CLIMATE VULNERABILITY AND ECONOMIC ASSESSMENT FOR AT-RISK TRANSPORTATION INFRASTRUCTURE IN THE LAKE CHAMPLAIN BASIN, NEW YORK

PREPARED BY NEW YORK STATE DEPARTMENT OF TRANSPORTATION
IN PARTNERSHIP WITH THE NATURE CONSERVANCY

SUBMITTED TO FEDERAL HIGHWAY ADMINISTRATION - PILOT PROJECTS: CLIMATE CHANGE AND EXTREME WEATHER VULNERABILITY ASSESSMENTS AND ADAPTATION OPTIONS ANALYSIS

DECEMBER 2015

Debra Nelson, NYSDOT Project Manager
Michelle Brown, TNC Principal Investigator

Note:

This report was developed by the New York State Department of Transportation in accordance with a grant from the Federal Highway Administration (FHWA). The statements, findings, conclusions and recommendations are those of the authors and do not necessarily reflect the views of FHWA or the U.S. Department of Transportation.

Technical Report Documentation Page
Form Approved OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY	2. REPORT DATE December 2015	3. REPORT TYPE AND DATES Final Report
4. TITLE AND SUBTITLE Climate Vulnerability and Economic Assessment for At-Risk Transportation Infrastructure in the Lake Champlain Basin, New York		**5. PROJECT ID NUMBER**
6. AUTHOR(S) Debra Nelson (New York State Department of Transportation), Michelle Brown and Jessica Levine (The Nature Conservancy)		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) New York State Department of Transportation 50 Wolf Road Albany, NY 12232 The Nature Conservancy 8 Nature Way PO Box 65 Keene Valley, NY 12943		**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) US Department of Transportation Federal Highway Administration Office of Natural Environment 1200 New Jersey Avenue, SE Washington, DC 20590		**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**
11. SUPPLEMENTARY NOTES		
12a. DISTRIBUTION/AVAILABILITY STATEMENT **Available From:**		**12b. DISTRIBUTION CODE**

13. ABSTRACT (Maximum 200 words)

The New York State Department of Transportation (NYSDOT), in partnership with The Nature Conservancy (TNC), wrote this report in fulfillment of a grant from the Federal Highway Administration's (FHWA) Climate Change Resilience Pilot Program. The purpose of the program was to pilot approaches to conduct climate change and extreme vulnerability assessments of transportation infrastructure and to analyze options for adapting and improving resilience. NYSDOT and TNC developed tools and approaches to assess vulnerability primarily focused on one asset – culverts. They evaluated vulnerability, criticality and risk, and developed a method to apply an environmental importance score to each culvert. Finally, they developed a benefits valuation approach to help decision makers prioritize infrastructure and assess when to undertake culvert replacements considering social, economic, and environmental factors.

14. SUBJECT TERMS Climate Change, Adaptation, Resilience, Infrastructure, Culverts		**15. NUMBER OF PAGES** 128
		16. ACCOUNTING DATA

17. SECURITY CLASSIFICATION OF REPORT **Unclassified**	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** Unlimited

CONTENTS

EXECUTIVE SUMMARY

The New York State Department of Transportation (NYSDOT), in partnership with The Nature Conservancy (TNC), has written this report in fulfillment of a grant from the Federal Highway Administration's (FHWA) Climate Change Resilience Pilot Program. The purpose of the program is to pilot approaches to conduct climate change and extreme vulnerability assessments of transportation infrastructure and to analyze options for adapting and improving resilience. NYSDOT and TNC developed tools and approaches to assess vulnerability primarily focused on one asset – culverts. We evaluated vulnerability, criticality and risk, and developed a method to apply an environmental importance score to each culvert. Finally, we developed a benefits valuation approach to help decision makers prioritize infrastructure and assess when to undertake culvert replacements considering social, economic, and environmental factors.

