Designing Sustainable Landscapes:
Aquatic Barriers settings variable

A project of the University of Massachusetts Landscape Ecology Lab

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Reference:

McGarigal K, Compton BW, Plunkett EB, DeLuca WV, and Grand J. 2017. Designing sustainable landscapes: aquatic barriers settings variable. Report to the North Atlantic Conservation Cooperative, US Fish and Wildlife Service, Northeast Region.

General description

Aquatic barriers is one of several ecological settings variables that collectively characterize the biophysical setting of each 30 m cell at a given point in time (McGarigal et al 2017). Aquatic barriers measures the relative degree to which road-stream crossings (i.e., bridges and culverts) and dams may physically impede upstream and downstream movement of aquatic organisms, particularly fish. It is derived from a custom algorithm (see below for details) applied to dams and derived road-stream crossings. Briefly, each dam has an aquatic barrier score based either on dam height or attributes indicating whether the dam has a partial/complete breach. Similarly, each road-stream crossing has an aquatic barrier score based either on an algorithm applied to field measurements of the crossing structure or predictions from a statistical model based on GIS data. Aquatic barriers is scaled 0-1, where dams and road-stream crossing are assigned values >0 (with 1=complete barrier) and all other cells (including terrestrial) are assigned 0 (**Fig. 1**).

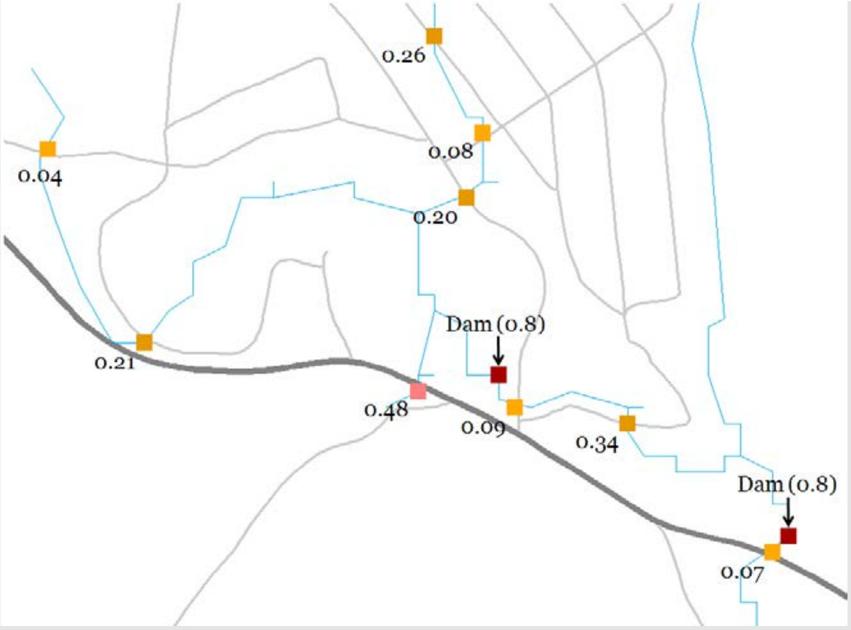

Figure 1. Aquatic barrier scores for dams and road-stream crossing with vector roads (gray scale) and streams (blue) in the background.

Use and interpretation of this layer

Aquatic barriers is used in the derivation of the aquatic connectedness metric in the context of the broader assessment of ecological integrity (see the technical document on integrity, McGarigal et al 2017). It is a measure of the degree to which a dam or road-stream crossing is predicted to be an impediment to movement of aquatic organisms, and its use should be guided by the following considerations:

- Aquatic barriers is formatted as a raster GIS data layer designed for use in the DSL Landscape Change, Assessment and Design (LCAD) model. It contains non-zero values only for cells classified as either dams or road-stream crossings; all other cells are assigned a value of 0. As such, it is a difficult layer to view since the eye is naturally drawn to the dominant matrix of zeros. For easier viewing and general purpose use, we also distribute two separate point shapefiles in vector format (dam removal impacts and culvert upgrade impacts) that contain the aquatic barrier scores along with many other statistics associated with the restoration potential of the structure, as described with those layers.

