This information product has been peer reviewed and approved for publication as a preprint by the U.S. Geological Survey.

An automatable method for developing preliminary stream crossing designs using lidar and hydraulic modeling in Massachusetts

Meghan McCallister[1], Luke Sturtevant[2], Brendan McCarthy[3], and Ian Armstrong[4]

[1]U.S. Geological Survey, New England Water Science Center, Northborough, MA, USA

mmccallister@usgs.gov

[2]U.S Geological Survey, New England Water Science Center, Augusta, ME, USA

lsturtevant@usgs.gov

[3]U.S Geological Survey, New England Water Science Center, Oswego, NY, USA

bmccarthy@usgs.gov

[4]U.S Geological Survey, New England Water Science Center, Waterbury, VT, USA

iarmstrong@usgs.gov

This preprint has been submitted to EarthArXiv. It was submitted to River Research and Applications and has not received peer review.

This information product has been peer reviewed and approved for publication as a preprint by the U.S. Geological Survey.

An automatable method for developing preliminary stream crossing designs using lidar and hydraulic modeling in Massachusetts

Meghan McCallister[1], Luke Sturtevant[2], Brendan McCarthy[3], and Ian Armstrong[4]

[1]U.S. Geological Survey, New England Water Science Center, Northborough, MA, USA

[2]U.S Geological Survey, New England Water Science Center, Augusta, ME, USA

[3]U.S Geological Survey, New England Water Science Center, Oswego, NY, USA

[4]U.S Geological Survey, New England Water Science Center, Waterbury, VT, USA

Corresponding author: Meghan McCallister, mmccallister@usgs.gov

Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Acknowledgements

Funding for this work was provided by the Massachusetts Department of Environmental Protection (MassDEP). The authors thank MassDEP, especially Lisa Rhodes, Christina Wu, Thomas Maguire, Rebecca Davis, and David Hilgeman (former employee) for their support of this study. The authors also thank Scott Jackson of University of Massachusetts Amherst for his contributions to the North Atlantic Aquatic

Connectivity Collaborative and analyses of aquatic habitat quality and stream restoration connectivity potential of stream crossings.

The authors appreciate the U.S. Geological Survey personnel who have contributed to the study: Alexander Graziano, Mark Poe, Amanda Tudor, Carl Carlson (former employee), Gardner Bent, Brian Nelson, Ryan White, Peter McCarthy, Andrea Medenblik, Harper Beckers, Hans Vraga, and Blake Draper.

Abstract

Upgrading aging and undersized stream crossings (places where culverts and bridges intersect a stream) with replacements designed for aquatic organism passage can improve infrastructure resiliency, geomorphic stability, and maintenance costs. The goal of this work is to develop preliminary culvert designs that convey hydraulic design floods and meet the Massachusetts Stream Crossings Standards for select existing stream crossing sites across Massachusetts. We derive stream and infrastructure data from lidar and other geospatial datasets as input for one-dimensional hydraulic models. Culvert dimensions are iteratively increased until the structures can convey the hydraulic design flood flows with adequate freeboard. The approach was evaluated by comparing lidar-derived designs to designs produced with surveyed data at 30 stream crossings across Massachusetts. The automatable methodology was then applied to 343 stream crossing sites in the Housatonic River watershed in southwestern Massachusetts. For each stream crossing site, preliminary designs were developed to meet the Massachusetts Stream Crossing Standards and convey the 10-, 4-, 2-, and 1-percent annual exceedance probability flood flows. The U.S. Geological Survey StreamStats web application hosts the 3-sided box, 3-sided arch, and pipe culvert preliminary designs. Provided supporting information includes site information, habitat quality assessments, and modeled water surface elevations. The publicly available preliminary designs can be used by municipalities, engineers, and others to evaluate design options, prioritize replacements, and analyze ecological benefits. These designs also may help municipalities pursue grant opportunities and estimate replacement costs prior to investing in field assessments and engineering design.

Keywords: culvert, geospatial analysis, hydraulic model, aquatic organism passage, Massachusetts

Introduction

There are over 37,000 miles of roads and 12,000 miles of streams within the state of Massachusetts, which intersect at an estimated 25,000 locations where stream crossings allow for the conveyance of vehicular traffic across streams (INDUS Corporation, 2013; Massachusetts Division of Local Services, 2026). Many of these culverts and small bridges are undersized and at the end of their design life (Massachusetts Culverts and Small Bridges Working Group for Senator Hinds and the Massachusetts Legislature, 2020). Undersized stream crossings can reduce habitat connectivity, disrupt sediment transport, and damage infrastructure and property (Castro, 2003; Levine, 2013; Makrakis et al., 2012; McEnroe, 2006; Moccetti et al., 2024; Perrin & Jhaveri, 2004). Effects of high flows on the natural and built environment at stream crossings could be further exacerbated by potential variability in flood magnitude and frequency due to climate change (Bjerklie & Sturtevant, 2018; Morsy et al., 2024; Olson et al., 2024; Wright et al., 2012) and land use change (Hopkins et al., 2015; Thompson et al., 2017). Replacement of undersized culverts with crossings designed for flood resiliency and habitat connectivity can also yield long-term fiscal benefits (Gillespie et al., 2014; O'Shaughnessy et al., 2016).

In Massachusetts, stream crossings are regulated by municipal, state, and federal agencies with interests in safety, transportation, and the environment. These agencies include municipal conservation commissions, the Massachusetts Department of Environmental Protection (MassDEP), Massachusetts Department of Transportation (MassDOT), the Federal Highway Administration (FHWA), and the U.S. Army Corps of Engineers (USACE). At a minimum, stream crossings should be designed to convey hydraulic design floods of selected annual exceedance probabilities (MassDOT, 2025a). To ensure that stream crossings are designed for resiliency and aquatic organism passage (AOP), the Massachusetts Stream Crossing Standards (MA SCS) were developed based on many of the U.S. Forest Service (USFS) principles of Stream Simulation (Massachusetts Division of Ecological Restoration [MA DER], 2012; USFS, 2008). The MA SCS describe six design standards:

- Three-sided arch or box culverts are preferred.
- Culverts should be embedded into the stream.
- The crossing width should be at least 1.2 times the bankfull width.
- The openness ratio (cross-sectional area divided by the culvert length) must be at least 0.82 feet (ft).
- The substrate of the crossing should be natural and match the upstream and downstream substrates.
- Water depth and velocities within the crossing should be comparable to those in the natural upstream and downstream channels.

All new stream crossings are required to fully meet the MA SCS. Stream crossing replacement projects must be designed to the MA SCS to the maximum extent practicable (sections 310 CMR 10.53(8) and 310 CMR 10.24(10), MassDEP, 2017). The regulations state that replacement projects must evaluate the potential to comply with the MA SCS to the maximum extent practicable by considering site constraints, undesirable effects or risk, and the environmental benefit compared with cost.

In Massachusetts, various tools and methods have been developed to identify stream crossing sites, evaluate stream crossings, and prioritize their replacement. Many of these efforts described below have informed our approach. Following the damage to stream crossings in northwestern Massachusetts by tropical storm Irene, a vulnerability assessment of stream crossings to climate change was conducted in the Deerfield River Basin (Sturdevant Rees et al., 2018). Stream crossings were assessed for structural, geomorphic, and hydraulic risk of failure and results were made available through the interactive “Stream Crossing Explorer” tool. That effort led to the North Atlantic Aquatic Connectivity Collaborative (NAACC) developing tools to identify probable stream crossing locations and protocols for field assessments (NAACC, 2026). The NAACC public database of probable and surveyed stream crossings includes location data, structure details, stream characteristics, and images. Studies and initiatives to evaluate stream crossings have utilized the NAACC assessment protocols and database (Briccetti, 2025; Martin, 2019; Sliger et al., 2024). For example, NAACC data are used in the National Aquatic Connectivity Collaborative Barrier Inventory & Prioritization tool to prioritize stream crossing improvements by network connectivity and watershed condition (National Aquatic Connectivity Collaborative, 2026).

Historically, stream crossings have been designed to convey flood events using methods including empirical flood-flow formulas, floods of record, and flood-frequency estimations to estimate peak flow hydrology (McEnroe, 2007; Schall et al., 2012). Design equations, such as the Talbot method and the FHWA inlet and outlet control equations allow for approximate hydraulic design of stream crossings (Schall et al., 2012; Talbot, 1888). More complex hydraulic analysis and design of stream crossings, done through iterative water-surface profile computation with hydraulic modeling software, requires data defining the road surface profile, stream channel geometry, and crossing characteristics (Schall et al., 2012). Software applications can be used for this hydraulic analysis. One example is HY-8, a culvert analysis and design tool that implements FHWA approaches (FHWA, 2024). The tool also includes AOP and Stream Simulation modules. To facilitate the evaluation and design of culverts for fish passage, the USFS developed the FishXing software (USFS, 2012). The software allows for water-surface profile hydraulic modeling, with comparisons of outputs to organism capabilities for passage. One of the main applications of the USACE Hydrologic Engineering Center River Analysis System (HEC-RAS) software is water surface-profile hydraulic modeling (USACE, 2024). Water surface profiles are computed by solving the energy and momentum equations. Culverts are modeled in HEC-RAS by computing energy losses due to expansion, contraction, and movement through the culvert (Brunner, 2020).

The advances in methods described above along with the increasing availability of geospatial datasets allow for desktop assessments to more closely follow engineering design processes that typically rely on field-surveyed data. The improvement in quality and availability of high-resolution light detection and ranging (lidar) data is especially critical for flood risk analyses (Walters, 2025). For example, a study in Italy used high-resolution digital elevation models (DEM) and a road network dataset to assess the overtopping potential of stream crossings (Amaddii et al., 2026). Road elevations above the stream crossing were compared to the elevation of the riverbanks. The elevations were estimated using geographic information system (GIS) landform cluster analyses that allowed for application of this screening method to 230 stream crossings in the study area. Mainland Massachusetts has full coverage of Quality Level 1 lidar data as of November 2025 (U.S. Geological Survey, 2026). Stream connectivity and habitat quality geospatial datasets can provide additional context to the stream networks and circumjacent ecosystems of stream crossings (Massachusetts Department of Conservation and Recreation, 2009; MassDEP & University of Massachusetts Amherst, 2023; Massachusetts Division of Fisheries and Wildlife, 2022; Massachusetts Division of Fisheries and Wildlife & The Nature Conservancy, 2026; Massachusetts Division of Marine Fisheries, 2023; USFS & Inter-agency Wild and Scenic River Council, 2022).