This report conveys details on our approach, findings, lessons learned, and recommendations for next steps on how to build resiliency into NYS infrastructure. The following are the key elements:

- More frequent and intense future storms are predicted to increasingly threaten the life span and ability of culverts to function properly.
- We developed an approach to assess vulnerability including an enhanced StreamStats tool that incorporates future climate projections and direct outreach to engaged experts at the local and state level.
- A new decision tool helps determine when a culvert replacement is warranted based on risk (vulnerability and criticality), environmental importance, and economic benefits and costs.
- A benefits valuation approach provides a framework for including social, economic, and environmental data, when data are available.
- NYSDOT is taking steps to incorporate climate vulnerability considerations into decisions through the institutionalization of an asset management framework that incorporates the Sustainability "Triple Bottom Line" of economic competitiveness, social equity and environmental stewardship in its investment decisions.

The FHWA Climate Change Resilience Pilot Program provided a helpful launching point to develop concepts for assessing and implementing climate-friendly culvert designs into NYSDOT's decision-making. While we accomplished a great deal, we look forward to continuing to refine and improve our abilities to assess and incorporate resilience into transportation planning beyond this project.

INTRODUCTION

"The transportation planners, designers, and operators of this nation's transportation systems face many daunting concerns, not the least of which is funding to maintain and improve the country's infrastructure and competitiveness. To these concerns is now added climate change or global warming." Schwartz (2011).

In the last decade, there has been much research undertaken on climate change and its various effects on transportation assets and operations. Major et al. (2011) focuses specifically on effects of climate change to New York State Department of Transportation operations. In their report, they indicate that impacts on transportation from changing climate include permanent inundation of facilities from rising seas; more frequent and extensive flooding of facilities from coastal storms; increased flooding and downtimes from potentially more intense inland and urban storms; and stresses on facilities from increased heat.

Like much of the Northeast, communities in the Lake Champlain Basin of northern New York and Vermont have experienced increased precipitation and extreme flooding over the past 50 years, which have caused major damage to homes, businesses, and infrastructure. In 2011, the Lake Champlain Basin experienced two record-breaking floods; unprecedented spring flooding led to the highest lake levels on record, and in August, intense precipitation created by Hurricane Irene led to widespread flooding and damage estimated between $7-10 billion. A single sub-watershed (Ausable River) experienced an estimated $6.4 million in damage to roads and bridges on town and county roads alone.

Considering climate change in transportation asset management may require modification to designs and specifications. Meyer (2006) postulates that "It is a basic tenet of civil engineering that the design of structures cannot be divorced from the environment within which they are built. The risks of doing otherwise could be catastrophic. This tenet of civil engineering leads to a challenging question of how such practice might vary given changes in this environment, such as those expected due to climate change." Hyman et al. (2011) stress that "adaptation to climate change necessitates a shift in existing design and planning paradigms, as the demands placed on transportation will require more robust systems that can cope with an increasingly extreme and volatile climate."

A 2010 report from The Nature Conservancy (TNC) used downscaled global circulation models to predict potential climate change impacts to the Basin through the year 2100 (Stager and Thill 2010). The models anticipate more frequent severe storm events, up to 15% increase in annual

precipitation, and mean lake levels rising by up to two feet by the end of this century. This suggests that the record floods of 2011 could actually be 'the new norm' for the region in the future. Already, climate records show that mean annual temperature in New York's North Country has warmed 1.5 degrees C in the last 30 years, and weather records from local stations show an increase in large, high-intensity rainstorms (Jenkins 2010).

Transportation agencies across the globe are beginning to consider how the impacts of climate change will influence their policies and programs for asset management. Lambert et al. (2013) explain the various impacts of climate change on transportation infrastructure, stressing the potential for regional transportation to be disrupted and system operations, such as evacuations, traffic management and monitoring, and other activities, to be impacted.

The impacts of climate change on the US Highway System were highlighted in a 2011 report conducted for the National Cooperative Highway Research Program (NCHRP), which called particular attention to increased precipitation, noting: "Risks to the highway system due to … increased precipitation amounts/intensity appear to be the biggest cause for concern and amongst the first priorities for action." Among the report's recommendations was the redesign of culverts to accommodate both fish passage and new patterns of precipitation (Meyer et al. 2011). Undersized and poorly designed culverts are often at ground zero of flood damage. They are the site of debris jams and the subsequent overflow of sediment and water, and are particularly vulnerable to changing precipitation patterns and storm events.

