crossings to create a statistical model to predict aquatic barrier scores for those crossings that had not been assessed in the field.

To assign terrestrial barrier scores for road-stream crossings we created a scoring algorithm using data collected by the River and Stream Continuity protocols. We included the following variables in the scoring algorithm: height, width, openness (cross-sectional area divided by structure length), substrate and span (an approximation of constriction ratio). As with aquatic

barriers we developed a statistical model to predict terrestrial barrier scores for crossings that had not been assessed in the field.

The road-stream crossing models for both aquatic barrier and terrestrial barrier produced noisy results ( $R^2 \approx 0.4$ ). Therefore, we calculated 60% confidence intervals for both scores to allow modeling both a “best estimate” scenario (based on the predicted score) and a reasonable “best case” scenario (described below). To calculate 60% confidence intervals on the scores we broke the data into three equal sized strata for predicted scores. For each stratum we then calculated a 60% confidence interval from the distribution of the residuals in the predictions. The lower bound of the confidence interval was the prediction minus the 20th quantile of the residuals for all observations in the stratum while the upper confidence interval was based on the 80th quantile of the residuals in the stratum. We smoothed the transitions between strata to force the confidence intervals to increase monotonically with predicted score (**Fig. 2**).

An expert team assigned terrestrial barrier scores for wildlife passage structures based on road class. Traffic rates for roads were assigned from MA Department of Transportation (MassDOT) interpolated road traffic data, using the ADT (average daily traffic) field. We modified traffic rates somewhat to correct errors; for example, when traffic rates were zero due to missing data, or where traffic was overestimated for unpaved roads running through state forests. We converted traffic rates to a probability of roadkill using a mechanistic model presented by Hels and Buchwald (2001) and Gibbs and Shriver (2002) (**Fig. 3**).

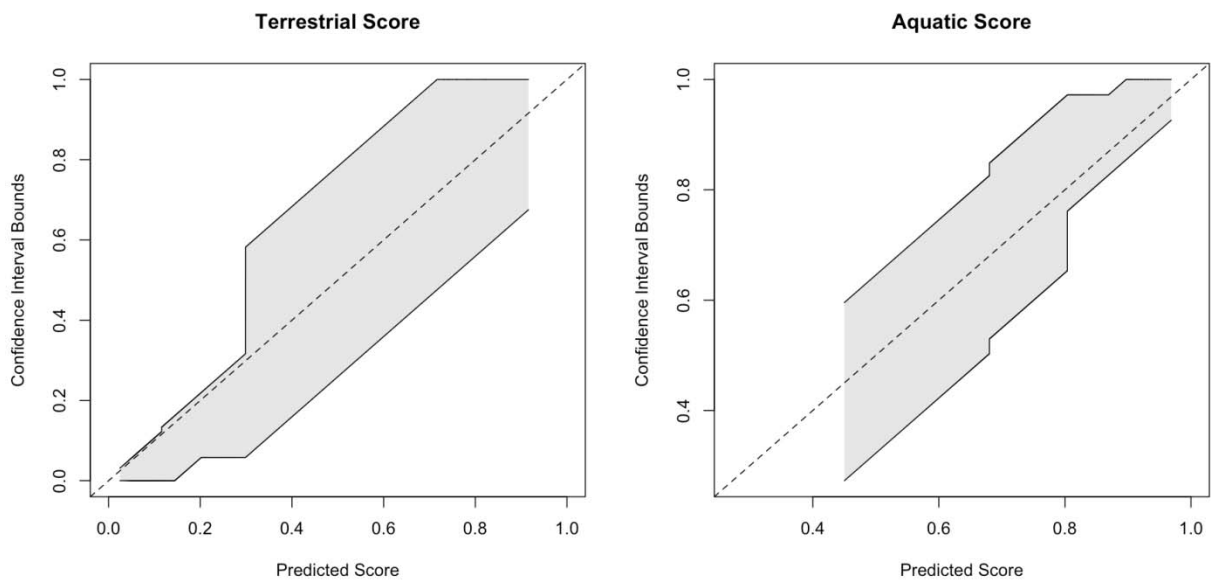


Figure 2. Sixty percent confidence intervals for terrestrial and aquatic barrier scores.

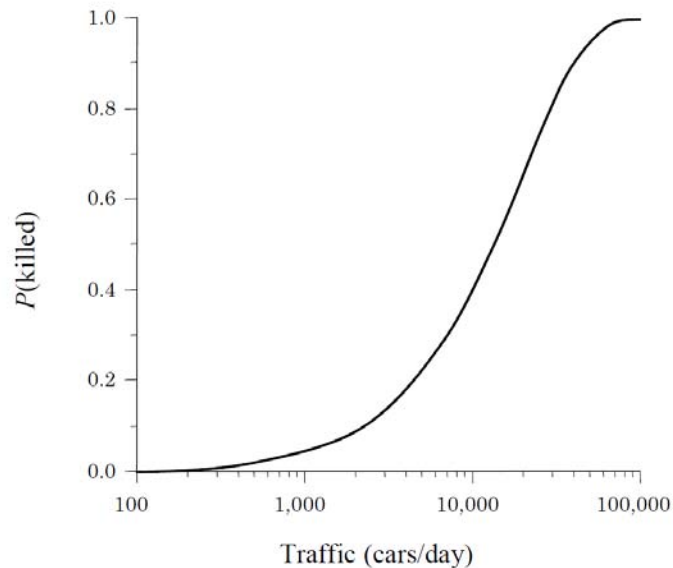


Figure 3. Relationship between traffic rate and probability of mortality.