Other studies have used geospatial datasets to estimate design flows for the hydraulic analyses of culverts (Greer et al., 2018; Kim et al., 2025; USFS, 2012). Flows are computed using methods such as U.S. Geological Survey (USGS) peak flow regional regression equations (USGS, 2019a), the Rational Method (Kuichling, 1889), and the Natural Resources Conservation Service (NRCS) Curve Number Method (NRCS, 2004). The Missouri Automated Culvert Analysis Tool was developed to assess the flood risks of culverts from lidar data using the NRCS Curve Number method and FHWA inlet and outlet control equations (Kim et al., 2025). The tool used GIS algorithms to derive streamlines and estimate culvert heights and over-topping elevations from lidar. In addition to evaluating existing stream crossings, hydraulic analyses that utilize geospatial datasets can also be used to develop stream crossing designs. A study in Tuscaloosa, Alabama used geospatial datasets, the Rational Method, and FHWA equations to develop pipe culvert designs at 10 sites (Greer et al., 2018). The culvert designs produced with the tool and some user inputs were all larger than the existing culverts. Integrating GIS processes into hydraulic analyses increased the efficiency and replicability of the studies. The increasing availability of geospatial datasets and the successes of other culvert design tools have informed the development of our automatable and field-tested method to produce preliminary culvert designs across Massachusetts.

Purpose and Scope

The objectives of this study are to (1) leverage existing datasets and studies to characterize Massachusetts streams and stream crossings, (2) develop preliminary culvert designs that meet regulatory requirements, and (3) to make the culvert designs and supporting information publicly accessible. The presented methods are developed from a USGS and University of Massachusetts Amherst (UMass Amherst) feasibility analysis for the creation of a preliminary culvert design tool for Massachusetts (Bent et al., 2022). The approach was piloted at 16 stream crossings in the Squannacook River watershed, where field-surveyed and lidar-based hydraulic models of culvert designs were compared (Taylor et al., 2024). We use the term "preliminary" to describe the culvert designs to signify the limitations of the lidar-derived methodology and the necessity of subsequent field verification and engineering design.

This paper describes the methodology for developing preliminary culvert designs from lidar. The development of lidar-derived preliminary culvert designs in a HUC-8 watershed is described to illustrate how the tool will be applied statewide (McCallister et al., 2026). Finally, the methodology is evaluated by comparing lidar-derived intermediary data and resulting designs to field-survey data and designs at 30 sites across Massachusetts (Armstrong et al., 2026).

Approach and Methods

Our approach leverages existing geospatial datasets, regression equations, and an iterative hydraulic modeling process to produce preliminary stream crossing designs (fig. 1). First, lidar data are used to derive road and stream features that are further attributed with basin characteristics. Regression equations are used to compute statistical peak flows and bankfull geometry. Next, cross sections are delineated to define the stream channel upstream and downstream of the structure. Design criteria are applied to hydraulic models built from the lidar-derived data, using HEC-RAS, version 6.6 (USACE, 2024). Culvert sizes are iteratively increased until they convey their corresponding hydraulic design flows. The stream crossings are contextualized through the provision of habitat quality and stream connectivity restoration potential assessment data. Finally, preliminary designs that convey selected flood flows and meet the MA SCS are made available on USGS StreamStats (USGS, 2019b). These methods are also described in the data releases associated with this study (Armstrong et al., 2026; McCallister et al., 2026). The programmability of ArcGIS software (Esri, 2025) and HEC-RAS hydraulic modeling software could allow for the presented methods to be automated.

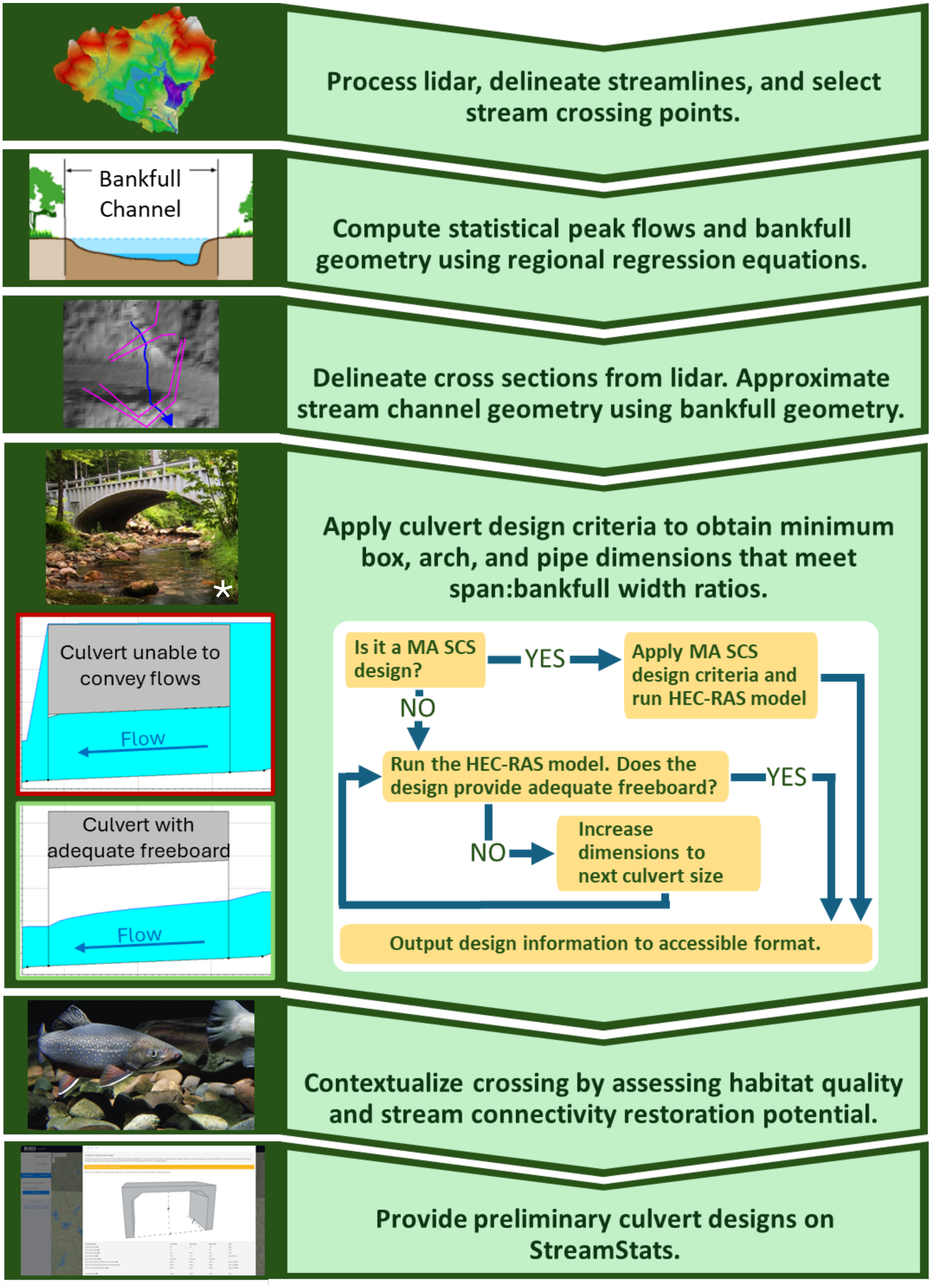
Process lidar, delineate streamlines, and select stream crossing points.
Bankfull Channel
Compute statistical peak flows and bankfull geometry using regional regression equations.
Delineate cross sections from lidar. Approximate stream channel geometry using bankfull geometry.
*
Culvert unable to convey flows
Flow
Culvert with adequate freeboard
Flow
Apply culvert design criteria to obtain minimum box, arch, and pipe dimensions that meet span:bankfull width ratios.
Is it a MA SCS design?
YES
Apply MA SCS design criteria and run HEC-RAS model
NO
Run the HEC-RAS model. Does the design provide adequate freeboard?
YES
NO
Increase dimensions to next culvert size
Output design information to accessible format.
Contextualize crossing by assessing habitat quality and stream connectivity restoration potential.
Provide preliminary culvert designs on StreamStats.

Figure 1. Flowchart of the methods for developing preliminary stream crossing designs using geospatial datasets and hydraulic modeling. The photograph with an asterisk is by Paul Nguyen, used with permission. MA SCS refers to the Massachusetts Stream Crossing Standards (MA DER, 2012).

Processing geospatial datasets

The first step is to derive hydrography from lidar in the vicinity of stream crossings. Stream crossing site locations are selected from the NAACC stream crossing database (NAACC, 2024). The stream crossing vector points are adjusted onto the crown of the road using a 1-meter (-m) lidar DEM raster (NOAA Office for Coastal Management Partners, 2016; USGS, 2020). To delineate stream centerlines in the vicinity of stream crossings, we use a hydrological enforcement process of breaching digital flow dams, which refer to areas such as road embankments and dams that appear to block the stream in the DEM (Poppenga et al., 2010). The hydrologically enforced rasters are used to derive flow direction and flow accumulation raster datasets, which are then used to delineate stream centerlines. Drainage areas are delineated at stream crossing locations using the flow direction raster. The percentage of impervious area within the drainage area is calculated from National Land Cover Data (NLCD) raster data (Dewitz, 2023).

Lidar-derived drainage areas are then used to filter out sites that are not well-suited for this approach. Stream crossings with drainage areas greater than 2 square miles are excluded from further processing due to our focus on small bridges and culverts. Stream crossings composed of 20 percent or greater impervious area are excluded from further processing because of limitations of the peak flow regional regression equations (Zarriello, 2017). The equations were developed from streamgage basins with a median imperviousness of 1.6 percent, and only 12 of the 199 used streamgage basins had over 20 percent impervious area (Zarriello, 2017). Additionally, the equations do not account for the complex interplay of imperviousness with other basin characteristics. Potential stream crossings identified through geospatial proximity analyses and manual reviews as waterbody equalizers, components of dams, buried stream segments, or structures serving other functions are also excluded.

The MassDOT Road Inventory is a geospatial dataset that contains the locations and attribute information for all public and some private roadways in Massachusetts (MassDOT, 2025b). The inventory is used to identify stream crossing sites for exclusion and to assign hydraulic design flows to stream crossing sites. Sites on unnamed roads, trails, and railroads are excluded from further processing in this study but could be addressed in future work. The functional classification obtained from the inventory is used to assign the associated hydraulic design flow to the stream crossing site via Table 2.6.3-1 of the MassDOT Bridge Manual, reproduced in Table 1 (MassDOT, 2025b, 2025a).

Table 1. Massachusetts Department of Transportation highway functional classification and associated hydraulic design flood flow (modified from (MassDOT, 2025a)).