- It is important to recognize the relative nature of the aquatic barrier scores. A score of 0 means that the structure (dam, bridge, or culvert) is predicted to have no effect on aquatic passability, and a score of 1 means 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 absolute value does not have a simple interpretation. Moreover, because the score is an index to passability for all aquatic organisms, but emphasizing fish passage, it does not have an specific interpretation for any single species. Increasing barrier scores should indicate fewer species that can pass, and, in general, fewer individuals of a particular species that can pass. However, because aquatic organisms vary widely in their vagility and their abilities to pass different types of barriers and data as to the exact nature of each barrier are unavailable, interpretation must be general.

- It is important to acknowledge that the aquatic barrier 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 dams and road-stream crossings are imperfect; they contain errors of both omission (e.g., missing dams) and commission (e.g., derived road-stream crossings that don't exist in the real world). Consequently, there will be many places where the model gets it wrong, not necessarily because the model itself is wrong, but rather because the input data are wrong. In addition, the scores themselves are derived from a model based on expert opinion of the factors affecting passability for aquatic organisms, and while the model incorporates many of the factors known or believed to affect passability, it is almost certainly an incomplete and imperfect representation of the real-world factors affecting passability. This model has not been extensively tested against empirical studies of passability in the field. Moreover, the vast majority of road-stream crossings (>98%) have not been surveyed in the field, and their predicted aquatic barrier scores are based on an even simpler and less perfect model derived from GIS data (as so many of the determinants of culvert and bridge passability are ideosyncratic, and unrepresented by GIS data). Thus, aquatic barriers should be used and interpreted with caution and an appreciation for the limits of the available data and models.

- While aquatic barriers has a wide variety of potential uses, perhaps its most significant application is to aid in the assessment of aquatic connectivity, for example via incorporation into the DSL aquatic connectedness metric and the assessment of aquatic ecological integrity and critical linkages (i.e., prioritization of dams for removal and road-stream crossings for culvert upgrades). Outside of these DSL applications, aquatic barriers could be used on its own to help direct conservation actions to restore aquatic connectivity.

Derivation of this layer

Aquatic barrier scores were assigned separately for dams, surveyed road-stream crossings and unsurveyed road-stream crossings, as follows:

1. Aquatic barrier scores for dams

Aquatic barrier scores for dams were based either on dam height (**Fig. 2**) or an attribute of the source data obtained from The Nature Conservancy (TNC) indicating whether the dam has a partial/complete breach, as given by the following algorithm:

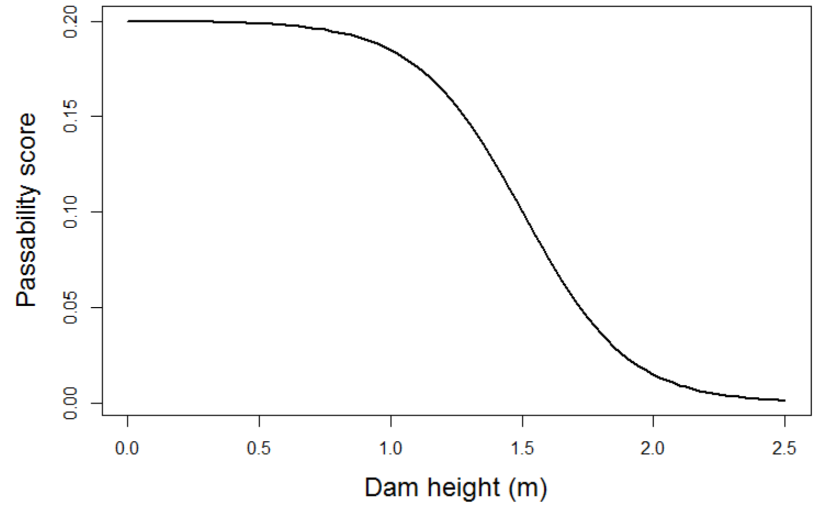

Figure 2. Logistic function for transforming dam height (m) into a passability score scaled 0-1 for inclusion in the calculation of aquatic barrier scores.

If dam = TNC DEG_BARR score 1, 3, 5, or 7,

then Passability ← corresponding score (0, 0.6, 0.9, 0.3) (see **Table 1**);

else, Passability ← 0.2 × LOGISTIC (height, inflection=1.5, scale=-0.2), where:

$$LOGISTIC = \frac{1}{1 + exp\left(\frac{-(height - inflection)}{scale}\right)}$$

and height is in meters.

Barrier score ← 1 - Passability.