### Aquatic Connectedness

Ecological flows modeled for *connectedness* are allowed to flow overland and diagonally from cell to cell. As a result, resistant kernels can wrap around highly resistant cells or patches of cells. This makes sense for organisms that move terrestrially because flows can go around a building, parking lot or subdivision. However, for aquatic organism passage this is a problem because what would otherwise be considered severe barriers (e.g., dams, bad culverts) are easily circumvented. We created *aquatic connectedness* to get around this problem. *Aquatic connectedness* functions much like *connectedness* but is constrained to move only along the centerlines of streams, rivers, water bodies and wetlands. *Aquatic connectedness* includes one settings variable not used by *connectedness* (aquatic barriers) and ignores four settings variables used by *connectedness* (terrestrial barriers, traffic, imperviousness, and developed). This allows *aquatic connectedness* to respond to the effects of culverts, bridges, and dams on aquatic passability, rather than the effects of roads that may pass overhead.

### Scenario Analysis

Within the framework of CAPS we used the *connectedness* and *aquatic connectedness* metrics to model various scenarios and quantify the differences among them. Specifically, we conducted a comprehensive statewide assessment of restoration potential for 1) dam removals, 2) culvert/bridge replacements and 3) construction of wildlife passage structures on roads and highways. For the dam removal scenario we systematically removed each dam, one at a time,

and compared the change in aquatic connectedness resulting from the dam removal. Similarly, for the culvert/bridge replacements we systematically upgraded each culvert, one at a time, to a bridge having the minimal aquatic barrier score and compared the change in aquatic connectedness resulting from the culvert replacement. Lastly, for the construction of wildlife passage structures on roads and highways we systematically located a road crossing structure on road segments, one at a time, and compared the change in connectedness resulting from the passage structure.

In calculating the change in *connectedness* and *aquatic connectedness* we used the modeled aquatic barrier and terrestrial barrier scores for road stream crossings to produce a “best estimate” delta score. In an effort to bracket these results and as a hedge against the uncertainty of the modeled scores we also used values associated with the 60 percent confidence intervals to produce what we called a reasonable “best case” value for the change in either *connectedness* or *aquatic connectedness*. Where terrestrial barrier and aquatic barrier scores based on field assessments were available these were used instead of modeled scores.

The purpose of calculating both “best estimate” and “best case” values was to minimize the chance of dismissing reasonably good restoration opportunities because uncertainty in the model resulted in inappropriately low restoration scores for those structures (dams or road-stream crossings). For any given structure our objective was to be able to express the result as “we believe the benefits of removing/replacing this structure to be “x” (best estimate) but they could be as high as “y” (best case).” Decision-makers can then use one or both of these values to assess restoration opportunities.

When conducting dam removal scenarios the restoration score is dependent to some extent on the degree to which road-stream crossings on the same waterway are acting as barriers to movement. For example, removal of a dam will result in less improvement in connectivity if there is an undersized culvert a short distance from the dam compared to that same dam but with no other movement barriers nearby (e.g. a bridge instead of a culvert). The undersized culvert will continue to depress *aquatic connectedness* values even after the dam is removed. We used the “best case” analysis to avoid having errors in the model for scoring road-stream crossings result in underestimating the restoration potential for dam removal.

The “best estimate” analysis for dam removal used the modeled aquatic barriers scores for road-stream crossings in the vicinity of dams. We believe that the modeled aquatic barriers scores were the best estimate of the passability for road-stream crossings that were not assessed in the field. For the “best case” analysis we used more optimistic assumptions about the passability of road-stream crossings in the vicinity of dams. Instead of using the modeled scores for these crossings we used the scores at the 60% confidence interval above their estimated score. In cases where all road-stream crossings in the vicinity of a dam had been assessed in the field these

field-based assessment scores would have been used for both the “best estimate” and “best case” analyses and there would have been no difference in their restoration scores.

As with dams the restoration potential for culvert replacement were affected by the aquatic barrier scores of other nearby crossings. For culvert replacement scenarios the restoration score were affected by uncertainty in the modeled aquatic barrier score both for the focal crossing and for nearby crossings. For culvert/bridge replacement scenarios the “best estimate” analysis was based on the modeled scores for aquatic barriers for all crossings involved (focal and nearby crossings). Our “best case” analysis again used more optimistic assumptions about the passability of nearby crossings but for focal crossings we used a more negative assumption (the lower the passability score to begin with the greater the improvement in aquatic connectedness when that structure is replaced). “Best case” analyses set the target crossing score at the 60% confidence interval below the estimated score with all other crossings scored at the 60% confidence interval above their estimated score. Where aquatic barrier scores were available from field-based assessments these were used instead of modeled scores.

When evaluating road segments for potential benefits of installing wildlife passage structures for “best estimate” analyses we used the modeled terrestrial barrier scores for road-stream crossings with potential to affect *connectedness* associated with road/highway segments. Again, uncertainty associated with these terrestrial barrier scores for road-stream crossings had the potential to affect the restoration score for the use of wildlife crossing structures. If the road segment being evaluated contained a road-stream crossing the baseline terrestrial barrier score for that crossing would affect the restoration potential of any wildlife crossing structure that might be used at that location. If the terrestrial barrier score for that structure is actually lower than that predicted by the model this would result in an underestimation of restoration potential for that scenario. Nearby crossings also affect the restoration potential because they present alternative pathways for movement that influence baseline *connectedness* values.