Highway Functional Classification	Hydraulic Design Flood Flow (annual exceedance probability, in percent)	Hydraulic Design Flood Flow (recurrence interval, in years)
Interstate, or limited access highways	1	100
Rural principal arterial	2	50
Rural minor arterial	2	50
Rural collector, major	4	25
Rural collector, minor	10	10
Rural local road	10	10
Urban principal arterial	2	50
Urban minor arterial street	4	25
Urban collector street	10	10
Urban local street	10	10
Bike trail/shared use path	10	10

Computing statistical peak flows and bankfull geometry

To compute peak flows at the selected stream crossing sites, basin characteristics are computed for each stream crossing's drainage area. The explanatory variables used in the USGS peak flow regression equations for Massachusetts are drainage area, mean basin elevation, and percent basin storage (Zarriello, 2017). The datasets from the original USGS regression analysis are assembled, including land cover data and a 10-m DEM. The areal percentages of storage (water bodies and wetlands) are computed from the 2006 NLCD data (USGS, 2011). Mean basin elevations are computed from the 10-m DEM (USGS, 2011). Further, 10-, 4-, 2-, 1-, and 0.2-percent annual exceedance probability (AEP) flood flows are computed.

The Massachusetts bankfull geometry equations are used to define the stream channel upstream and downstream of each stream crossing (Bent & Waite, 2013). These equations relate bankfull width and mean depth to drainage area and mean basin slope. Mean basin slopes are computed from a slope raster derived from the 10-m DEM. The estimated bankfull width is then used to define the locations of left and right banks of the stream. The banklines are offset from the stream centerline at a distance of half of the bankfull width.

Delineating cross sections and stream geometry

The stream crossing and stream channel are defined by cross sections in the hydraulic models. These cross-sections represent the road (deck), the upstream and downstream culvert openings (upstream face and downstream face, respectively), and upstream and downstream of the culvert (approach and exit, respectively). A relative extrema algorithm is used to find peaks and valleys along the stream centerline (Virtanen et al., 2020). The stream centerline elevation and stationing values are passed through a one-dimensional Gaussian filter with a sigma kernel of six standard deviations to reduce noise in the stream centerline elevations. The resulting peak corresponds to the stationing of the road deck. The station of the closest valley, or local minima, upstream of the crossing site along the stream centerline is set as the station for the upstream face cross section. The closest valley downstream of the crossing is set as the station for the downstream face cross section. A profile view of the placement of cross sections along the stream centerline is shown in fig. 2a. The approach and exit cross section stations are placed two bankfull widths upstream of the upstream face and downstream of the downstream face, respectively.

After the stationing of the cross sections is defined along the stream centerline, the cross sections are delineated. To delineate the cross sections, the 1-m DEM is used. The road deck cross section is extended along the road centerline. If the resulting road deck, or portion of it, has a downslope gradient, the road deck cross section is derived from the DEM without consideration of the road network. The approach, upstream face, downstream face, and exit cross sections are first extended to the left and right banklines, perpendicular to the stream centerline. The points that intersect with the banklines are the bank stations. The cross sections are then further extended perpendicular to DEM contour lines using least-cost path analyses until an elevation of 3 ft above the road deck is reached. Intersections within a cross section are resolved by iteratively removing vertices of the polyline nearest to the intersection until no intersections are present. Intersections with other cross sections are resolved by cutting the cross-section polyline at the intersecting segment and then extending the polyline in the same direction and extent as the adjacent cross section. Next, bankfull channel geometry is integrated into the approach, upstream face, downstream face, and exit cross sections. The channel geometry of the stream bottom is approximated as a trapezoid. At each cross section, the bankfull depth is subtracted from the minimum lidar elevation between the bank stations, as shown in fig. 2c. The resulting elevation is applied across the channel bottom, which has a width equivalent to half of the bankfull width.

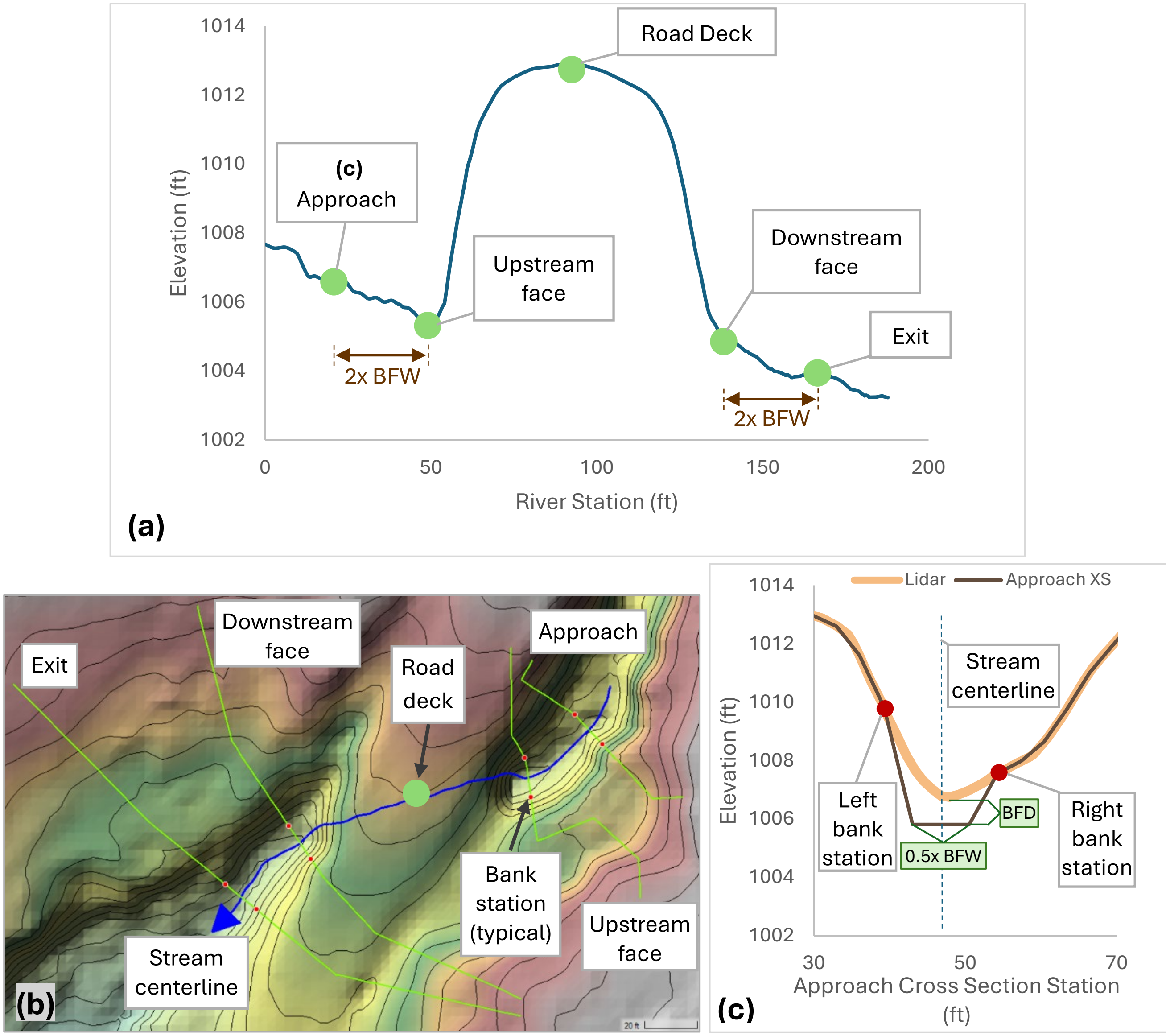

Figure 2. (a) Stream profile showing cross section placement, (b) map view of cross sections on terrain, and (c) approach cross section geometry. BFW refers to bankfull width, BFD refers to bankfull mean depth, and XS refers to cross section.

The stream crossing length and the downstream boundary condition are also derived from lidar. The length of the crossing is estimated by using an inflection point algorithm to determine the first inflection points (indicators of embankments) upstream and downstream of the stream centerline smoothed with a one-dimensional Gaussian filter with a sigma kernel of three standard deviations (Harris et al., 2020). The normal depth slope of the stream centerline downstream of the culvert is computed from the 1-m DEM and used as the downstream boundary condition. At sites where the stream crossings may alter natural stream conditions, we compute the slope in a section of the stream entirely downstream of the modeled reach. The reach along which the slope is computed is terminated prior to hydroflattened areas. If the normal depth slope is computed to be less than 0.01 percent, the normal depth slope is set to 0.01 percent.

Applying culvert design criteria

At each stream crossing site, preliminary culvert designs are developed for 3-sided box, 3-sided arch, and pipe culvert types using HEC-RAS hydraulic models. For each of the three culvert types, the designs convey one of the four hydraulic design flows (10-, 4-, 2-, and 1-percent AEP flood flows) or meet the MA SCS, resulting in a total of 15 designs for each stream crossing site. A HEC-RAS project file is generated for each stream crossing site. Plan and geometry files are created from the cross-section and river-profile GIS outputs for each of the 15 designs. A flow file is populated with boundary conditions and the calculated peak flows for each stream crossing site. Output and run files are also generated when the model is run.

Potential dimensions for the box, arch, and pipe culvert design types were chosen to represent commercially available pre-cast concrete sizes. The 3-sided box design sizes were sourced from the American Society for Testing and Material (ASTM) Standard C1577-20, excluding any sizes that exceed a 4:1 culvert span to rise ratio to ensure structural integrity (ASTM International, 2022). Increases in box culvert spans are prioritized ahead of increases in culvert rises. The arch culvert design sizes are predefined in HEC-RAS (Brunner, 2020). Pipe culverts are sized at 0.5-ft diameter intervals, beginning at a diameter of 3.5 ft (American Concrete Pipe Association, 2022). Pipe culverts are also designed to be embedded with natural substrate to align with that standard of the MA SCS for all designs. Pipe culvert designs with diameters less than 8 ft are embedded with 2 ft of natural substrate, and all larger culverts have embedded depths equal to 25 percent of the culvert diameter. Minimum culvert spans (0.8 times bankfull width for the 10-percent AEP flood flow, 0.9 times bankfull width for the 4-percent AEP flood flow, and 1.0 times bankfull width for the 2- and the 1-percent AEP flood flow) are set for the hydraulic designs to minimize potential increases in stream velocity compared to natural flow conditions. Implementation of minimum culvert spans also contributes to the conservatism of the design approach.

To run the steady-state hydraulic models, it is necessary to apply additional assumptions about stream characteristics and the culvert designs. A subcritical flow regime is assumed. The roughness coefficients (Manning's n) values for all stream channels and overbanks are assumed to be 0.04 and 0.10, respectively (Arcement & Schneider, 1989; Bent & Waite, 2013; Coon, 1997). The culvert material is assumed as pre-cast concrete, with a Manning's n of 0.011 (Chow, 1959). A minimum of 1.5 ft of fill, or roadway surface above the culvert low chord, is included in all designs (MassDOT, 2017). Typical entrance and exit losses of 0.4 to 0.5 and 1.0, respectively, are applied (Brunner, 2020). All stream crossings are assumed to be perpendicular to the channel. Ineffective flow areas are applied, assuming 1:1 contraction and expansion rates relative to the constriction of the culvert.