Thus, if a dam was classified as a complete barrier, partial/complete breach or lock it was assigned the corresponding value from **Table 1**; otherwise, it was assigned a value based on a logistic function of its height, such that the barrier score ranged from 0.8 (a dam with low height) to 1 (a dam with a height >2.5 m).

2. Aquatic barrier scores for road-stream crossings

We derived road-stream crossings in the landscape based on the intersection of the cleaned and trimmed vector National Hydrology Dataset (NHD) streams and Open Street Map (OSM) roads and railroads. Each of these point crossings was then moved to the nearest crossing pixel in the raster representation of the streams and roads for representation in the aquatic barriers layer. However, we retained both the original (vector) and moved (cell)

Table 1. Assignment of aquatic barrier scores to classified dams.

TNC DEG_BARR Score	Description	Aquatic Passability Score	Comment on Passability Score	Aquatic Barrier score
1	Complete barrier to all fish (>3.65 m/>12 ft)	0		1
2	Small dam barrier (0.3-3.65 m/1-12 ft)	HEIGHT		(see **Fig. 2**)
3	Partial breach	0.6		0.4
4	Barrier with fish ladder	HEIGHT	Previously set to 0.3, but revised due to FWS request, as fish ladders are poorly represented in the data and many are known to be ineffective	(see **Fig. 2**)
5	Unlikely barrier - fully breached, weir, under 0.3 m/1 ft dam	0.9	Assumed to be comparable to a culvert with a 1-foot outlet drop	0.1
6	Unknown, assumed full barriers	HEIGHT	If HEIGHT is 0 (unavailable), dam gets maximum passability score of 1	(see **Fig. 2**)
7	Locks	0.3	We assume that locks are passable for certain periods of time as they are allowing boat passage but are comparable to a small dam barrier at other times. We feel least confident about this one.	0.7

locations for subsequent use (see below). We assigned an aquatic barrier score to each crossing in the raster representation, but the derivation of the score depended on whether the crossing was surveyed in the field or not, as follows.