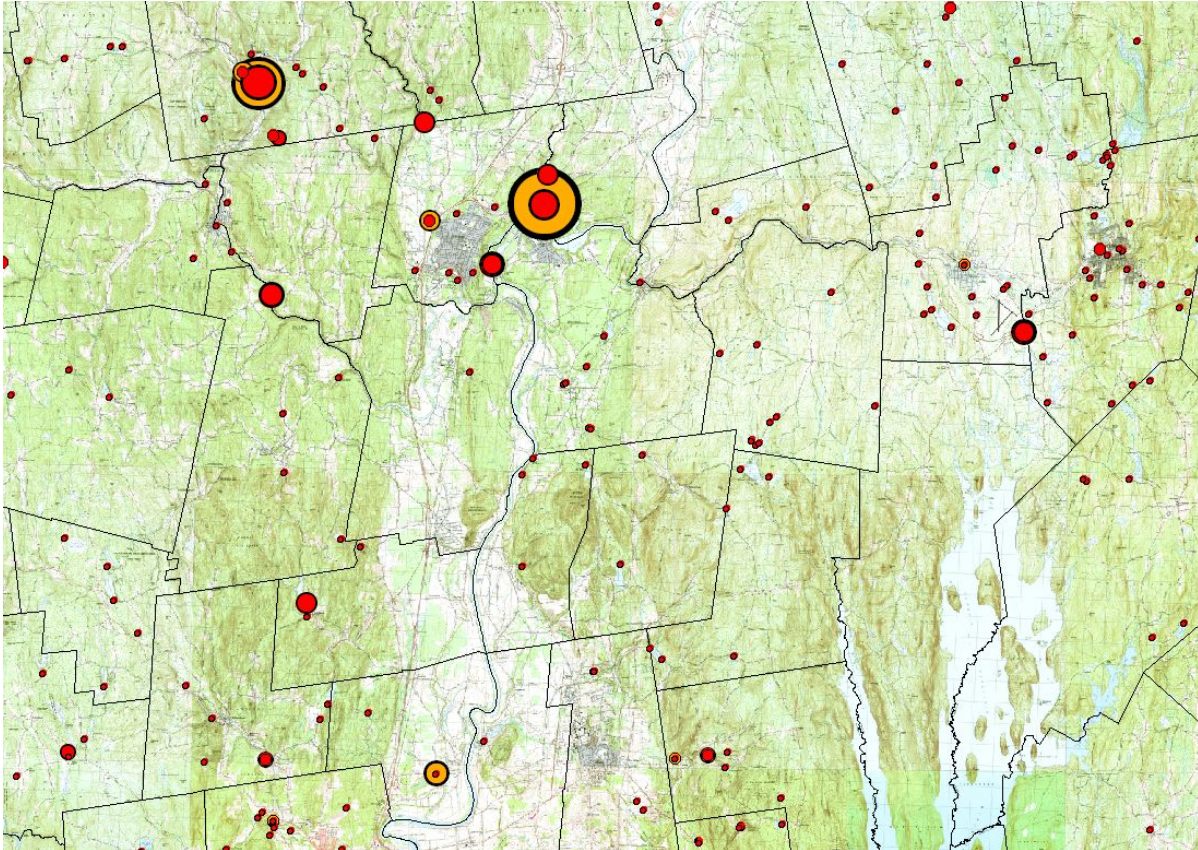
Whether considering a road-stream crossing within the road segment being evaluated or crossings nearby, more pessimistic assessments of passability will result in higher restoration scores. For the “best case” analysis road-stream crossings in the vicinity of the road segment being assessed were scored at the 60% confidence interval below their estimated terrestrial barrier score. As was the case for dam removal and culvert replacement terrestrial barrier scores based on field assessments were used instead of modeled scores whenever they were available. For wildlife passage structures the scaled traffic rate, impervious, and terrestrial barriers settings variables were reduced by 90 percent.

