Designing Sustainable Landscapes: Critical Local Linkages

A project of the University of Massachusetts Landscape Ecology Lab

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General description

Critical local linkages includes Designing Sustainable Landscapes (DSL) products that measure the relative potential to improve local aquatic connectivity through restoration, including dam removals and culvert upgrades. A complete description of the critical local linkage assessment is provided in the technical document on connectivity (McGarigal et al 2017. Here, we briefly describe the dam removal and culvert upgrade layers. These particular products were initially developed as part of Massachusetts Conservation and Prioritization System (Mass CAPS, umasscaps.org). We expanded the analysis to the Connecticut River watershed as part of the Connect the Connecticut project (connecttheconnecticut.org) — a collaborative partnership under the auspices of the North Atlantic Landscape Conservation Cooperative (NALCC), and subsequently developed it for the entire Northeast region as part of the Nature's Network project (naturesnetwork.org). This document describes both versions, and contains links to the two separate datasets.

Each dam or road-stream crossing is scored based on its potential to improve local connectivity through the corresponding restoration action, but only where it matters — in places where the current ecological integrity is not already seriously degraded.

With **culvert upgrades**, each road-stream crossing is scored based on its potential to improve local connectivity by upgrading a culvert to a bridge. The passability of road-stream crossings is based on estimates from surveys of culverts and bridges coordinated by the North Atlantic Aquatic Connectivity Collaborative (NAACC). We use the NAACC passability estimate for surveyed crossings, and a model based on surveyed crossings for those that have not been surveyed.

Our measure of local connectivity for culvert upgrades is based on the aquatic connectedness metric, as described in detail in the technical document on integrity (McGarigal et al 2017). Aquatic connectedness represents the estimated amount of ecological flow (e.g., movement of organisms) to the focal cell from neighboring aquatic cells (i.e., cells upstream and downstream of the focal cell) weighted by their *geographic* distance (upstream or downstream) and their *ecological* distance (based on differences in a suite of ecological settings variables) via the use of a resistant kernel (as described in the ecological integrity document). Underlying the aquatic connectedness metric is the assumption that ecological flow from similar ecological communities is more important to local connectivity (at least in the short term) than those from dissimilar communities. Aquatic barriers (i.e., dams and road-stream crossings) is one of several ecological settings variables that determines the *ecological* distance between the focal cell and neighboring cells, and it weighs heavily in determining aquatic connectedness. Aquatic barriers is a measure of the degree to which road-stream crossings (i.e. , culverts and bridges) and dams are estimated to act as impediments to ecological flows in aquatic systems. Thus, aquatic connectedness measures the degree of local aquatic connectivity for each focal cell as principally affected by nearby road-stream crossings and dams. The culvert upgrade metric measures the improvement in aquatic connectedness from upgrading a road-stream crossing from a culvert with its estimated degree of passability for aquatic organisms to a bridge with minimal impediment to ecological flows. The result is a shapefile with a point location for each estimated road-stream crossing and a suite of attributes about the crossing and an estimate of the effect of upgrading the crossing to a bridge based on the delta in aquatic connectedness (**Fig. 1**).

With **dam removals**, each dam is similarly scored based on its potential to improve local connectivity by removing the dam. Our measure of local connectivity for dam removals is again the aquatic connectedness metric, as described above. The dam removal metric measures the improvement in aquatic connectedness from removing a dam with its estimated degree of passability for aquatic organisms to a free-flowing river with no impediment to ecological flows. The result is a shapefile with a point location for each estimated dam and a suite of attributes about the dam and an estimate of the effect of removing the dam on the delta in aquatic connectedness (**Fig. 1**).