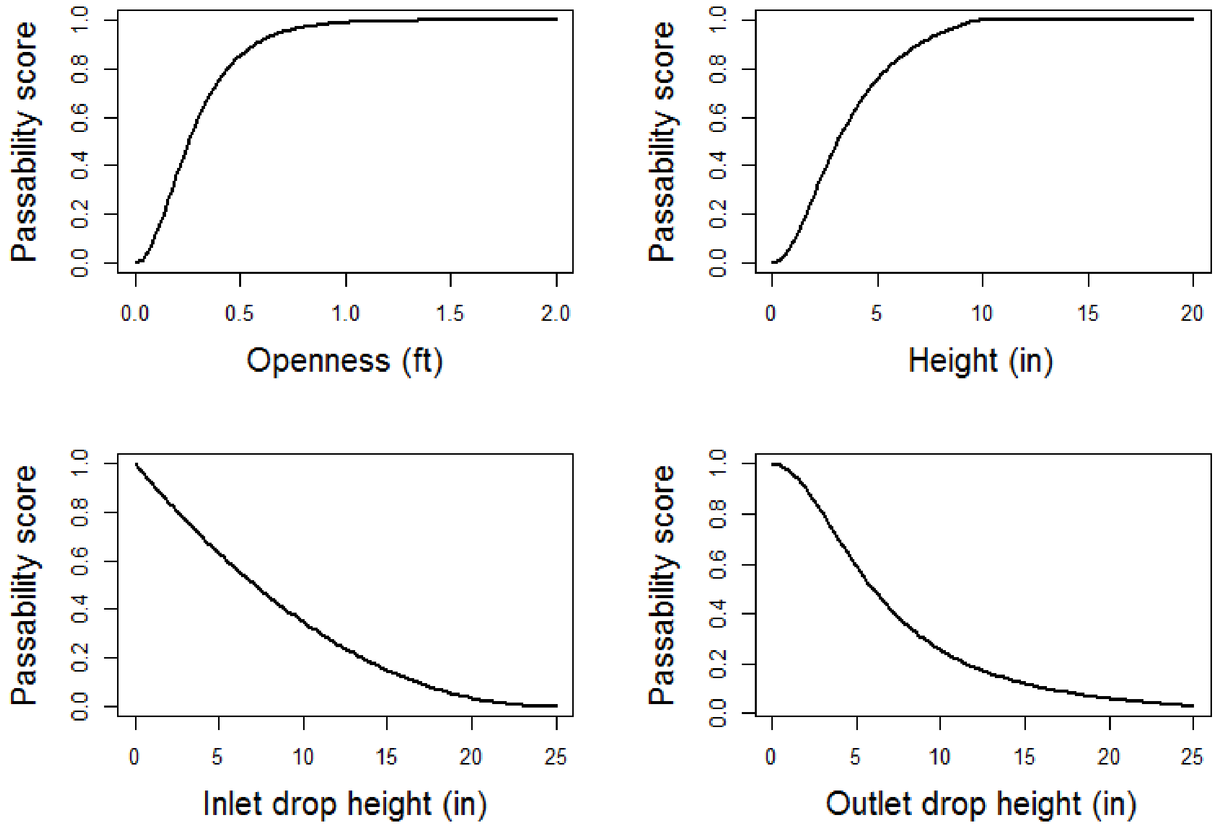

Figure 3. Functions for transforming the continuous predictor variables (openness, height, inlet.drop, and outlet.drop) into passability scores scaled 0-1 for inclusion in the calculation of aquatic barrier scores.

2.1 *Surveyed road-stream crossings*

To assign aquatic barrier scores for surveyed road-stream crossings we used an assessment protocol and scoring system developed by the North Atlantic Aquatic Connectivity Collaborative (NAACC) and its predecessor, the Stream Continuity Project. 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 Collaborative also created an algorithm for scoring crossing structures according to the degree of obstruction they pose to aquatic organisms (i.e., passability) based on field-measured variables. The scoring algorithm is currently being revised by the Collaborative. The current aquatic barriers layer is based on the algorithm developed in 2010. We used scores based on the November 10, 2015 scoring algorithm for a set of 12,133 crossings after considerable filtering of the original crossings database (see **Appendix**) to ensure correspondence with our derived road-stream crossings.

The 2010 scoring algorithm was based on the opinions of experts who decided both the relative importance of all the available predictors of passability as well as a way to score each predictor. Scoring involved two steps: 1) generating a component passability score for each predictor variable, and 2) combining these predictions with a weighted average to generate the final aquatic barrier score for the crossing.

1. *Scoring individual predictors*

   Scoring categorical predictors was simply a matter of assigning a passability score for each possible category. **Table 2** lists all of the categorical predictors and the scores associated with each category. See NAACC for definitions of these predictors.

   Scoring continuous predictors required a function to convert the predictor to a passability score. There were four continuous predictors and four associated functions (**Fig. 3**). The forms of these functions used were chosen because they had shapes desired by the expert team or because they fit the series of points depicting the relationship specified by the expert team.

   (1) The scoring equation for openness was given by the von Bertalanffy function, as follows:

$$s_o = a(1 - e^{-kx(1-d)})^{1/(1-d)}$$

   where S_o is the passability score for openness, a=1, k=15, d = 0.62, and x is the value for openness of the crossing structure measured in the field. Openness was computed as the cross-sectional area of the inlet or outlet (ft^2), whichever was smaller, divided by crossing length (ft).

   (2) The scoring equation for height was given by the Holling Type II function, as follows:

$$s_h = \frac{ax^2}{b^2 + x^2}$$

   where S_h is the passability score for height, a = 1.13, b=3.5, x is the value of height (ft) of the crossing structure measured in the field, and S_h was truncated at 1.

   (3) The equation for inlet drop was given by the quadratic function, as follows:

$$s_{id} = a + bx + cx^2$$

   where S_{id} is the passability score for inlet drop, a= 1, b= -0.08198, c=0.00168, x is the value of inlet drop (ft) measured in the field, and S_{id} was set to 0 for any inlet drop >2 ft.

   (4) The equation for outlet drop was given by the Holling Type II function, as follows:

Table 2. Component passability scores for the levels of each categorical predictor used in calculating the crossing score.