## **RESULTS**

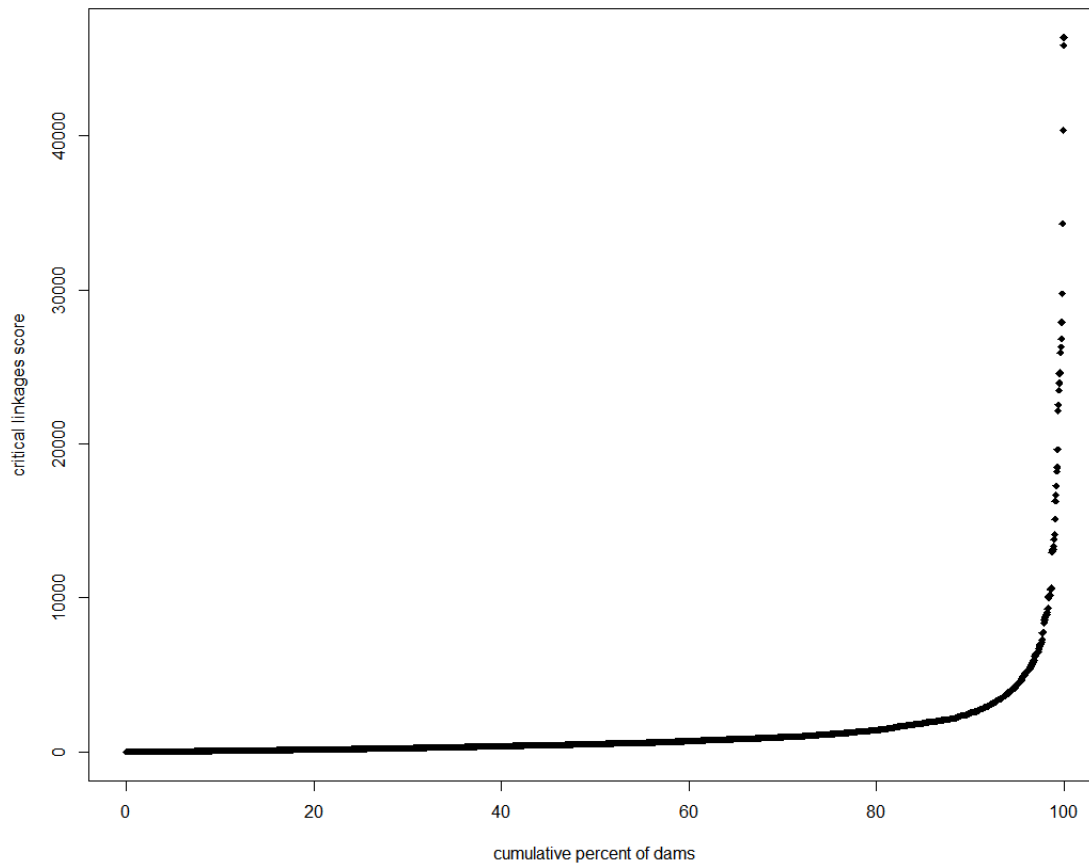
### **Dams**



A total of 2,467 dams were included in the dam removal scenario analysis. Dams varied considerably in their potential for increased aquatic connectivity via their removal (**Fig. 4**). A cumulative histogram of the dams arranged by change in *aquatic connectedness* (**Fig. 5**) suggests that much improvement in aquatic connectivity could be achieved with the removal of a relatively small number of dams.



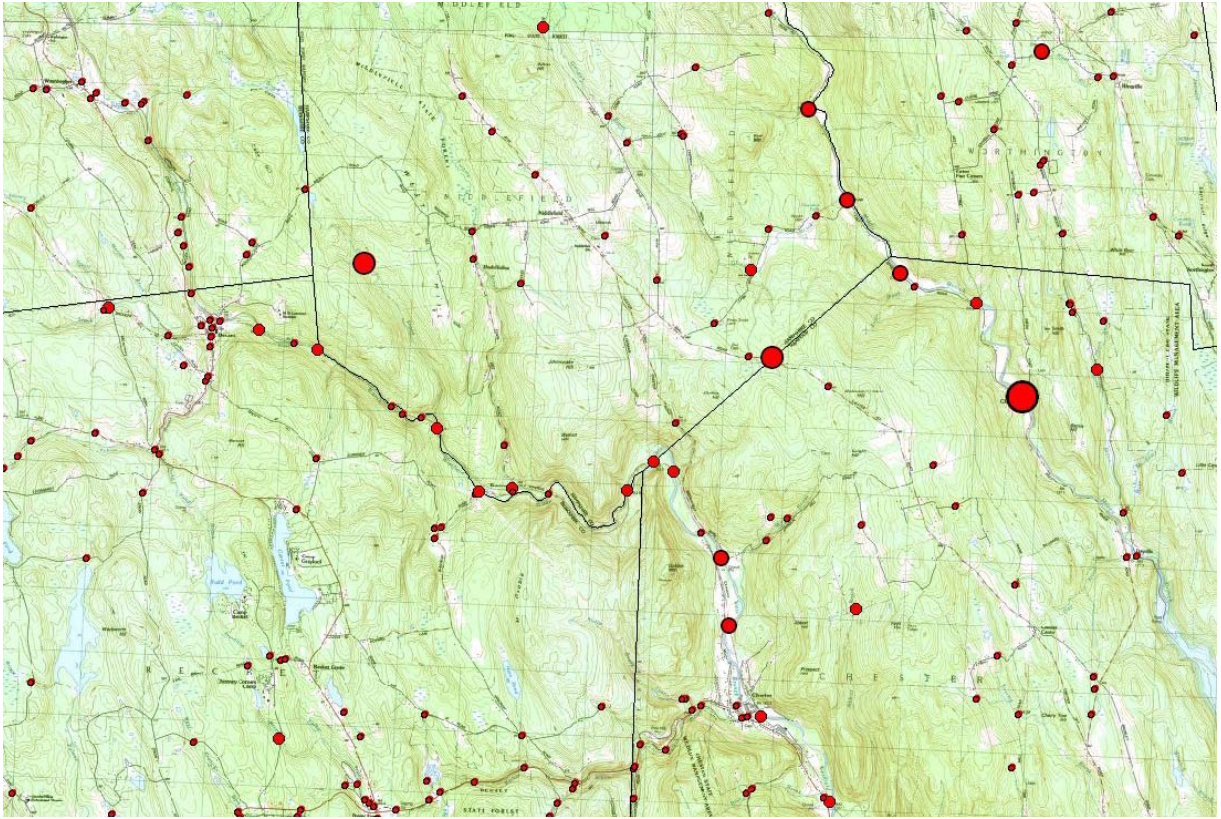
*Figure 4. Results of dam removal scenario analyses for a portion of Massachusetts. Size of the circles is proportional to the change in “aquatic connectedness” that would be achieved by dam removal. Red circles are “best estimate” and yellow circles “best case” results.*