For the culverts that are designed to meet the MA SCS, additional criteria are incorporated. The SCS designs require an openness ratio (the culvert cross-sectional area divided by the culvert length) of at least 0.82 ft. At minimum, culvert spans are set to 1.2 times bankfull width. The MA SCS design dimensions are set to the minimum size that would meet the openness ratio and span requirements. The hydraulic models are run to determine the resulting water surfaces, freeboard, and velocities. Because these designs are intended to solely meet the MA SCS, no freeboard (vertical distance from the culvert crown to the modeled water surface) requirements are incorporated into the MA SCS designs. It is noted that most MA SCS designs convey hydraulic design flows with sufficient freeboard.

Iterating culvert size to convey design flows

For the culverts designed to convey hydraulic design flows, the dimensions of each culvert are increased until sufficient freeboard is provided at the inlet for the associated flood flow. A minimum of 1.0 ft of freeboard at the culvert inlet is required for culverts less than 10 ft in span that convey the 10-percent AEP flood flow. A minimum of 2.0 ft of freeboard is required for all other culvert designs. For box culvert designs, precedence is given to minimizing the height of the opening over minimizing cross-sectional area. At each size iteration, ineffective flow areas are added to the cross sections. If the elevation of the culvert low chord plus 1.5 ft of fill over the culvert exceeds the elevation of the road, the modeled road elevation is raised to accommodate the increase. It is assumed that the road would need to be raised as part of the culvert replacement project.

Assessing habitat quality and stream restoration potential

Information on stream habitat quality and the potential connectivity benefits of adequately sized stream crossings can provide additional context to culvert design choices. The previous processing steps result in 15 preliminary designs for each stream crossing site, sized to either accommodate hydraulic design flows or meet the MA SCS. The resulting assessments could be used by practitioners to inform the extent to which the MA SCS are considered in stream crossing replacement projects.

Habitat quality is assessed using published GIS layers that provide a general assessment of a stream's habitat quality. The five GIS-based aquatic habitat criteria (BioMap Core Habitats and Critical Natural Landscapes, Coldwater Fisheries Resources, Areas of Critical Environmental Concern, Wild and Scenic Rivers, and Diadromous Fish Runs) are additionally available through the MassDEP culvert and bridge assessment tool (Massachusetts Department of Conservation and Recreation, 2009; MassDEP & UMass Amherst, 2023; Massachusetts Division of Fisheries and Wildlife & The Nature Conservancy, 2026; Massachusetts Division of Fisheries and Wildlife, 2022; Massachusetts Division of Marine Fisheries, 2023; USFS & Inter-agency Wild and Scenic

River Council, 2022). At each stream crossing, the habitat quality criteria met at that segment of the stream are provided.

The importance of stream crossings to local aquatic connectivity was evaluated by the UMass Amherst Designing Critical Linkages team for the Massachusetts Conservation and Prioritization System (CAPS). An index of the improvement in ecological connectivity resulting from an upgrade of each stream crossing was developed (McGarigal et al., 2023). Data on the stream crossing sites were acquired from CAPS (UMass Amherst, Department of Environmental Conservation, 2023). Stream crossings on coldwater streams are defined in the dataset as coldwater critical linkages. All other stream crossings are defined as critical linkages. All critical linkages are ranked, and the percentiles are used to indicate the relative stream connectivity restoration potential.

Providing preliminary designs on USGS StreamStats

The preliminary culvert designs are served through USGS StreamStats—a map-based web application that provides estimates of streamflow statistics and other analytical tools that can be used for water-resources planning, management, and engineering (Ries et al., 2017). Users can navigate to the Massachusetts study area where stream crossing sites can be selected. The application then displays a printable “Hydraulic Model Report,” which includes site information, basin characteristics, peak-flow statistics, and bankfull geometry statistics. The application also includes the stream habitat quality and stream connectivity restoration potential information and the associated hydraulic design flood for the road functional classification. Lastly, the 15 preliminary culvert designs are provided, including culvert dimensions, channel invert elevations, deck elevations, velocities, and water depths. The report also indicates the extent to which each of the 15 designs meet the MA SCS.

Users can download the delineated watershed of the stream crossing site in multiple geospatial formats, the report in a tabular CSV format, and a folder of HEC-RAS model files. The HEC-RAS folder includes the project, flow, geometry, output, plan, run files, and a summarizing ReadMe file, that encompass the inputs and outputs of the preliminary culvert designs.

Results

Application of the method to the Housatonic River watershed

In the Housatonic River watershed, we developed preliminary culvert designs for 343 existing stream crossing sites, including the culvert on Swamp Road over an unnamed tributary to Cone Brook in Richmond, MA (referred to in the NAACC database as xy4236095673353262). The locations of the 343 culverts including the Swamp Road culvert are shown in fig. 3. According to a 2019 NAACC survey, the existing stream crossing is a metal pipe culvert with a diameter that ranges from 4.6 to 5.1 ft (NAACC, 2024). The designs, hydraulic models, and supporting information are available in the accompanying USGS data release (McCallister et al., 2026).

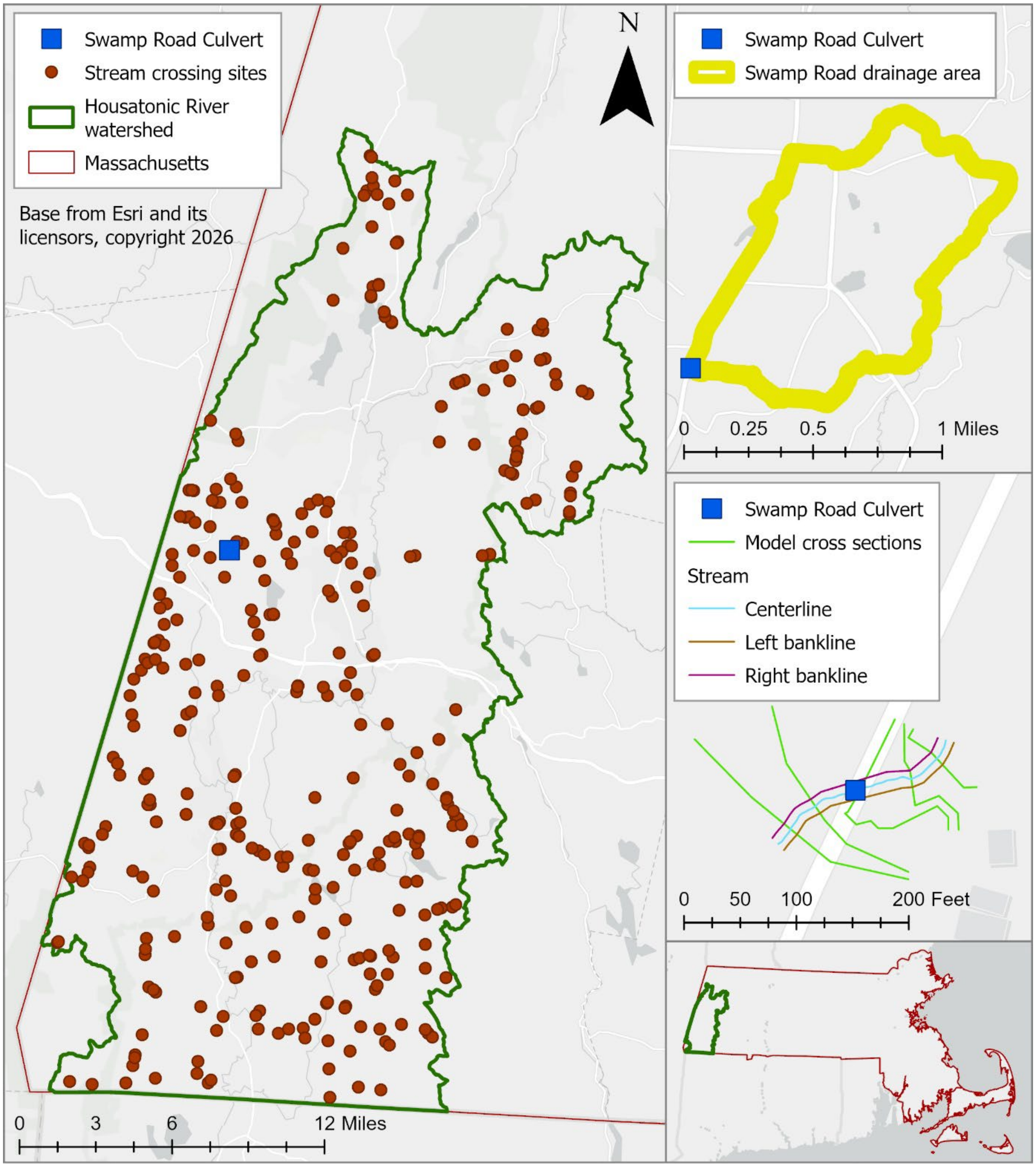

Figure 3. Locations of 343 studied stream crossing sites in the Housatonic River watershed, western Massachusetts, including the Swamp Road culvert in Richmond, MA (42.36106° N, -73.35323° W) (McCallister et al., 2026).

Following the approach and methods and summarized in fig. 1, we present the steps taken to develop the preliminary culvert designs in the Housatonic River watershed and at the Swamp Road culvert.

1. <u>Processing geospatial datasets:</u> In the Housatonic River watershed, there are 1,377 potential stream crossings listed in the NAACC database. A total of 1,034 stream crossing sites were excluded from the analyses. Of those, 468 sites were excluded because their drainage areas were greater than 2 mi^2. 464 sites were excluded because they were not found on an intersection of a named road and lidar-derived stream. 102 sites were removed because the crossing location is representative of buried sections of streams, waterbody equalizers, and dam-associated structures. The drainage areas of stream crossing sites modeled in the Housatonic River watershed ranged from 0.01 square miles to 1.99 square miles. The Swamp Road culvert had a delineated drainage area of 0.75 square miles, 2.2 percent of which was estimated to be impervious. Swamp Road has a “Major Collector” road functional classification, and as shown in table 1, the hydraulic design flow for the culvert would be the 4-percent AEP flood flow (MassDOT, 2025a).
2. <u>Computing statistical peak flows and bankfull geometry</u>: Peak flows and bankfull geometry were computed from regression equations (Bent & Waite, 2013; Zarriello, 2017). Computed peak flows for the 10-percent AEP flood flow ranged from 6 to 130 cubic feet per second (ft^3/s) in the watershed. Bankfull widths ranged from 2.7 to 24 ft. Peak flows at the Swamp Road culvert ranged from a 10-percent AEP flood flow of 61 ft^3/s to a 0.2-percent AEP flood flow of 212 ft^3/s. The hydraulic design flow (4-percent AEP) was estimated to be 111 ft^3/s. At the Swamp Road culvert, the unnamed stream’s bankfull width and bankfull mean depth were calculated to be 15 ft and 0.95 ft, respectively.
3. <u>Delineating of cross sections and stream geometry</u>: The approach, upstream face, downstream face, and exit cross-sections of the Swamp Road culvert were placed 169 ft, 140 ft, 48 ft, and 17 ft upstream of the downstream end of the reach, respectively. Left and right bank lines were set 7.5 ft away from the centerline,

resulting in bank stations being placed 15 ft apart at the four cross sections. The minimum elevation of the downstream face cross section is 1,004.8 ft above the North American Vertical Datum of 1988 (NAVD88). Subtracting the bankfull depth of 0.95 ft results in a channel bottom elevation of 1003.9 ft NAVD88. The culvert was estimated to be 72.2 ft long by determining the distance between the points of inflection upstream and downstream of the crossing on the stream centerline. For the downstream boundary condition, the normal depth slope was computed as 0.042 ft/ft.