The magnitude of the New York State Department of Transportation's (NYSDOT) culvert program presents a serious logistical and financial challenge. New York State owns approximately 9,000 large culverts (spans between 5 feet and 20 feet) and an estimated 128,000 small culverts (spans less than or equal to 5 feet). As noted by Greco and Nelson (2009), large and small culverts need to be replaced at annual amounts of 50 and 1,600, respectively, estimated at that time to cost approximately $90M annually. NYSDOT investigations have determined that ecologically-based design of highway stream crossings, if applied indiscriminately, could increase the overall cost of the culvert program by as much as 80%, with a disproportionately large cost increase in the small culvert size class (300%). This cost does not even incorporate additional design alterations to address potential risk to infrastructure from climate change. Cost increases may be justifiable at particular locations based on vulnerability and compelling environmental benefits. However, sometimes the cost may not be justified because existing conditions prevent environmental improvements, such as in streams with severe and systemic water quality impairments.

Development and application of prioritization methods are imperative to ensure that vital resources will be available for improvements on higher priority streams and at-risk infrastructure, especially given the current fiscal climate and focus on reinvestments (e.g., maintenance). DOTs need to understand the full benefits and full costs of the options they may choose in short and long time frames. This work requires collective understanding of the broad range of issues associated with culvert and road repair, replacement and installation, direct and diffuse benefits and costs, as well as stream dynamics and characteristics of natural resources.

OBJECTIVES

The objectives of this study are to:

1) **Prioritize road-stream crossings and road segments** that are the most vulnerable to expected climate change impacts, of greatest safety importance, and the most ecologically important;
2) **Evaluate engineering-based design adaptation options** for vulnerable road-stream crossings;
3) **Create an economic tool that evaluates the full benefits and costs of adaptation options,** primarily culvert replacements, to help DOTs prioritize adaptation investments and evaluate alternative design options; and
4) **Incorporate climate vulnerability results into existing NYSDOT standards, guidelines, and tools**.

GEOGRAPHIC FOCUS

The geographic focus of this project is the New York portion of the Lake Champlain Basin, which is roughly 3,015 square miles (Fig. 1). The Basin contains roughly 5,400 miles of mapped rivers and streams and overlaps with five counties in NY. Although focused in NY, the results are relevant in the Vermont portion of the Basin and far beyond the region.

CLIMATE RISK FOCUS

The climate risk focus of this project is changing precipitation patterns and extreme precipitation events. Climate change during the past century has resulted in altered precipitation amounts, form (rain vs. snow), and intensity (Huntington et al. 2009). Additional changes in precipitation are forecast over the next century as the global and regional climate is expected to warm substantially (Hayhoe et al. 2007).