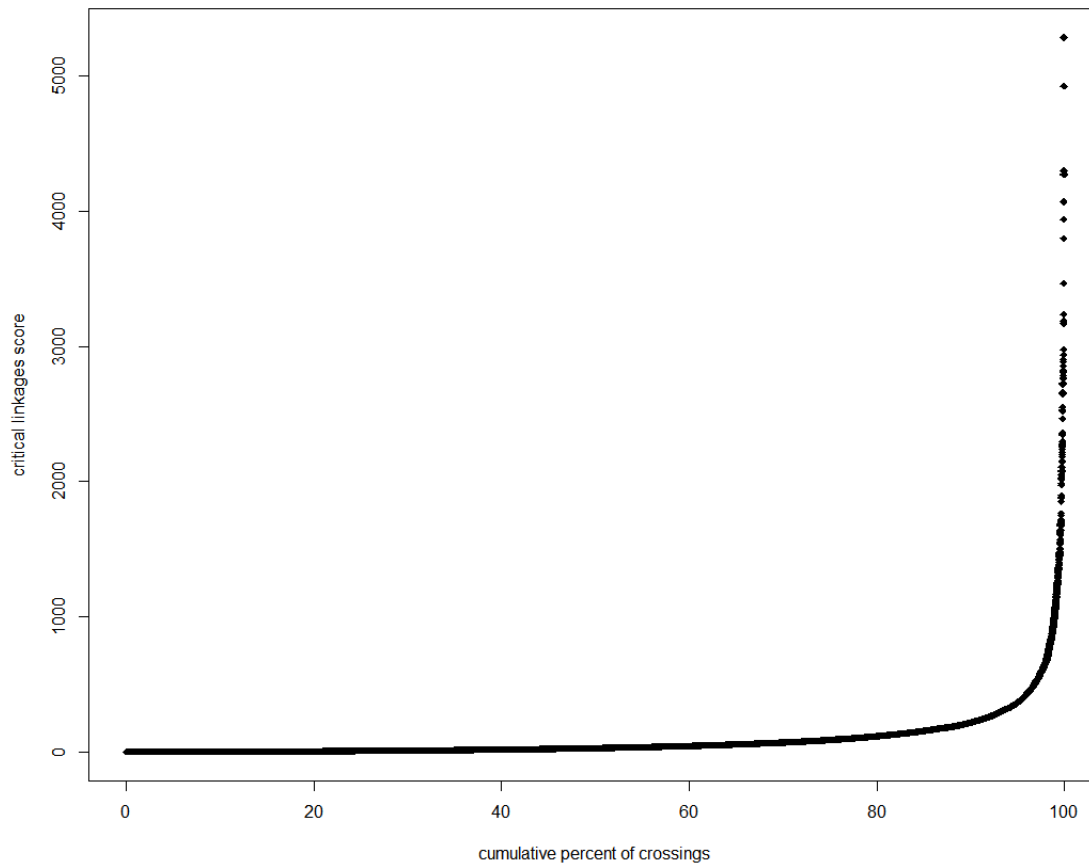
*Figure 5. Cumulative histogram of dams arranged by change in “aquatic connectedness.”*

### **Road-Stream Crossings**

A total of 26,582 road-stream crossings were included in the culvert/bridge replacement scenario analysis. As with dams, culverts varied considerably in their potential for increased aquatic connectivity via their removal (**Fig. 6**). A cumulative histogram of the culverts arranged by change in *aquatic connectedness* (**Fig. 7**) suggests that selective replacement of a small proportion of culverts/bridges would yield disproportionate benefits in terms of aquatic connectivity.



*Figure 6. Results of culvert/bridge replacement scenario analyses for a portion of Massachusetts. Size of the circles is proportional to the change in “aquatic connectedness” that would be achieved by crossing replacement. The larger the circles the greater the improvement in “aquatic connectedness.”*



*Figure 7. Cumulative histogram of road-stream crossings arranged by change in “aquatic connectedness.”*