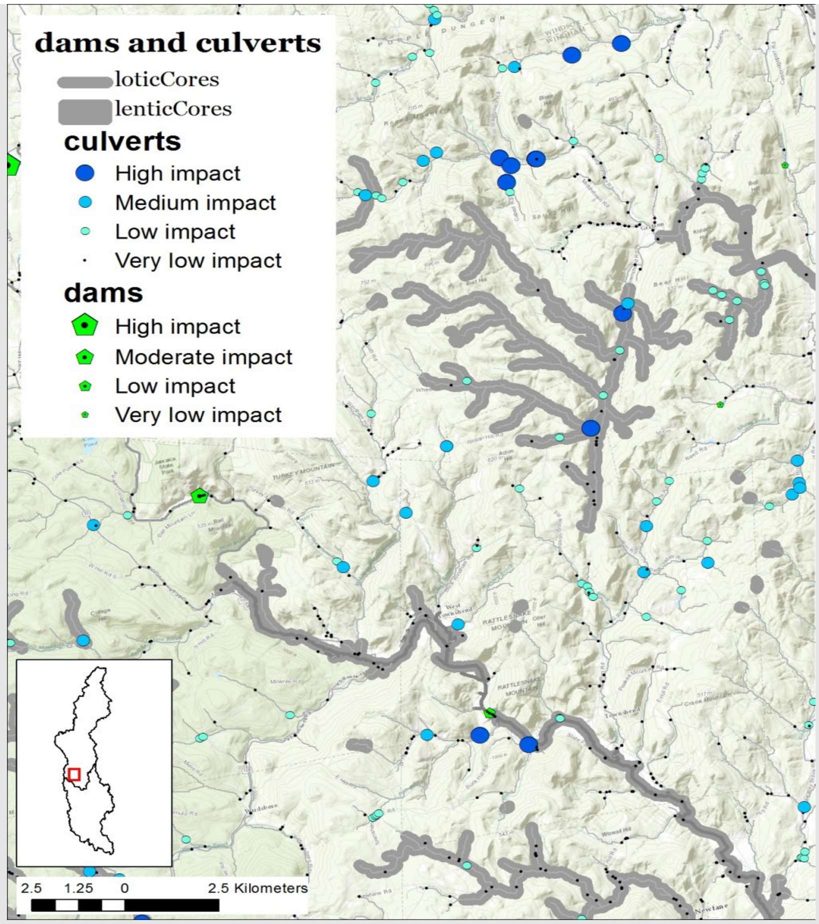

Figure 1. Dam removal and culvet upgrade effect scores in four tiers representing very low to high effects on aquatic connectivity overlaid on the stream network and potential aquatic core areas.

A special application of Critical Linkages focusing on **cold water streams** was developed and implemented as part of a project funded by a USFWS Hurricane Sandy Recovery and Mitigation grant. In this analysis cold water streams defined by various mean summer temperature thresholds (16°C, 18°C, 20°C and 22°C) were identified using The Nature Conservancy's stream temperature data (see Stream Temperature settings variable, McGarigal et al. 2017). For each temperature threshold, Critical Linkages was used to evaluate crossings and calculate the "effect" of crossing upgrades or replacements on aquatic connectivity for cold water streams. Effect is calculated as the change in aquatic connectedness for cold water stream reaches multiplied by the IEI values for those stream reaches. All crossings were included in the analyses because it is conceivable that a stream reach that does not meet the definition of cold water (based on chosen temperature thresholds) might still be important for linking together various cold water stream reaches, though crossings far from coldwater streams (where delta = 0) were dropped from the analysis.