4. Applying culvert design criteria: A HEC-RAS project file, flow file, and 15 geometry files, plan files, output files, and run files were generated using GIS-derived data for the Swamp Road culvert and other stream crossings in the Housatonic River watershed. For each stream crossing site, design criteria were applied for the four hydraulic design flows and the MA SCS for each of the three culvert types. The minimum spans of the Swamp Road culvert designs were 12 ft, 13.5 ft, 15 ft, 15 ft, and 18 ft for the 10-, 4-, 2-, and 1-percent AEP flood flows, and the MA SCS, respectively. The MA SCS designs for the Swamp Road culvert were sized using the span and openness ratio requirements of the MA SCS. For example, the MA SCS box culvert design has a span of 18 ft and a rise of 6 ft, with an openness ratio of 1.5, (fig. 4).

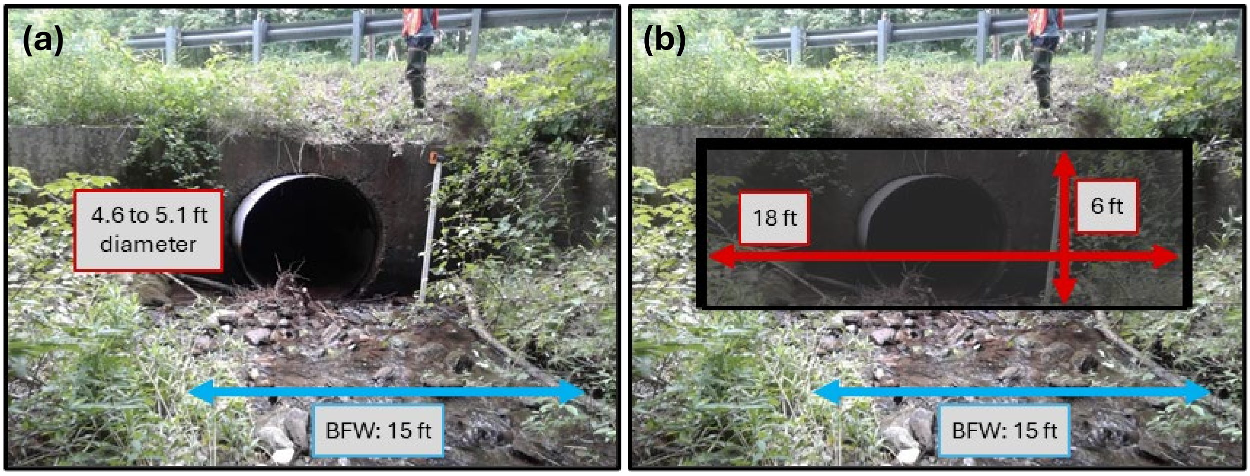

Figure 4. (a) Photograph of existing 4.6 to 5.1-ft diameter pipe culvert, (b) photograph of existing pipe culvert with superimposed MA SCS box culvert design (McCallister et al., 2026; North Atlantic Aquatic Connectivity Collaborative, 2019). BFW refers to the estimated bankfull width.

5. Iterating culvert size to convey design flows: For the hydraulic designs for the Swamp Road culvert site, the culvert dimensions were initially set to the minimum dimensions that met the span to bankfull width ratios. The hydraulic model was then run with the corresponding hydraulic design flows. The culvert dimensions were iteratively increased until the minimum freeboard requirement was met. For example, the minimum dimensions for the 4-percent AEP arch culvert design were set to a 14 ft span and 3 ft rise, which did not allow for 2 ft of freeboard. The dimensions were then increased to a 16 ft span by 3.53 ft rise, which again did not allow for 2 ft of freeboard. The dimensions were increased to a 20 ft span by 4.13 ft rise, which resulted in a modeled freeboard of 2.54 ft; this iteration was used for the final design for the 4-percent AEP arch culvert design.
6. Assessing habitat quality and stream connectivity restoration potential: 23 stream crossings in the Housatonic River watershed met two or more habitat quality criteria. In terms of stream connectivity restoration potential, 35 stream crossings were determined to be within either the top five percent of critical linkages or the top 10 percent of coldwater critical linkages. The unnamed stream through the Swamp

Road is classified as a coldwater fisheries resource (Massachusetts Division of Fisheries and Wildlife, 2022). Although the stream is designated as a coldwater fisheries resource, the stream crossing did not meet the criteria for a coldwater critical linkage. For stream connectivity restoration potential, it was in the top 10 percent of critical linkages.

7. Providing preliminary designs on USGS StreamStats: Culvert designs for the Swamp Road culvert and the 342 other stream crossing sites were then made available on USGS StreamStats (USGS, 2019b).

Comparison of lidar-derived designs to survey-derived designs

To evaluate the efficacy of our approach, lidar-derived culvert designs were compared to survey-derived designs at 30 stream crossing sites across Massachusetts (Armstrong et al., 2026). Field surveys were conducted to collect existing stream crossing dimensions and elevation data upstream and downstream of the crossing. Survey-derived designs were generated using HEC-RAS hydraulic models and the same approach as the lidar-derived designs, except they were populated with the field-surveyed cross section, culvert length, and existing deck elevation data. The results and methodology used for surveying, development of survey data-derived designs, and lidar-derived designs are described in the associated data release (Armstrong et al., 2026). Lidar-derived and field-surveyed input and output data at 30 stream crossings sites were analyzed to assess the performance of our methodology for developing preliminary culvert designs.

Lidar-derived elevations and culvert lengths were compared to survey data. As shown in fig. 5(a), lidar-derived approach cross section thalweg elevations were on average 0.4 percent less than surveyed elevations. The mean absolute difference was 1.04 ft (Armstrong et al., 2026). Outliers of the lidar-derived approach elevations range from 2.8 percent below to 1.6 percent above surveyed elevations. Lidar-derived culvert invert elevations were also on average 0.4 percent less than surveyed elevations. The mean absolute difference was 0.95 ft (Armstrong et al., 2026). Comparisons of the approach thalweg elevation and culvert inlet elevations indicate that most lidar-derived elevations are lower than elevations determined in the field. Culvert lengths derived from lidar were also compared to field-measured culvert lengths. On average, lidar-derived culvert lengths were 22 percent smaller than surveyed lengths. Differences ranged from 92 percent shorter to 36.4 percent longer than surveyed data. The mean absolute difference was 12.97 ft. Culvert lengths ranged from being underestimated by 45.50 ft to being overestimated by 31.00 ft (Armstrong et al., 2026). It is expected that estimated culvert lengths vary from survey data more than channel elevations because culvert lengths are based on the difference along the stream centerline between two estimated locations. Differences in culvert length are likely attributable to the difficulty at some stream crossing sites of determining an inflection point in the stream channel profile at the downstream cross section from lidar. These inflection points likely represent embankments, so it is also possible that the lidar-derived culvert lengths are underestimated when culvert openings protrude out of the embankment. The underestimation of culvert length could result in decreased hydraulic resistance for stream crossings in outlet control flow conditions. This would result in lower water surface elevations and, consequently, smaller culvert designs. For inlet control flows, the length of the culvert is unlikely to affect water surface elevations and the resulting culvert designs.

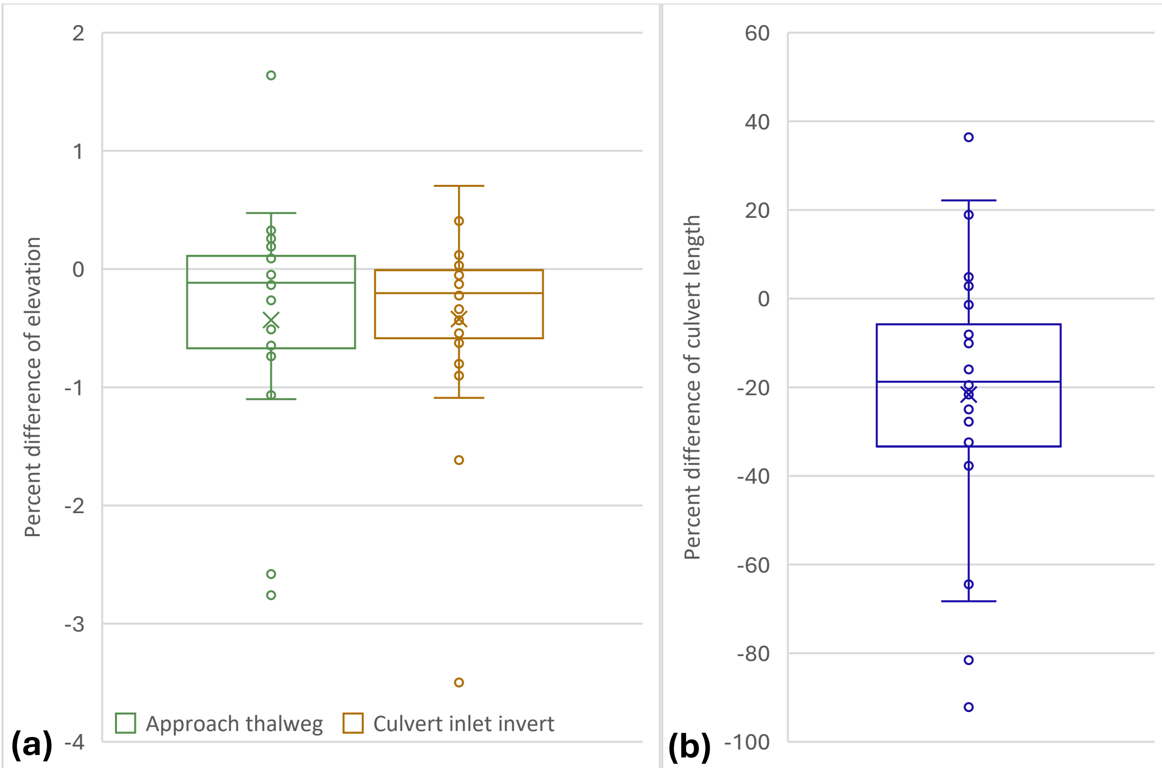

Figure 5. Boxplots of (a) percent difference of lidar-derived elevations from surveyed elevations and (b) percent difference of lidar-derived culvert length from surveyed culvert length at 30 sites across MA (Armstrong et al., 2026). Circles indicate datapoints, the "X" indicates the mean of the series, the box represents the interquartile range, the line across the box is the median, and the extent of the whiskers indicate 1.5 times the interquartile range.