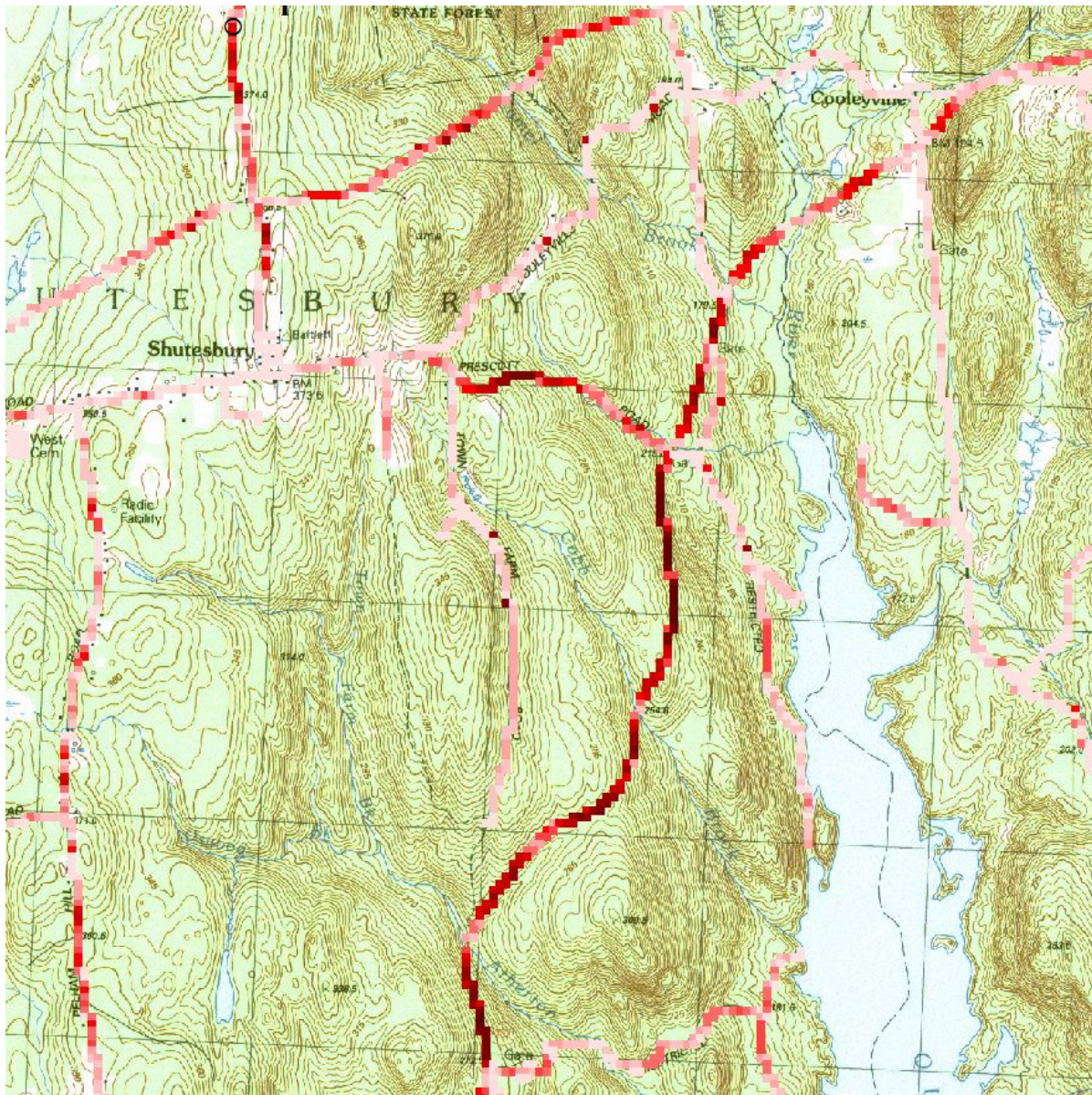
### **Wildlife Passage Structures**

A total of 48,859 miles of roads and highways were included in the scenario analysis for wildlife passage structures. Due to computational constraints, we restricted the analysis to roads with  $\geq 1000$  cars/day (because we presume wildlife passage structures are unlikely to be installed on low traffic roads) and road segments in areas with relatively high IEs, in order to exclude urbanized areas where passage structures are unlikely to have much of a positive effect. For technical reasons railroads were not included in this analysis.

Because connectedness tends to be dominated by forests (the dominant community in most areas), road results are provided separately for forest communities, wetland and aquatic communities, other communities, as well as for all communities. This allows, for instance, a user

to assess the estimated effect of installing wildlife passage structures for wetland species such as turtles and salamanders.

Road segments varied considerably in their potential for increased connectivity via a wildlife passage structure (**Fig. 8**). Because the score for road segments is highly dependent on adjacent road segments, a cumulative histogram of road segments arranged by potential for increased connectedness is not particularly meaningful and thus is not shown.



*Figure 8. Results of wildlife passage structure scenario analyses for a portion of Massachusetts. The color of the lines is proportional to the change in “connectedness” that would be achieved by the construction of a wildlife passage structure. The darker the color the greater the benefit of using a passage structure.*

## Availability of Results

See Appendix A for links that can be used to download the results of the Critical Linkages Phase 1 analyses. Links to these results will also be included on our web site: [www.umasscaps.org](http://www.umasscaps.org).

## DISCUSSION

We developed scenario-testing software to efficiently assess restoration potential for large numbers of possible restoration projects and applied it statewide to identify road segments, road-stream crossings and dams that currently obstruct aquatic and terrestrial wildlife movement and that offer the greatest opportunity for restoration of landscape connectivity in Massachusetts. Cumulative histograms of dams and road-stream crossings arranged by change in *aquatic connectedness* (**Figs. 5 and 7**) indicate that a relatively small proportion of dams and crossings accounts for much of the restoration potential statewide. These histograms suggest that there is much to be gained from prioritizing restoration efforts.

CAPS Scenario analysis provides an efficient method for comprehensive assessment and prioritization of movement barriers. It is, however, important to remember the limitations of a modeling exercise such as the Critical Linkages analysis.

Data gaps and errors inherent in the source data used in CAPS are likely to affect the accuracy and usefulness of the analysis. Examples include:

- Unmapped dams
- Unmapped natural barriers to aquatic organism passage (e.g., waterfalls)
- Phantom road-stream crossings erroneously generated by the intersection of roads and streams data in GIS
- Lack of information on the passability of dams (e.g., fish passage structures)
- Lack of information about passability for most road-stream crossings (only about ten percent had been assessed in the field)
- Lack of information about the location of wildlife movement barriers associated with roads (Jersey barriers, fencing)

Another limitation of this analysis is that it only included single structure (e.g., dam or culvert) restoration scenarios. This focus on single structures can mask benefits of restoration potential for multi-structure projects. As part of our comprehensive state-wide analysis it was not feasible to evaluate all possible combinations of structure scenarios. However, we have recently developed separate software to be used with CAPS allowing users to define custom scenarios that can include multiple structures and combinations of different types of structures (e.g., culverts and dams).

The CAPS coarse filter, community-based approach is an efficient means for integrating needs of a variety of organisms as well as ecological processes (flow of energy, materials and information). However, scale is important for community-based analyses. Phase 1 of the Critical Linkages project presented here is based on analyses at the local scale. The results of these analyses may be less appropriate for highly vagile species such as birds, bats, and some anadromous fish. The next phase of the Critical Linkages project will focus on regional scale assessment of connectivity. Results from this next phase of analysis are likely to be more relevant for these highly vagile species.