Use and interpretation of these layers

As described above, culvert upgrades, coldwater culvert upgrades, and dam removals are three of the DSL measures of critical local linkages that can be used in the context of landscape design to inform where restoration actions might do the most good. Each layer provides an index of the potential improvement in local aquatic connectivity to be achieved in places where ecological integrity is not already completely degraded if the road-stream crossing structure (i.e., culvert) were to be replaced with a properly sized bridge or the dam were to be removed. However, it is important to be aware of the major sources of uncertainty in these layers, and thus their use should be guided by the following considerations:

- Aquatic barrier scores and the subsequent aquatic connectedness scores, and thus the culvert upgrade and dam removal scores, are derived from a model, and thus subject to the limitations of any model due to incomplete and imperfect data, and a limited understanding of the phenomenon being represented. In particular, the GIS data on road-stream crossings and dams are imperfect; they contain errors of both omission (e.g., missing real-world road-stream crossings and dams) and commission (e.g., derived road-stream crossings that don't exist in the real world). Moreover, the vast major of road-stream crossings have not been surveyed in the field, and their predicted aquatic barrier scores are based on an imperfect model derived from GIS data. Consequently, there will be many places where the Critical Linkages model gets it wrong, not necessarily because the model itself is wrong, but rather the input data are wrong. Thus, culvert upgrades and dam removals should be used and interpreted with a healthy degree of caution and an appreciation for the limits of the available data and models.

- Culvert upgrades and dam removals contain information only for point locations identified as road-stream crossings or dams in our spatial data layers. As such, data gaps and errors inherent in the source data are a major concern, including:

  Missing crossings. We model road-stream crossings at intersections of vector road and stream data. Crossings may be missing where roads are not mapped. This is fairly common for private roads and smaller unpaved roads (especially for Version 5 of the DSL data, which relies on Open Street Map, which does a poor job of representing unpaved roads). However, crossings that were assessed by NAACC will be included in Critical Linkages even on unmapped roads. Crossings may also be missing where streams are not mapped. This usually occurs for small headwater streams. To control for the variability in photo-interpretation of stream networks, we excluded streams with a watershed size < 30 ha, so crossings on some small mapped streams will be excluded.

  Spurious crossings. Road-stream crossings that don’t exist on the ground are most often the result of spatial errors where roads run immediately alongside streams, and the linework incorrectly make two or more spurious crossings. These are relatively rare, as current road and stream vector data are of fairly high spatial accuracy. Spurious crossings can also occur where discontinued roads that no longer have a culvert or bridge are mapped, or rarely where a non-existent road or stream are mapped.

Missing or spurious dams. Some dams (usually smaller ones) are missing from our dams data, and breached dams that no longer act as barriers may be mapped.

- There exist phantom road-stream crossings erroneously generated by the intersection of roads and streams data in GIS, and of course there exist omissions of road-stream crossings due to the incompleteness and/or inaccuracy of the roads and stream GIS layers. Similarly, there are both errors of omission and commission in the dams layer.
- Perhaps the biggest concern is the lack of information about aquatic passability for most road-stream crossings and dams. Aquatic passability is the most important component of the aquatic connectedness metric which forms the basis for estimating the effect of a culvert upgrade or dam on local connectivity. In particular, fewer than 2% of the road-stream crossings within the Northeast region (11,118/584,245) have been assessed in the field. We use this field-based assessment where it exists, but for the vast majority of road-stream crossings that have not been assessed in the field we are obligated to predict aquatic passability based on a statistical model using GIS data as the predictors. Not surprisingly, the performance of this model is not great. We incorrectly predicted a bridge to be a culvert ~45% of the time (omission error) and we incorrectly predicted a culvert to be a bridge ~6% of the time (commission error), with the latter errors being more problematic because we end up predicting a much greater passability score than possible for a culvert. Overall, the predictions of aquatic passability scores are extremely noisy (adjusted R^2=0.26). Thus, the actual restoration potential of a road-stream crossing may be quite different than the modeled estimate. Fortunately, there is a region-wide effort underway to expand the field-based assessments: North Atlantic Aquatic Connectivity Collaborative (NAACC). Updated results are incorporated each time we rerun the models and release results (typically every couple of years).
- It is important to recognize the relative nature of the culvert upgrade and dam removal scores which are derived from changes in aquatic connectedness scores, which are in turn derived in part from aquatic barrier scores. Aquatic barrier scores, and thus aquatic connectedness scores and, in turn, culvert upgrade and dam removal scores, are relative. An aquatic barrier value of 0 does mean that the structure (dam, bridge, or culvert) is predicted to have no effect on aquatic passability, and a value of 1 does mean that the structure is predicted to be a complete barrier to most aquatic organisms, particularly fish. However, intermediate values represent an index of the relative degree of obstruction to the movement of aquatic organisms, such that a 0.4 score is predicted to confer roughly twice the degree of impediment to movement than a 0.2 score. Because the score is a relative index, the values do not have a simple absolute interpretation. Moreover, because the score is an index to passability for all aquatic organisms, but emphasizing fish passage, it does not have an exact interpretation for any single species. Nevertheless, it may be useful to think of the aquatic barrier index as roughly translating into one or all of the following: 1) the proportion of aquatic species for which the structure acts as a complete barrier; 2) the proportional reduction in passability for any single species (i.e., proportion of individuals unable to successfully pass the structure); and 3) the proportion of time during which the structure acts as complete barrier to movement. Given the relative nature of the aquatic barrier score applied to each road-stream crossing and dam, by