Culvert designs developed from lidar-derived data were compared to culvert designs derived from survey data. Across all culvert designs, lidar-derived designs are on average 3.5 percent larger than those developed from survey data. As shown in fig. 6, the differences in design types range from a mean percent difference of 12.1 percent smaller to 12.9 percent larger than designs developed from survey data. The box and arch culvert designs that meet the MA SCS were the only categories with negative mean percent differences. All lidar-derived MA SCS pipe culverts were identical to field data-derived designs, except for one culvert, which was 0.5 ft larger in diameter. Bankfull widths and peak flows are computed using the same methods for lidar-derived and survey data-derived approaches. The differences in MA SCS designs are therefore attributable to the underestimation of culvert lengths in the lidar-derived designs, which then leads to smaller cross-sectional areas needed to meet the MA SCS span ratio.

In contrast, the culvert designs sized to convey specific flood flows are influenced by the placement and elevations of cross sections in addition to culvert length. The mean percent difference for designs intended to convey hydraulic design flows was zero percent or higher across all culvert types. Lidar-derived pipe culvert designs produced for both conveying hydraulic design flows were identical to field-based designs. Lidar-derived arch designs differ the most from designs developed from field survey data, which is likely attributable to fewer possible increments in design sizes when compared to the potential box and pipe sizes. This may contribute to the similarities observed in the resulting designs. Overall, the design culvert dimensions (cross-sectional area) derived from lidar data and survey data were similar, indicating that the methodology for producing preliminary culvert designs from a lidar-based method is effective and efficient. It also demonstrates that although some lidar-derived modeling input data such as culvert length can vary from field data, the method results in similar designs.

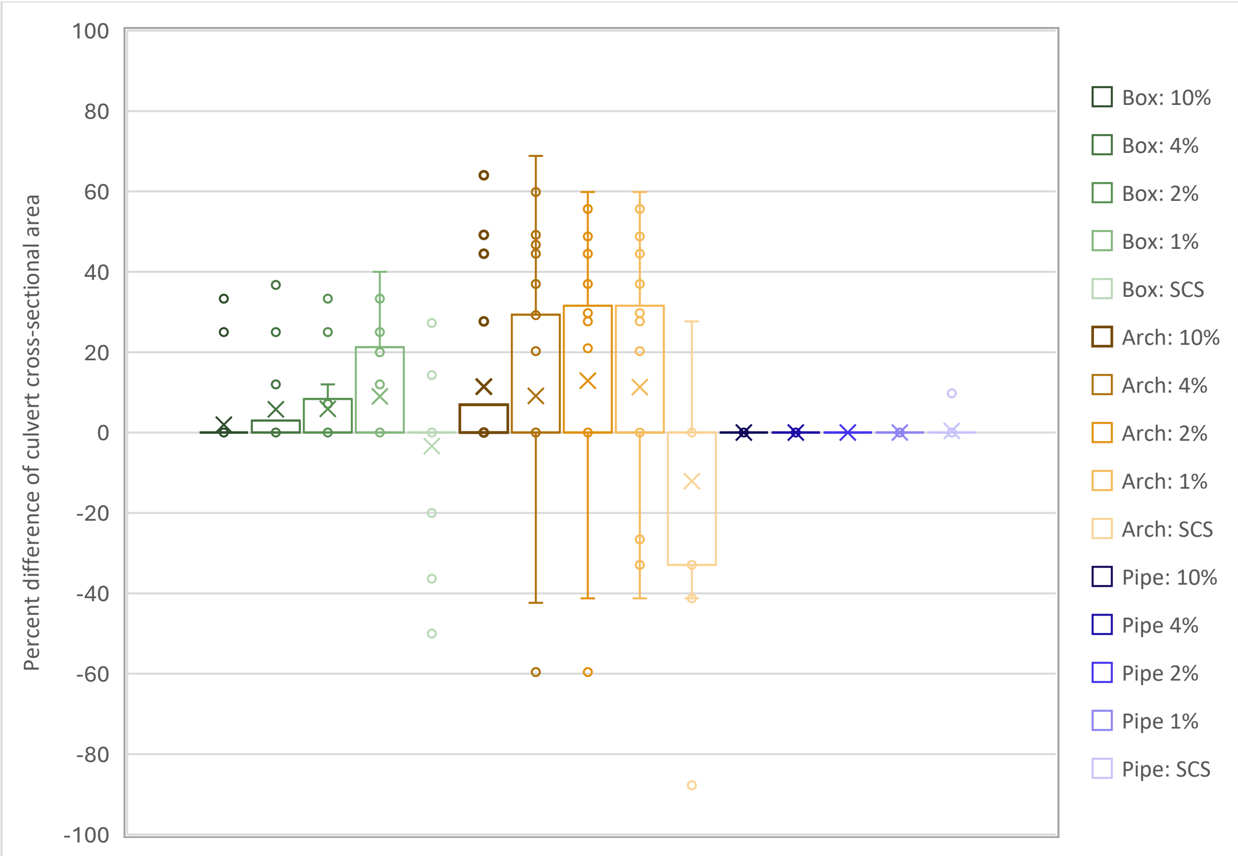

Figure 6. Boxplot of the percent difference of culvert cross-sectional area of designs derived from lidar data to designs derived from survey data for 3 culvert types at 30 sites across MA (Armstrong et al., 2026). SCS refers to designs intended to meet the Massachusetts Stream Crossing Standards. Circles indicate datapoints, the "X" indicates the mean of the series, the box represents the interquartile range, the line across the box at 0 percent for all designs is the median, and the extent of the whiskers indicate 1.5 times the interquartile range.

Hydraulic models were also developed for the existing stream crossings, using survey data and assessment data from the NAACC (Armstrong et al., 2026). When the 10-, 4-, 2-, and 1- AEP flood flows were run, the road deck was overtopped at 9, 12, 18, and 19 of the 30 stream crossings. None of the existing culverts meet the MA SCS. The spans of the existing culverts were all less than 1.2 times bankfull width. Three culverts met the openness ratio requirement of 0.82 ft. Few were 3-sided structures with natural stream bottoms or were closed bottom structures embedded with natural substrate.

Discussion

The methodology can be used to evaluate thousands of stream crossings in a consistent, defensible, and reproducible manner. The public availability of preliminary designs could allow municipalities and practitioners to consider potential designs and facilitate grant applications prior to conducting design and engineering analyses. The availability and use of these designs could help prevent in-kind replacements of undersized culverts with identically sized culverts and thereby result in resilient and AOP-friendly stream crossing replacement projects. For instance, according to the 2019 NAACC assessment, the condition of the Swamp Road culvert was characterized as “OK”. If the culvert were to be replaced to convey the 4% AEP hydraulic design flow, our preliminary culvert designs show that it would have to be 3.4 to 5.8 times larger in cross-sectional area than the existing culvert. If the replacement culvert were to meet the MA SCS, the crossing’s span would have to be widened to at least 18 ft to meet the span ratio requirements, almost 4 times as wide as the existing culvert. If the 30 stream crossings across Massachusetts used to assess the lidar-derived design method (Armstrong et al., 2026) were to be replaced in-kind, the stream crossings would still not meet the MA SCS and many of those culverts would not be sufficiently sized to convey the hydraulic design flows.

By providing preliminary designs of three different culvert types and five different sizing drivers, design professionals can evaluate potential options that may be appropriate given the site conditions of a stream crossing. For example, if site conditions, costs, or other considerations prevented large culvert spans, a pipe culvert may be appropriate; if raising the road deck is infeasible, a box with a higher span to rise ratio may be selected (Federal Emergency Management Agency, 2022). The provision of culvert designs that convey the four hydraulic design flows, regardless of the classification of the road, gives design professionals additional options to consider. To reduce risk of overtopping or culvert failure due to larger flood flows, practitioners could choose a culvert size that conveys a larger design flood than what is required. Practitioners could compare preliminary designs that convey the stream crossing's hydraulic design flow to designs that meet the MA SCS. The additional context of the provided habitat quality and stream restoration potential connectivity information could inform decision-making about the extent to which implemented designs meet the MA SCS.

There are, however, several limitations associated with the automatable lidar-derived method. The preliminary culvert designs produced are intended for stream crossings less than 20 ft in width. Crossings with spans of 20 ft or greater are considered to be bridges (Commonwealth of Massachusetts, 2025) and require more rigorous design and permitting processes beyond the scope of a one-dimensional hydraulic model. Other limitations include hydraulic modeling assumptions and uncertainties in the regional regressions used to compute peak flows and bankfull geometry.

The preliminary culvert designs are developed with hydraulic models that use lidar data and do not represent all site-specific conditions in all cases. For instance, culvert skew (the degree to which the road is not perpendicular to the flow) are not incorporated into the model and may lead to underestimation of water surface elevations in the models. Hydraulic characteristics upstream and downstream of the modeled reaches are not defined in the model, which could result in water surface elevations higher or lower than modeled elevations. One-dimensional HEC-RAS models assume uniform flow and velocity distributions across the channel and can be less effective at representing more complex flows than two- and three-dimensional hydraulic models (Brunner, 2020). Standard values for hydraulic roughness coefficients are applied for all channel and overbank areas. The designs also do not encompass all engineering design considerations. For instance, to allow for AOP at low flows, an engineering design professional may consider inclusion of low-flow channels or other modifications.

The regional regression equations used to compute peak flows have associated uncertainties and limitations (Zarriello, 2017). The drainage areas of stream crossing sites modeled in the Housatonic River watershed ranged from 0.01 mi^2 to 1.99 mi^2, with a mean of 0.57 mi^2. To develop the peak flow regional regression equations, the minimum drainage area of streamgages used was 0.16 mi^2, and only 16 percent of the streamgages had drainage areas less than 1.99 mi^2. Confidence in computed peak flows for stream crossing sites with drainage areas less than 0.16 square miles have not been determined, which may contribute to lower or higher peak flows and under- or oversized preliminary culvert designs. Future analyses could consider evaluating designs that convey the upper and lower 90-percent prediction intervals for each hydraulic design flow. Stream crossing sites with drainage areas composed of over 20 percent impervious area are excluded from the tool because of limitations of the peak flow regional regression equations. The USGS is currently (2026) developing peak flow regression equations applicable to urban streams in Massachusetts and Rhode Island, which could be used to develop preliminary culvert designs in more urban areas.

There is also associated uncertainty with the use of Massachusetts bankfull channel geometry regression equations (Bent & Waite, 2013). Of the 33 streamgage sites used to develop these equations, only one site (0.60 mi^2) was within the range of drainage areas of the stream crossing sites studied in the Housatonic River watershed. The other 32 streamgage sites ranged from 2.55 mi^2 to 329 mi^2. This could result in underestimation or overestimation in bankfull geometry. Bankfull width determines the minimum span required for culvert designs, so errors and uncertainties in bankfull geometry could result in under- or oversized designs.