## **ACKNOWLEDGEMENTS**

The Critical Linkages project is funded by The Nature Conservancy and the Federal Highway Administration via a grant administered by the Massachusetts Department of Transportation. Additional support for CAPS has been provided by the U.S. Environmental Protection Agency, Massachusetts Department of Environmental Protection, Massachusetts Office of Energy and Environmental Affairs, and the Trustees of Reservations – Highlands Community Initiative. The following people made significant contributions to the development of CAPS and the implementation of the Critical Linkages project: Kasey Rolih (UMass Amherst), Andrew Finton, Mark Anderson, Jessica Dyson, Alison Bowden and Laura Marx (TNC), Lisa Rhodes, Michael McHugh, Lealdon Langley, James Sprague and Michael Stroman (MassDEP), Jan Smith and Marc Carullo (Mass CZM) and James DeNormandie (Massachusetts Audubon Society).

## **REFERENCES CITED**

- Beier, P., D.R. Majka, and W.D. Spencer. 2008. Forks in the road: choices in procedures for designing wildland linkages. *Conservation Biology* 22(4): 836-851.
- Calabrese, J.M. and W.F. Fagan. 2004. A comparison-shopper's guide to connectivity metrics. *Frontiers in Ecology and Environment* 2(10): 529-536.
- Chetkiewicz, C.L.B., C.C. St. Clair, and M.S. Boyce. 2006. Corridors for conservation: integrating pattern and process. *Annual Review of Ecology, Evolution, and Systematics*. 37:317-342.
- Compton, B.W., K. McGarigal, S.A. Cushman, and L.R. Gamble. 2007. A resistant-kernel model of connectivity for amphibians that breed in vernal pools. *Conservation Biology* 21(3):788-799.
- Crooks, K.R., and M.A. Sanjayan, editors. 2006. *Connectivity Conservation*. Cambridge University Press, New York.
- Czucz, B., A. Csecserits, Z. Botta-Dukat, G. Kroel-Dulay, R. Szabo, F. Horvath, and Z. Molnar. 2011. An indicator framework for the climatic adaptive capacity of natural ecosystems. *Journal of Vegetation Science* 22:711-725.

- Elmqvist, T., C. Folke, M. Nystrom, G. Peterson, J. Bengtsson, B. Walker, and J. Norberg. 2003. Response diversity, ecosystem change, and resilience. *Frontiers in Ecology and the Environment* 9:488-494.
- Estrada, E. and O. Bodin. 2008. Using network centrality measures to manage landscape connectivity. *Ecological Applications* 18(7): 1810-1825.
- Fagan, W.F. and J.M. Calabrese. 2006. Quantifying connectivity: balancing metric performance with data requirements. In: Crooks, K.R. and M.A. Sanjayan (eds.). *Connectivity conservation: Maintaining connections for nature*. Cambridge University Press. Pgs. 297-317.
- Forman, R. T.T., D. Sperling, J. A. Bissonette, A. P. Clevenger, C. D. Cutshall, V. H. Dale, L. Fahrig, R. France, C. R. Goldman, K. Heanue, J. A. Jones, F. J. Swanson, T. Turrentine, & T. C. Winter. 2003. *Road Ecology; Science and Solutions*. Island Press, Covelo, California.
- Fuller, T., and S. Sarkar. 2006. LQGraph: A software package for optimizing connectivity in conservation planning. *Environmental Modelling & Software* 21(5): 750-755.
- Gibbs, J. P., and W. G. Shriver. 2002. Estimating the effects of road mortality on turtle populations. *Conservation Biology* 16:1647-1652.
- Hels, T., and E. Buchwald. 2001. The effect of road kills on amphibian populations. *Biological Conservation* 99:331-340.
- Hilty, J.A., W.Z. Lidicker, A.M. Merenlender. 2006. *Corridor ecology: The science and practice of linking landscapes for biodiversity conservation*. Island Press, Washington, DC.
- Kindlmann, P. and F. Burel. 2008. Connectivity measures: a review. *Landscape Ecology* 23:879-890.
- Merriam, G. 1984. Connectivity: A fundamental ecological characteristic of landscape pattern. In: Brandt, J. and Agger, P. (eds), *Proceedings First international seminar on methodology in landscape ecological research and planning. Theme I. International Association for Landscape Ecology*. Roskilde Univ., Roskilde, pp. 5-15.
- Ricketts T.H. 2001. The Matrix Matters: Effective Isolation in Fragmented Landscapes. *The American Naturalist* 158: 87-99.
- River and Stream Continuity Partnership, 2010. "Field Data Form: Road-Stream Crossing Inventory" and "Instruction Guide for Field Data Form: Road-Stream Crossing Inventory." May 27, 2010.
- Roberts, J.J., B.D. Best, D.C. Dunn, E.A. Treml, and P.N. Halpin. 2010. Marine Geospatial Ecology Tools: An integrated framework for ecological geoprocessing with ArcGIS, Python, R, MATLAB, and C++. *Environmental Modelling & Software* 25:1197-1207.



Saura, S., and L. Pascual-Hortal. 2007. A new habitat availability index to integrate connectivity in landscape conservation planning: comparison with existing indices and application to a case study. *Landscape and Urban Planning* 83: 91-103.

Taylor, P. D., L. Fahrig, K. Henein, and G. Merriam. 1993. Connectivity is a vital element of landscape structure. *Oikos* 68:571-573.

Theobald, D.M., J.B. Norman, and M.R. Sherburne. 2006. FunConn v1 User's Manual: ArcGIS tools for Functional Connectivity Modeling. Natural Resource Ecology Lab, Colorado State University. April 17, 2006. 47 pages. [www.nrel.colostate.edu/ftp/theobald](http://www.nrel.colostate.edu/ftp/theobald).

Theobald, D.M., K.R. Crooks, and J.B. Norman. (In Press). Assessing effects of land use on landscape connectivity: loss and fragmentation of western US forests. *Ecological Applications*.