extension then the aquatic connectedness values for cells in the neighborhood of each road-stream crossing are also relative, and finally, therefore, the effect of the culvert upgrade and dam removal (i.e., the delta in aquatic connectedness summed across all cells in the affected neighborhood of the road-stream crossing or dam) is also a relative index. Ultimately, it is best not to consider the culvert upgrade and dam removal effect score in any absolute sense, but instead consider it a relative index from which to compare among road-stream crossings and dams, respectively.

- Culvert upgrade and dam removal scores represent the potential gain in local aquatic connectivity from upgrading each road-stream crossing to a bridge with the minimum aquatic barrier score or removing each dam, but without consideration of other socio-economic factors, such as the cost of a particular upgrade given local engineering considerations, that ultimately will determine the cost-benefit tradeoffs of any particular culvert upgrade or dam removal.
- Culvert upgrade and dam removal scores represent the potential gain in local aquatic connectivity from upgrading each road-stream crossing to a bridge with the minimum aquatic barrier score or removing each dam, but without consideration of other potential nearby restoration actions to improve connectivity. Of course, road-stream crossings and dams often don't exist as isolated barriers. The restoration score of a road-stream crossing, for example, is dependent to some extent on the degree to which road-stream crossings and dams nearby on the same waterway are acting as barriers to movement. For example, upgrading a culvert will result in less improvement in connectivity if there is a dam or an undersized culvert a short distance from the crossing compared to that same crossing but with no other movement barriers nearby. The nearby dam or undersized culvert will continue to depress aquatic connectedness values even after the target culvert is upgraded. Unfortunately, evaluating the combined (and possibly synergistic) effect of multi-structure restoration scenarios, such as upgrading all nearby undersized culverts, is fraught with several computational challenges and thus we did not attempt it here. This remains an important item for future model improvement. An interactive tool that supports exploration of the combined effects of multiple restorations is available at https://ecosheds.org/aq-connectivity-tool/.

- While culvert upgrades and dam removals have a wide variety of potential uses, their primary utility is to aid in the prioritization of road-stream crossings for culvert upgrades and dams for removal. However, because of the considerations discussed above, it is probably best used at the watershed or regional scale for broad-scale strategic planning, e.g., identifying subbasins where significant improvements in local connectivity might be achieved through one or more culvert upgrades or dam removals, or prioritizing field surveys of road-stream crossings to improve aquatic barrier scores.