The provision of modeling files and the ability to adjust portions of the automatable approach help overcome some limitations of this methodology. The StreamStats web application allows users to download all HEC-RAS model files. If the user has additional knowledge of site conditions, the model files can be modified, and new designs can be developed. Increasing the resolution and accuracy of any of the input datasets or updating the regression equations with additional data would likely result in more accurate preliminary results, which could extend the utility of this work. The method could be modified to allow for application to unnamed roads, trails, and railroads.

The method could also be adapted to non-stationarity in flood flow determinations. To better account for potential variability in peak flows due to climate change (Morsy et al., 2024; Olson et al., 2024), future development of the tool could include additional preliminary culvert designs sized to accommodate future flood flows. Future peak flows could be modeled in the designs generated from the existing methodology to indicate changes in freeboard and conveyance capacity. Future peak flows could also be used to generate preliminary designs that could convey flood flows for the design life of the culvert. These potential features could easily be incorporated into the approach, which could extend the utility of the method and product, and perhaps provide a basis for analysis of societal costs associated with changing conditions and infrastructure improvements.

Although the methodology presented here was developed for and calibrated to stream crossings in Massachusetts, the approach could be applied to other states or regions with study area-specific calibration and customization. Regression equations, design assumptions, and regulatory information could be modified to represent the new study area. Using this methodology in other areas could assist in the efficient development of preliminary culvert designs with greater flood resiliency and AOP for those communities.

Despite the limitations of the automatable lidar-derived method, its application demonstrates that the resulting designs are similar to those that come from field-derived data. The approach and methods presented here may be used to inform the development of preliminary designs at a large number of sites at a comparatively small cost in time and resources, as exemplified by the application to 343 sites in the Housatonic River watershed. The provision of preliminary culvert designs, the underlying hydraulic models, and supporting information to the public via USGS StreamStats could facilitate initial design, permitting, and cost estimations. If implemented, the designs could result in improvements to stream connectivity and resiliency that benefit both people and the environment.

References

Amaddii, M., Castelli, F., & Arrighi, C. (2026). Assessing road-watercourse crossing overtopping potential using GIS and remote sensing: A large-scale screening approach. *Natural Hazards*, *122*(3), 108. https://doi.org/10.1007/s11069-025-07907-8

American Concrete Pipe Association. (2022). *Concrete Pipe Design Manual*. https://resources.concretepipe.org/design-manual

Arcement, G. J., & Schneider, V. R. (1989). *Guide for selecting Manning's roughness coefficients for natural channels and flood plains*. https://doi.org/10.3133/wsp2339

Armstrong, I. P., McCarthy, B.A., McCallister, M.A., Sturtevant, L.P., Poe, M.W., Graziano, A.P., Tudor, A.L., Carlson, C.S., & Bent, G.C. (2026). *Hydraulic models and supplementary data for 30 stream crossing sites in Massachusetts*: U.S. Geological Survey data release. https://doi.org/10.5066/P9BSB3C1

ASTM International. (2022). *C1577-20: Standard Specification for Precast Reinforced Concrete Monolithic Box Sections for Culverts, Storm Drains, and Sewers Designed According to AASHTO LRFD*. https://compass.astm.org/content-access?contentCode=ASTM%7CC1577-20E01%7Cen-US

Bent, G. C., Trickey, K., & Jackson, S. D. (2022, October). *Developing a Statewide Hydraulic Modeling Tool*. U.S. Geological Survey, University of Massachusetts Amherst. https://newengland.water.usgs.gov/web_app/Stream_Crossing/index.html

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

Bjerklie, D. M., & Sturtevant, L. P. (2018). *Simulated hydrologic response to climate change during the 21st century in New Hampshire* (Scientific Investigations Report Nos. 2017–5143). U.S. Geological Survey. https://doi.org/https://doi.org/10.3133/sir20175143

Briccetti, L. (2025). *Assessing the Management and Impact of Private Road Crossings in the Lake Champlain Basin* (Lake Champlain Basin Program Technical Report No. 108). SUNY Plattsburgh. https://www.lcbp.org/wp-content/uploads/2025/04/108_Assessing-the-Management-and-Impact-of-Private-Road-Crossings-in-the-Lake-Champlain-Basin-1.pdf

Brunner, G. W. (2020). *HEC-RAS, River Analysis System Hydraulic Reference Manual* (CPD-69). U.S. Army Corps of Engineers, Hydrologic Engineering Center (HEC). https://www.hec.usace.army.mil/confluence/rasdocs/rasum/latest

Castro, J. (2003). *Geomorphologic Impacts of Culvert Replacement and Removal*. U.S. Fish and Wildlife Service. https://www.fs.usda.gov/biology/nsaec/fishxing/fplibrary/USFWS_2003_Geomorphic_impacts_of_culvert_replacement.pdf

Chow, V. T. (1959). *Open-Channel Hydraulics*. McGraw-Hill.

Commonwealth of Massachusetts. (2025). *Municipal Bridge Projects, Massachusetts General Laws chapter 85 section 35 review process*.

https://www.mass.gov/doc/new-bridge-and-bridge-replacement-project-requirements/download

Coon, W. F. (1997). *Estimation of roughness coefficients for natural stream channels with vegetated banks*. (Water Supply Paper 2441, x, 133 p). U.S. Geological Survey. https://doi.org/10.3133/wsp2441

Dewitz, J. (2023). *National Land Cover Database (NLCD) 2021 Impervious Surface Conterminous United States*. U.S. Geological Survey. https://doi.org/10.5066/P9JZ7AO3

Esri. (2025). ArcGIS Pro, version 3.5.2: Redlands, Calif., Esri software documentation.

Federal Emergency Management Agency. (2022). *Hurricane and Flood Mitigation Handbook for Public Facilities: Fact Sheet 1.4: Bridges*. https://www.fema.gov/sites/default/files/documents/fema_p-2181-fact-sheet-1-4-bridges.pdf

Gillespie, N., Unthank, A., Campbell, L., Anderson, P., Gubernick, R., Weinhold, M., Cenderelli, D., Austin, B., McKinley, D., Wells, S., Rowan, J., Orvis, C., Hudy, M., Bowden, A., Singler, A., Fretz, E., Levine, J., & Kirn, R. (2014). Flood Effects on Road–Stream Crossing Infrastructure: Economic and Ecological Benefits of Stream Simulation Designs. *Fisheries*, *39*(2), 62–76. https://doi.org/10.1080/03632415.2013.874527

Greer, A. D., Wilbanks, Z. B., Clifton, L. D., Wilson, B., & Graettinger, A. J. (2018). GIS-Enabled Culvert Design: A Case Study in Tuscaloosa, Alabama. *Advances in Civil Engineering*, *2018*(1), 4648134. https://doi.org/10.1155/2018/4648134

Harris, C. R., Millman, K. J., & Van der Walt, S. J. (2020). *Array programming with NumPy*. https://doi.org/10.1038/s41586-020-2649-2

Hopkins, K. G., Morse, N. B., Bain, D. J., Bettez, N. D., Grimm, N. B., Morse, J. L., & Palta, M. M. (2015). Type and timing of stream flow changes in urbanizing watersheds in the Eastern U.S. *Elementa: Science of the Anthropocene*, *3*, 000056. https://doi.org/10.12952/journal.elementa.000056

INDUS Corporation. (2013). *Streams and Waterbodies in Massachusetts*. U.S. Environmental Protection Agency. https://19january2021snapshot.epa.gov/sites/static/files/2014-09/documents/massachusetts.pdf

Kim, S., Lee, J., Mwaipopo, C., Baker, D., & Sprague, A. (2025). *Asset Characterization Using Automated Methods* (MoDOT Research Report Cmr 25-005). Missouri Department of Transportation. https://rosap.ntl.bts.gov/view/dot/85304

Kuichling, E. (1889). The Relation Between the Rainfall and the Discharge of Sewers in Populous Districts. *Transactions of the American Society of Civil Engineers.* 20(1). https://doi.org/10.1061/TACEAT.0000694

Levine, J. (2013). *An Economic Analysis of Improved Road-Stream Crossings*. The Nature Conservancy, Adirondack Chapter. https://www.cwicny.org/files/Road-Stream%20Crossing%20Economic%20Analysis.pdf

Makrakis, S., Castro-Santos, T., Makrakis, M. C., Wagner, R. L., & Adames, M. S. (2012). Culverts in paved roads as suitable passages for Neotropical fish species.

Neotropical Ichthyology, 10(4), 763–770. https://doi.org/10.1590/S1679-62252012000400009

Martin, E. H. (2019). Assessing and Prioritizing Barriers to Aquatic Connectivity in the Eastern United States. *JAWRA Journal of the American Water Resources Association*, *55*(2), 401–412. https://doi.org/10.1111/1752-1688.12694

Massachusetts Culverts and Small Bridges Working Group for Senator Hinds and the Massachusetts Legislature. (2020). *Recommendations for Improving the Efficiency of Culvert and Small Bridge Replacement Projects*. https://www.mass.gov/doc/massachusetts-culverts-and-small-bridges-working-group-report/download

Massachusetts Department of Conservation and Recreation. (2009). *MassGIS Data: Areas of Critical Environmental Concern*. https://www.mass.gov/info-details/massgis-data-areas-of-critical-environmental-concern

Massachusetts Department of Environmental Protection [MassDEP]. (2017). Wetlands protection, section 10 of Code of Massachusetts Regulations, title 310. https://www.mass.gov/doc/310-cmr-1000-the-wetlands-protection-act

Massachusetts Department of Environmental Protection [MassDEP] & University of Massachusetts Amherst [UMass Amherst]. (2023). *MassDEP culvert and bridge assessment tool*. https://landeco.umass.edu/web/Jun/DEP-MEP.zip

Massachusetts Department of Transportation [MassDOT]. (2017). *Construction standard details*. Highway Division. https://www.mass.gov/doc/2017-construction-standard-details/download

Massachusetts Department of Transportation [MassDOT]. (2025a). *Bridge Manual—Part I, Hundredth Anniversary Addition*. https://massdot.docs.mass.gov/hwy-bridge-manual/part-1/ch2-prelim-engineering-guidelines-w-appendix_0125.pdf

Massachusetts Department of Transportation [MassDOT]. (2025b). *MassDOT Road Inventory 2024*. https://geo-massdot.opendata.arcgis.com/datasets/MassDOT::road-inventory-2024/explore

Massachusetts Division of Ecological Restoration [MA DER]. (2012). *Massachusetts Stream Crossing Handbook, 2nd edition, 2018*. Massachusetts Department of Fish and Game. https://www.mass.gov/files/documents/2018/08/23/Stream%20Crossings%20booklet%20Web.pdf

Massachusetts Division of Fisheries and Wildlife. (2022). *MassGIS Data: MA Wildlife Coldwater Fisheries Resources*. https://www.mass.gov/info-details/massgis-data-ma-wildlife-coldwater-fisheries-resources