Component	Category	Score
crossing.embedment	not embedded	0
crossing.embedment	partially embedded	0.5
crossing.embedment	fully embedded	0.9
crossing.embedment	no bottom	1
crossing.span	severe	0
crossing.span	mild	0.5
crossing.span	spans bank to bank	0.9
crossing.span	spans channel and banks	1
crossing.substrate	none and smooth bottom	0
crossing.substrate	inappropriate, roughened, or corrugated	0.25
crossing.substrate	contrasting	0.75
crossing.substrate	comparable	1
crossing.substrate	none	0.875
physical.barriers	none	1
physical.barriers	minor	0.9
physical.barriers	moderate	0.8
physical.barriers	severe	0
physical.barriers	temporary	1
physical.barriers	permanent	0.5
scour.pool	large	0
scour.pool	small	1
scour.pool	none	1
tailwater.armoring	extensive	0
tailwater.armoring	not extensive	0.5
tailwater.armoring	none	1
water.depth	No (significantly deeper)	0.5
water.depth	No (significantly shallower)	0

Component	Category	Score
water.depth	Yes (comparable)	1
water.depth	DRY	0.75
water.velocity	No (significantly faster)	0
water.velocity	No (significantly slower)	0.5
water.velocity	Yes (comparable)	1
water.velocity	DRY	0.75

$$s_{od} = 1 - \frac{ax^2}{b^2 + x^2}$$

where S_{od} is the passability score for outlet drop, a=1.029412, b=6.173949, x is the value of outlet drop (ft) measured in the field, and S_{od} was set to 0 for any outlet drop >3 ft.

2. *Combining component scores into the overall barrier score*

   The individual component scores from step 1 above were combined with a weighted average to generate the overall passability score for the observed crossing. The weights assigned to each component are listed in **Table 3**. The overall passability score was the sum of the products of each component score and its weight (which is equivalent to the weighted average), and the aquatic barrier score was given as the complement of the overall passability score, as follows:

$$Barrier\ score = 1 - \sum (c_i * w_i)$$

2.2 Unsurveyed road-stream crossings

To assign aquatic barrier scores for those crossings that had not been assessed in the field (i.e., unsurveyed crossings), we used GIS data and crossing scores from the filtered set of 12,133 crossings (see **Appendix**) to create a statistical model to predict aquatic barrier scores, as follows.

1. We assembled a suite of predictors to be used in the model either by sampling grids at the cell location of the crossing or by analysis of a window centered on the crossing (**Table 4**). For the scale-dependent variables, we calculated their values in square windows with sides of 90, 150, 210, 270, 330, 390, 450, 510, 570, and 630 meters.
2. We then performed additive stepwise variable selection with a Random Forest model to find the set of variables that resulted in a Random Forest with the highest R-squared between the field survey-based aquatic passability score and the out-of-bag prediction from the model. Note, Random Forest is a non-parametric method that is effective at optimizing reliable predictions.

Table 3. Weights associated with each parameter in the aquatic passability scoring algorithm.

Component (c_i)	**Weight (w_i)**	**Component (c_i)**	**Weight (w_i)**
outlet.drop	0.149	crossing.substrate	0.084
physical.barriers	0.107	crossing.embedment	0.083
water.velocity	0.104	openness	0.061
water.depth	0.098	scour.pool	0.058
inlet.drop	0.093	tailwater.armoring	0.041
crossing.span	0.089	height	0.033

3. We fit similar models from the same suite of variables to estimate whether the crossing was a bridge or not.
4. Note, for the Connecticut River watershed Landscape Conservation Design pilot (CTR LCD) we used the predicted bridge status of the crossing to assign the mean terrestrial passability score of crossings with the same status from the surveyed crossings to the unsurveyed crossings. Thus, all unsurveyed crossings predicted to be bridges were assigned the mean passability of the surveyed bridges, and all unsurveyed crossings predicted not to be bridges (including, e.g., culverts, fords, open-bottom arches) were assigned the mean passability of the surveyed crossing there were not bridges.

   However, for the Northeast regional product that we are distributing, the terrestrial barrier scores reflect the predicted passability scores from the Random Forest model. Note, in the culvert upgrade impacts shapefile we include both the modeled score and the mean score, for those that prefer to use the latter, along with many other statistics associated with the restoration potential of the structure, as described for that layer.
5. Lastly, the aquatic barrier score for unsurveyed road-stream crossings was given as the complement of the aquatic passability score (i.e., 1 - passability).

GIS metadata

This data product is distributed as a geotiff raster (30 m cells). The cell value = aquatic barrier score and ranges from 0 (all cells not mapped as either a dam or road-stream crossing) to 1 (maximum barrier score; i.e., likely to be a complete barrier to most aquatic organisms, particularly fish). This data product can be obtained at McGarigal et al (2017).