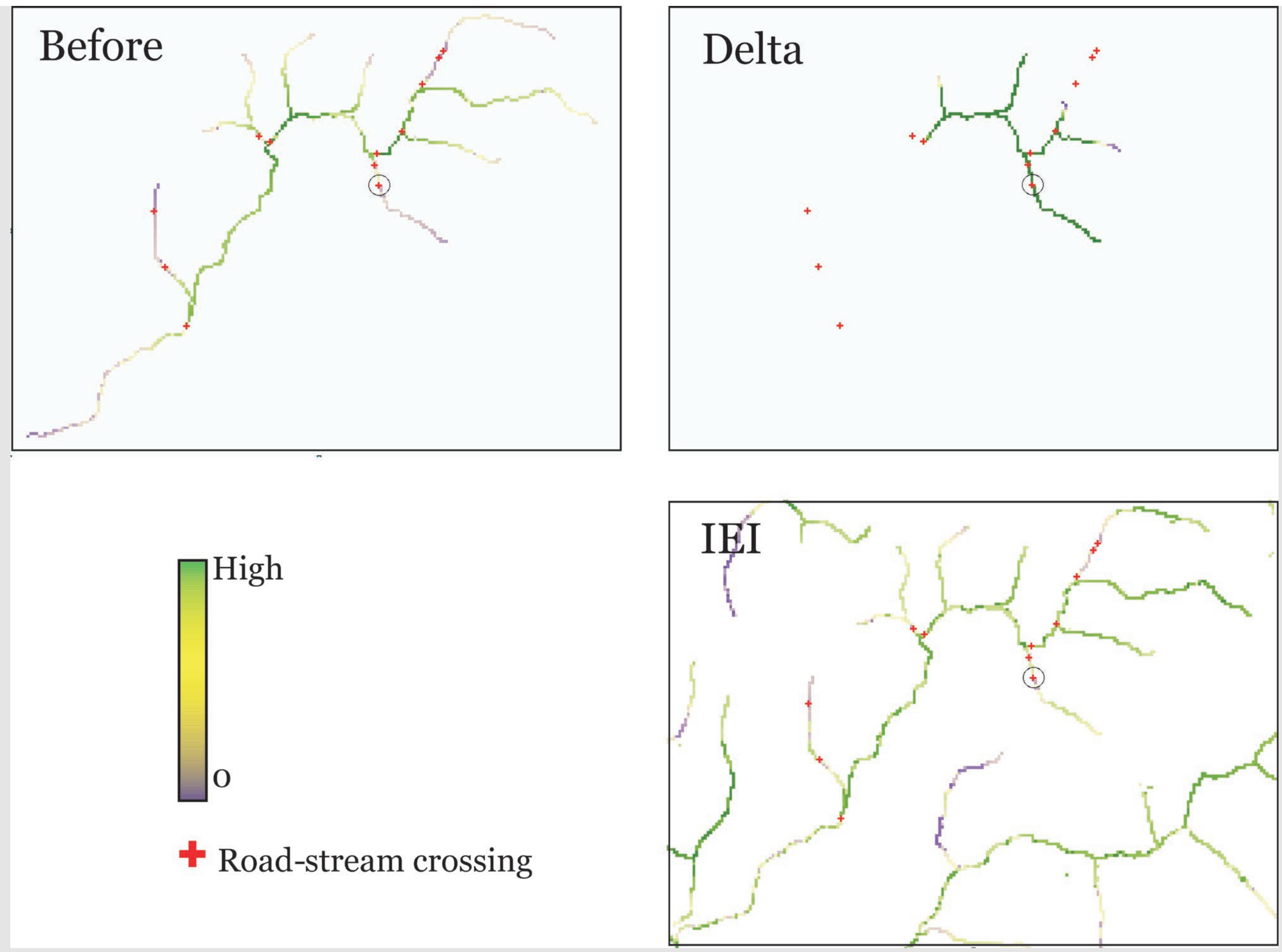

Figure 2. Illustration of the process to compute the critical local linkage culvert upgrade effect score for a random road-stream crossing. Upper left figure depicts aquatic connectedness before the virtual culvert upgrade; upper right figure depicts the delta in aquatic connectedness due to upgrading the culvert to bridge with maximum passability for aquatic organisms; lower right depicts the index of ecological integrity (IEI) for the aquatic systems in the affected neighborhood of the focal road-stream crossing (circled '+'). The effect score for the culvert upgrade is computed as delta x IEI summed across the affected area.