Massachusetts Division of Fisheries and Wildlife & The Nature Conservancy. (2026). *BioMap: The future of conservation in Massachusetts*. https://biomap-mass-eoeea.hub.arcgis.com/

Massachusetts Division of Local Services. (2026). *Road Miles*. Massachusetts Department of Revenue. Road Miles 2004 through Present. https://dls-gw.dor.state.ma.us/reports/rdPage.aspx?rdReport=socioeconomic.roadmiles

Massachusetts Division of Marine Fisheries. (2023). *MassGIS Data: Diadromous Fish*. https://www.mass.gov/info-details/massgis-data-diadromous-fish

McCallister, M. A., Armstrong, I. P., Sturtevant, L. P., McCarthy, B. A., Graziano, A. P., Poe, M. W., & Bent, G. C. (2026). *Housatonic River basin hydraulic models and supplementary data for stream crossings in Massachusetts*: U.S. Geological Survey data release. https://doi.org/10.5066/P13XIP93

McEnroe, B. M. (2006). *Downstream Effects of Culvert and Bridge Replacement*. Kansas Department of Transportation, University of Kansas Center for Research, Inc. https://rosap.ntl.bts.gov/view/dot/36542

McEnroe, B. M. (2007). *Sizing of Highway Culverts and Bridges: A Historical Review of Methods and Criteria*. University of Kansas & Kansas Department of Transportation. https://rosap.ntl.bts.gov/view/dot/37975

McGarigal, K., Compton, B. W., Jackson, S. D., Plunkett, E. B., DeLuca, W. V., & Grand, J. (2023). *Designing sustainable landscapes: Critical local linkages*. US Fish and Wildlife Service, North Atlantic-Appalachian Region. https://umasscaps.org/pdf/DSL_documentation_critical_linkages.pdf

Moccetti, P., Dodd, J. R., Joyce, D. A., Nunn, A. D., Gillespie, B., & Bolland, J. D. (2024). Genetic consequences of improved river connectivity in brown trout (Salmo trutta L.). *Evolutionary Applications*, *17*(4), e13660. https://doi.org/10.1111/eva.13660

Morsy, M. M., Roy, B., Shen, Y., Sadler, J. M., Chen, A. B., Zahura, F. T., & Goodall, J. L. (2024). Quantifying the Impact of Climate Change on Peak Stream Discharge for Watersheds of Varying Sizes in the Coastal Plain of Virginia. *Journal of Hydrologic Engineering*, *29*(3), 04024012. https://doi.org/10.1061/JHYEFF.HEENG-6114

National Aquatic Connectivity Collaborative. (2026). *National Aquatic Barrier Inventory & Prioritization Tool*. https://tool.aquaticbarriers.org/priority/small_barriers/

Natural Resources Conservation Service. (2004). *National Engineering Handbook*, Title 210, Part 630 Hydrology, Chapter 10 Estimation of Direct Runoff from Storm Rainfall. https://directives.nrcs.usda.gov/sites/default/files2/1712930608/7300.pdf

NOAA Office for Coastal Management Partners. (2016). *Maine and Massachusetts 2015 QL1 and QL2 Lidar*. NOAA National Centers for Environmental Information. https://www.fisheries.noaa.gov/inport/item/49614

North Atlantic Aquatic Connectivity Collaborative [NAACC]. (2019). *Display NAACC Non-tidal Aquatic Connectivity (after 6/1/2015) Data*. *Survey ID: 70078*. NAACC Data Center. https://naacc.org/naacc_display_crossing.cfm?aqId=70078

North Atlantic Aquatic Connectivity Collaborative [NAACC]. (2024). *North Atlantic Aquatic Connectivity Collaborative (NAACC) data for road-stream crossing assessments*. https://naacc.org/naacc_search_crossing.cfm

North Atlantic Aquatic Connectivity Collaborative [NAACC]. (2026). *About: North Atlantic Aquatic Connectivity Collaborative: UMass Amherst*. University of Massachusetts Amherst. https://streamcontinuity.org/about

Olson, S. A., Shabestanipour, G., Lamontagne, J., & Steinschneider, S. (2024). *Characterizing future streamflows in Massachusetts using stochastic modeling—A pilot study* (Scientific Investigations Report Nos. 2023–5134, p. 19). U.S. Geological Survey. https://doi.org/10.3133/sir20235134

O'Shaughnessy, E., Landi, M., Januchowski-Hartley, S. R., & Diebel, M. (2016). Conservation Leverage: Ecological Design Culverts also Return Fiscal Benefits. *Fisheries*, *41*(12), 750–757. https://doi.org/10.1080/03632415.2016.1246875

Perrin, J., & Jhaveri, C. S. (2004). *The Economic Costs of Culvert Failure*. TRB 2004 Annual Meeting. https://concretepipe.org/wp-content/uploads/2015/05/economiccosts.pdf

Poppenga, S. K., Worstell, B. B., Stoker, J. M., & Greenlee, S. K. (2010). *Using Selective Drainage Methods to Extract Continuous Surface Flow from 1-Meter Lidar-Derived Digital Elevation Data* (Scientific Investigations Report Nos. 2010–5059; p. 12 p). U.S. Geological Survey. https://doi.org/10.3133/sir20105059

Ries, K. G., III, Newson, J., Smith, M., Guthrie, J. D., Steeves, P., Haluska, T., Kolb, K., Thompson, R., Santoro, R., & Vraga, H. (2017). *StreamStats, version 4* (Fact Sheet Nos. 2017–3046). U.S. Geological Survey. https://doi.org/10.3133/fs20173046

Schall, J. D., Thompson, P. L., Zerges, S. M., Kilgore, R. T., & Morris, J. L. (2012). *Hydraulic Design of Highway Culverts—HDS-5—Third Edition* (FHWA-HIF-12-026). U.S. Department of Transportation, Federal Highway Administration. https://www.fhwa.dot.gov/engineering/hydraulics/pubs/12026/hif12026.pdf

Sliger, R., Graham, J., Hoenke, K., Kimball, M. E., Sterling, K. A., & Peoples, B. K. (2024). Integrating fish swimming abilities into rapid road crossing barrier assessment: Case studies in the southeastern United States. *PLOS ONE*, *19*(2), e0298911. https://doi.org/10.1371/journal.pone.0298911

Sturdevant Rees, P. L., Jackson, S. D., & Mabee, S. B. (2018). *A Proposed Method for Assessing the Vulnerability of Road-Stream Crossings to Climate Change: Deerfield River Watershed Pilot* (MassDOT Project 83226). University of Massachusetts Amherst. https://mass.gov/files/documents/2020/03/13/dot_Vunerability_RoadStream_Dec2019.pdf

Talbot, A. N. (1888). *The determination of water-way for bridges and culverts. Technograph No. 2.* University of Illinois.

Taylor, N. J., Sturtevant, L. P., & McCarthy, B. A. (2024). *Hydraulic Models and Supplementary Data for Selected Stream Crossing Sites in the Squannacook River Basin, North-Central Massachusetts (ver. 1.1, July 2024)*: U.S. Geological Survey data release. https://doi.org/10.5066/P9IUR97R

Thompson, J. R., Plisinski, J. S., Olofsson, P., Holden, C. E., & Duveneck, M. J. (2017). Forest loss in New England: A projection of recent trends. *PLOS ONE*, *12*(12), e0189636. https://doi.org/10.1371/journal.pone.0189636

University of Massachusetts Amherst [UMass Amherst], Department of Environmental Conservation. (2023). *Critical Linkages Phase I Results*. http://www.umasscaps.org/applications/critical-linkages.html

U.S. Army Corps of Engineers [USACE]. (2024). *Hydrologic Engineering Center's River Analysis System (HEC-RAS) software* (Version 6.6). https://www.hec.usace.army.mil/software/hec-ras/download.aspx

U.S. Federal Highway Administration [FHWA]. (2024). *HY-8 Culvert Hydraulic Analysis Program*. https://rosap.ntl.bts.gov/view/dot/88716

U.S. Forest Service [USFS]. (2008). *Stream simulation: An ecological approach to providing passage for aquatic organisms at road-stream crossings*. https://www.fs.usda.gov/eng/pubs/pdf/StreamSimulation/lo_res/Cover_TOC.pdf

U.S. Forest Service [USFS]. (2012). *FishXing*. FishXing. https://www.fsl.orst.edu/geowater/FX3/help/FX3_Help.html

U.S. Forest Service [USFS] & Inter-agency Wild and Scenic River Council. (2022). *National Wild and Scenic River Segments*. http://data.fs.usda.gov/geodata/edw/datasets.php

U.S. Geological Survey [USGS]. (2011). *National Land Cover Database (NLCD) 2006 (Land Cover (CONUS) 2006)*. https://www.mrlc.gov/data?f%5B0%5D=project_tax_term_term_parents_tax_term_name%3AAnnual%20NLCD

U.S. Geological Survey [USGS]. (2019a). *National Streamflow Statistics Application: Regional Regression Equation Publications by State or Territory.* https://www.usgs.gov/mission-areas/water-resources/science/national-streamflow-statistics-application-regional#overview

U.S. Geological Survey [USGS]. (2019b). *The StreamStats Program*. https://streamstats.usgs.gov/ss/

U.S. Geological Survey [USGS]. (2020). *USGS Lidar Point Cloud NY_ColumbiaRensselaer_2016_C18 u_5970067400_2016*. https://www.sciencebase.gov/catalog/item/600c626bd34e162231fbd634

U.S. Geological Survey [USGS]. (2026). *USGS Lidar Explorer Map*. https://apps.nationalmap.gov/lidar-explorer

Virtanen, P., Gommers, R., & Oliphant, T. E. (2020). *SciPy 1.0: Fundamental algorithms for scientific computing in Python*. https://doi.org/10.1038/s41592-019-0686-2

Walters, D. (2025). *The 3D Elevation Program—Supporting the Economy of Massachusetts* (Fact Sheet Nos. 2025–3044, 2 p). U.S. Geological Survey. https://doi.org/10.3133/fs20253044

Wright, L., Chinowsky, P., Strzepek, K., Jones, R., Streeter, R., Smith, J. B., Mayotte, J.-M., Powell, A., Jantarasami, L., & Perkins, W. (2012). Estimated effects of climate change on flood vulnerability of U.S. bridges. *Mitigation and Adaptation Strategies for Global Change*, *17*(8), 939–955. https://doi.org/10.1007/s11027-011-9354-2

Zarriello, P. J. (2017). *Magnitude of flood flows for selected annual exceedance probabilities for streams in Massachusetts* (Scientific Investigations Report Nos. 2016–5156, 54 p). U.S. Geological Survey. https://doi.org/10.3133/sir20165156

Data Availability Statement

The data that support the findings of this study are publicly available as data releases (Armstrong et al., 2026; McCallister et al., 2026).