With, K.A., R.H. Gardner, and M.G. Turner. 1997. Landscape connectivity and population distributions in heterogeneous environments. *Oikos* 78:151-169.

With, K.A. 1999. Is landscape connectivity necessary and sufficient for wildlife management? Pages 97-115 in J. A. Rochelle, L. A. Lehmann, and J. Wisniewski, (eds). *Forest fragmentation: wildlife and management implications*. Brill, The Netherlands.

## APPENDIX A: CRITICAL LINKAGES I RESULTS

**Data organization.** Critical Linkages results are available for download. This section lists the results and provides links. Data are available in grouped .zip files, listed below.

**Data formats.** All results from Critical Linkages are supplied as point shapefiles. In addition, geoTIFF raster versions of the roads results are available, as they're sometimes more convenient for viewing.

**Shapefiles.** All results are available as shapefiles. Shapefiles have the following fields:

*Crossings:*

crossingid	unique crossing id <sup>1</sup>
aqscore	aquatic crossing score

*Dams:*

damid	unique dam id
dam	name of dam
damheight	structural height of dam (m)
river	name of river

*Roads:*

linkgroup	group: forest, wetlands & aquatic, other, or all
-----------	--

*Fields common to all shapefiles:*

x-coord	easting, Massachusetts State Plane
y-coord	northing
base	sum of connectedness in vicinity in current condition
alt	sum of connectedness after upgrading crossing, removing dam, or installing wildlife crossing structure on road
delta	alt – base, the potential improvement in connectedness
<b>IEIdelta</b>	$IEI \times (alt - base)$ , the potential improvement in connectedness weighted by Index of Ecological Integrity

For most uses, IEIdelta is the field of interest. Higher values of IEIdelta indicate locations where a crossing upgrade, dam removal, or installation of a wildlife crossing structure will result in the greatest predicted improvement in ecological integrity.

**GeoTIFFs.** We've included raster versions of the IEIdelta values for roads results for forests, formatted as geoTIFFs. Values from the point shapefiles were converted to grids, and expanded with a focal maximum to make roads wider, and thus more visible. These grids have been scaled from 0 to 255, so the numeric values are not meaningful, except as a relative measure. These raster results are included because they display more quickly than the large point shapefiles in GIS software, and display more clearly at some scales. We did this only for forest results,

---

<sup>1</sup> This is not the same as the crossing code used in the River and Stream Continuity project.

because the results for wetlands & aquatic and for other were driven by a handful of points, resulting in grids with only a few visible cells. These results are best viewed as pointfiles.

**Included roads.** Because of the large number of road cells in Massachusetts (over 3 million 30 m cells) and the computational intensity of the Critical Linkages analysis, we've only run the roads analysis for a subset of road cells, representing 8% of road cells in Massachusetts. We excluded roads with traffic rates lower than 1000 cars/day on the assumption that wildlife passage structures would be unlikely to be targeted to smaller roads. We also excluded all road cells that had a mean IEI within a 1 km circle of  $\leq 0.25$ , because roads in highly urbanized areas with low surrounding IEI will get low scores from the Critical Linkages analysis.

The coordinate reference system for all data is Massachusetts mainland State Plane, NAD83.

## Basic results

<http://jamba.provost.ads.umass.edu/web/CL2011/basic.zip>

### shapefiles

Crossings	link_crossings.shp <a href="http://jamba.provost.ads.umass.edu/web/CL2011/crossings.zip">http://jamba.provost.ads.umass.edu/web/CL2011/crossings.zip</a>
Dams	link_dams.shp <a href="http://jamba.provost.ads.umass.edu/web/CL2011/dams.zip">http://jamba.provost.ads.umass.edu/web/CL2011/dams.zip</a>
Roads (forest)	link_roads_forest.shp <a href="http://jamba.provost.ads.umass.edu/web/CL2011/roads_forest.zip">http://jamba.provost.ads.umass.edu/web/CL2011/roads_forest.zip</a>
Roads (wetlands & aquatic)	link_roads_wetaq.shp <a href="http://jamba.provost.ads.umass.edu/web/CL2011/roads_wetaq.zip">http://jamba.provost.ads.umass.edu/web/CL2011/roads_wetaq.zip</a>

## Complete results

<http://jamba.provost.ads.umass.edu/web/CL2011/complete.zip>

---

### *Standard results*

---

### shapefiles

Crossings	<a href="http://jamba.provost.ads.umass.edu/web/CL2011/standard.zip">http://jamba.provost.ads.umass.edu/web/CL2011/standard.zip</a> link_crossings.shp
Dams	link_dams.shp
Roads (forest)	link_roads_forest.shp
Roads (wetlands & aquatic)	link_roads_wetaq.shp
Roads (other)	link_roads_other.shp
Roads (all)	link_roads_all.shp

### geoTIFF grid

Roads (forest)	<a href="http://jamba.provost.ads.umass.edu/web/CL2011/roadgrid.zip">http://jamba.provost.ads.umass.edu/web/CL2011/roadgrid.zip</a> roads_fo_g
----------------	---

---

---

**Best case results**

---

shapefiles<http://jamba.provost.ads.umass.edu/web/CL2011/bestcase.zip>

Crossings

link\_crossings\_bc.shp

Dams

link\_dams\_bc.shp

Roads (forest)

link\_roads\_bc\_forest.shp

Roads (wetlands &  
aquatic)

link\_roads\_bc\_wetaq.shp

Roads (other)

link\_roads\_bc\_other.shp

Roads (all)

link\_roads\_bc\_all.shp

geoTIFF grid<http://jamba.provost.ads.umass.edu/web/CL2011/roadgridbc.zip>

Roads (forest)

roads\_fobc\_g