Derivation of these layers

For culvert upgrades and dam removals, we systematically upgraded each culvert to a bridge having the minimal aquatic barrier score or a removed each dam, one at a time, and compared the change in aquatic connectedness resulting from the culvert replacement or dam removal. Each road-stream crossing and dam has an aquatic barrier score based either on an algorithm applied to field measurements of the crossing structure or dam, or predictions from a statistical model based on GIS data (see aquatic barriers document, McGarigal et al 2017). Specifically, we computed the road-stream crossing and dam removal restoration effect scores as follows (**Fig. 2**):

1. first, for each road-stream crossing or dam, we computed the baseline aquatic connectedness metric with the existing road-stream crossing structure or dam in place for every cell within the affected neighborhood of the crossing or dam (i.e., any cell whose aquatic connectedness value is influenced by the crossing or dam);
2. next, we replaced the road-stream crossing structure (virtually) with a bridge having the minimum Aquatic Barrier score (0) or removed the dam and recomputed the aquatic connectedness metric for each cell within the affected neighborhood;
3. next, we computed the delta, or difference, in aquatic connectedness score before and after the culvert upgrade or dam removal for each cell within the affected neighborhood;
4. next, we multiplied the delta value by the baseline Index of Ecological Integrity (*IEI*) value for each cell (sans aquatic connectedness; see below) within the affected neighborhood (see technical document on ecological integrity, McGarigal et al 2017, for a detailed description of IEI); and
5. lastly, we summed the values across all affected cells and let this be the restoration effect score for the road-stream crossing or dam. Note, restoration effect score is given by the attributed named "effect" in the shapefiles, as described below.

Thus, the restoration effect score is an index of the potential improvement in local aquatic connectedness to be achieved in places where it matters most (where the current ecological integrity is not already severely degraded) if the crossing structure were replaced with a properly sized bridge or the dam were removed. Based on these restoration scores, road-stream crossing structures and dams can be ranked and prioritized for restoration (**Fig. 1**).

Note that as of 2021, effect uses a version of IEI that omits aquatic connectedness in order to avoid depressing scores for crossings that have low aquatic connectedness due to stream crossings. Our previous approach, which used full IEI, led to masking the restoration potential of some crossings.

GIS metadata

Critical linkages results are available in the following shapefiles:

DSL Northeast region

Road-stream crossings:

https://landeco.umass.edu/web/lcc/dsl/design/DSL_data_cl_crossings.zip

Coldwater road-stream crossings:

https://landeco.umass.edu/web/lcc/dsl/design/DSL_data_cl_coldwater.zip

Dams:

https://landeco.umass.edu/web/lcc/dsl/design/DSL_data_cl_dams.zip

Massachusetts CAPS

Road-stream crossings:

https://landeco.umass.edu/web/masscaps/cl_crossings.zip

Coldwater road-stream crossings (contains 4 shapefiles, one for each temperature threshold of 16 C, 18 C, 20 C, and 22 C):

https://landeco.umass.edu/web/masscaps/cl_coldwater.zip

Dams:

https://landeco.umass.edu/web/masscaps/cl_dams.zip

Culvert upgrades shapefile — Point shapefile including the attributes listed below for each road-stream crossing. The most commonly-used fields are in **boldface**.

Field	Description
FID, shape	Fields used internally by GIS software.
id	A unique numeric crossing ID.
crosscode	For surveyed crossings (and some unsurveyed crossings), the crossing code used in the NAACC database.
survey_id	The unique ID of the NAACC survey (for surveyed crossings only).
x_coord, y_coord	The coordinates of the crossing after it has been moved to an appropriate raster cell.
moved	1 = the crossing did not need to be moved.