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://scholarworks.umass.edu/designing_sustainable_landscapes/

Table 4. Variables used to predict whether a road-stream crossing was a bridge or culvert and the aquatic passability score for the structure.

Variable	**Description**
d8accum	Number of cells that flow into the crossing.
gradient	Stream gradient at crossing.
elevation.range.[scale]	The range of elevation observed in a window of [scale] dimension (in meters).
incisement.[scale]	Within a window of [scale] meters centered on the crossing cell, the difference between the mean elevation of the water cells and the mean elevation of all other cells.
elevation.sd	The standard deviation in elevation within a window of [scale] dimension centered on the crossing.

Appendix

The following is a detailed description of the process for filtering the crossing records in the source database obtained from NAACC in order to include only those records and unique surveys that we could reliably associate with one of our derived road-stream crossings.

We began with source data from NAACC (https://www.streamcontinuity.org/cdb2) contained in two databases, one with older data migrated from the original UMass Stream Continuity Project and one with newer data in a revised format settled on by NAACC. The crossings in these two databases were scored based on the algorithm dated November 10, 2015 (https://streamcontinuity.org/pdf_files/Aquatic_Passability_Scoring.pdf). Filtered records were exported from both databases, then cleaned, converted into a standard format, merged, and filtered further, as follows:

Database 1 export (from Stream Continuity Project):

1. We started with 12,578 records for 11,104 unique surveys at 10,234 unique crossings.
2. We dropped 1,474 duplicated records (probably due to the crossing having multiple structures each with its own line in the data export), leaving 11,104 records for 11,104 unique surveys at 10,234 unique crossings.
3. We dropped 14 records that were on a list of "bad" records provided by Scott Jackson, leaving 11,090 records for 11,090 unique surveys at 10,228 unique crossings.
4. We dropped 315 records where the GPS location was greater than 200 meters from the crossing location (GPS is a field measure), leaving 10,775 records for 10,775 unique surveys at 9,959 unique crossings.

5. We dropped 909 records with missing location data, leaving 9,866 records for 9,866 unique surveys at 9,057 unique crossings.
6. We dropped 109 records where either the aquatic or terrestrial crossing scores (described in DSL_documentation_tbarriers.pdf) were NA (usually it was both), leaving 9,757 records of 9,757 unique surveys at 8,114 unique crossings.
7. We dropped 805 records with duplicate crossing codes (repeat surveys of the same crossing), keeping the most recent survey, leaving 8,952 records of 8,952 unique surveys at 8,952 unique crossings.

Database 2 export (from NAACC):

1. We started with 9,799 records for 8,264 unique surveys at 8,216 unique crossings.
2. We dropped 1,535 duplicated records (probably due to the crossing having multiple structures each with its own line in the data export), leaving 8,264 records for 8,264 unique surveys at 8,216 unique crossings.
3. We dropped 38 records where the GPS location was greater than 200 meters from the crossing location (GPS is a field measure), leaving 8,226 records for 8,226 unique surveys at 8,180 unique crossings.
4. We dropped 1,074 records where either the aquatic or terrestrial crossing scores (described in DSL_documentation_tbarriers.pdf) were NA (usually it was both), leaving 7,152 records of 7,152 unique surveys at 7,118 unique crossings.
5. We dropped 34 records with duplicate crossing codes (repeat surveys of the same crossing), keeping the most recent survey, leaving 7,118 records of 7,118 unique surveys at 7,118 unique crossings.

Merge of two databases:

1. We dropped 210 records from dataset 1 that had crossing codes identical to those in dataset 2, and merged the two datasets, resulting in 15,860 records for 15,860 unique surveys at 15,860 unique crossings.
2. We dropped 861 crossings that were greater than 30 m from our derived road-stream crossing locations, leaving 14,999 crossings. These threshold distances were decided based on visual inspection of histograms of the distance to the nearest-neighbor match.
3. We dropped 2,340 crossings that were matched to the same road-stream crossing as another, closer survey (probably due to the two databases having records for the same crossing, but with different crossing codes), leaving 12,659 unique crossings.
4. We dropped 526 crossings that the field survey indicated were not actual crossings, leaving 12,133 unique crossings for fitting the Random Forest models.