Field	**Description**
	2 = the crossing was moved from the original to an adjacent cell to ensure it falls on a road-stream crossing in our data.
oldx, oldy	The original vector based coordinates of the crossing.
surveyed	1 if the aquatic crossing score is based on a survey, 0 if it's modeled.
database	The source database for surveyed road-stream crossings.
group	Group ID for grouped crossings (multiple nearby crossings when a stream crosses a divided highway).
groupsize	Number of crossing in group.
bridge	0 = non-bridge 1 = bridge This is from NAACC surveys for surveyed crossings; otherwise it is modeled.
bridgeprob	The modeled probability that the crossing is a bridge.
bsurveyed	1 if the bridge status is based on a survey, 0 if not.
no_cross	For surveyed crossings this is 1 if the location is not actually a crossing even though it was predicted to be one by intersection of roads and streams GIS data.
aquatic	The aquatic passability score (modeled or directly from NAACC surveys), ranging from 0 to 1 with higher values being more passable.
aquaLCI, aquaUCI	The lower and upper confidence interval on the aquatic score.
base	The sum of aquatic connectedness in the neighborhood of the focal road-stream crossing for the current condition (i.e., before culvert upgrade).
alt	The sum of aquatic connectedness in the neighborhood of the focal road-stream crossing for the altered condition (i.e., after culvert upgrade).
delta	The difference between the altered and base aquatic connectedness, multiplied by 1000 to make the numbers more tractable. This represents **the potential improvement in aquatic connectedness from upgrading the crossing.**

Field	Description
effect	The restoration potential index, defined as IEI × delta, representing the potential improvement in local aquatic connectedness weighted by IEI (Index of Ecological Integrity). Note that as of 2021, effect uses a version of IEI that omits aquatic connectedness in order to avoid depressing scores for crossings that have low aquatic connectedness due to stream crossings.
effectln	The logarithm of effect, for display on maps.
loss	Log-transformed delta, rescaled from 0-1.
restore	Log-transformed effect, rescaled from 0-1.
rank	Rank of effect. Lower numbers indicate higher restoration potential.
percentile	Percentile of effect.
ADT	The estimated average daily traffic rate over the crossing structure.
roadclass	The road or train class associated with the crossing.

Dam removals shapefile — Point shapefile including the attributes listed below for each dam.

Field	Description
FID, shape	Fields used internally by GIS software.
dsl_id	A unique ID for each dam, based on neac_id. When duplicate dam points were added to cover multiple flowlines existing an impoundment, a letter was appended, e.g., "MA_MA00068_a."
x_coord, y_coord	The coordinates of the dam after it has been moved to an appropriate raster cell.
height	The Structural height of dam (m), from the NEAC "height" field. Missing values and zeros were replaced with 5.5 m, the mean dam height in the Northeast.
base	The sum of aquatic connectedness in the neighborhood of the focal dam for the current condition (i.e., before dam removal).

Field	Description
alt	The sum of aquatic connectedness in the neighborhood of the focal dam for the altered condition (i.e., dam removal).
delta	The difference between the altered and base aquatic connectedness, multiplied by 1000 to make the numbers more tractable. This represents **the potential improvement in aquatic connectedness from removing the dam.**
effect	The restoration potential index, defined as IEI × delta, representing the potential improvement in local aquatic connectedness weighted by IEI (Index of Ecological Integrity).
effectln	The logarithm of effect, for display on maps.
loss	Log-transformed delta, rescaled from 0-1.
restore	Log-transformed effect, rescaled from 0-1.
rank	Rank of effect. Lower numbers indicate higher restoration potential.
percentile	Percentile of effect.

Literature Cited

McGarigal K, Compton BW, Plunkett EB, DeLuca WV, and Grand J. 2017. Designing sustainable landscapes products, including technical documentation and data products. https://umassdsl.org/