These ongoing and projected future changes in precipitation, along with other related changes to evapotranspiration rates and land use patterns, will result in changes to streamflow patterns (Hayhoe et al. 2007). Although precipitation amounts have generally increased in the Northeast during the past 20-30 years (Huntington et al. 2009), climate models show a wide range of variation in future precipitation patterns, though consensus has emerged around several trends: (1) snow will make up a declining proportion of total precipitation, (2) the size and intensity of large storms is likely to increase, and (3) droughts will become more frequent and severe (Trenberth et al. 2003).
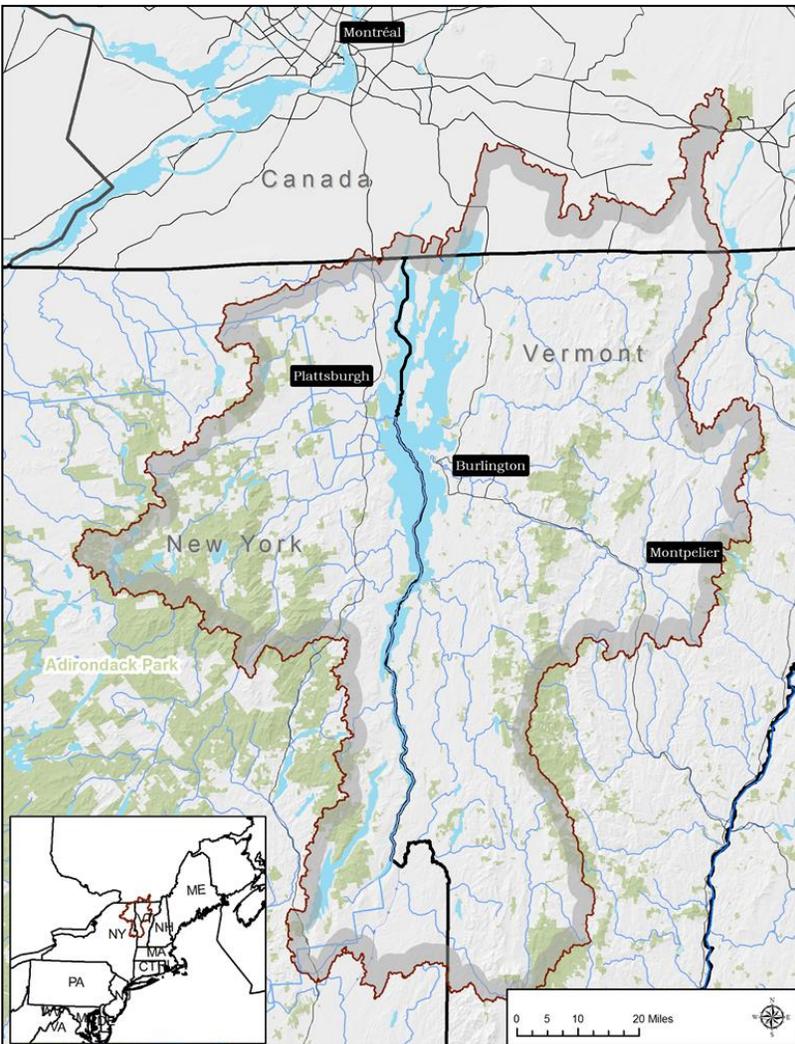
To set the stage for this study, we examined local patterns of rainstorm intensity over the last century in the Adirondack-Champlain region. We looked at the relationship between extreme rainstorms and river discharge to forecast changes in rainstorm intensity and discharge over the next 50 to 100 years (see Appendix A). As presented in Appendix A, several findings emerged from this analysis. First, the intensity of extreme rainfall events has increased significantly in the Adirondack-Champlain region during the last century. Second, damaging flood events that are now considered to be highly unusual are likely to become more common and more intense in coming decades. To design and build safe infrastructure, changes in precipitation patterns should be considered to ensure road and stream crossings can withstand expected changes in peak streamflow.

Figure 1. Lake Champlain Basin watershed.

4

PROJECT APPROACH

OBJECTIVE 1: PRIORITIZE ROAD-STREAM CROSSINGS AND ROAD SEGMENTS THAT ARE THE MOST VULNERABLE TO EXPECTED CLIMATE CHANGE IMPACTS, OF GREATEST SAFETY IMPORTANCE, AND THE MOST ECOLOGICALLY IMPORTANT.

CLIMATE PROJECTIONS IN DESIGN DISCHARGES
Introduction. To determine expected climate change impacts, we incorporated future climate projections into StreamStats to determine design discharges for bridge and culvert designs. The StreamStats Program (http://water.usgs.gov/osw/streamstats/new_york.html) is a program set up and maintained by the United States Geological Survey (USGS) to determine stream discharges that can be expected for a range of probabilities or return periods. New York State DOT hydraulic engineers use the StreamStats routine to determine design discharges for bridge and large culvert designs. These hydraulic structures are sized to pass flows having a standard probability or risk of occurrence.

StreamStats, along with other techniques for predicting flood frequencies for design, uses past observations of rainfall and stream flow to calculate discharge. This presents a challenge for designing resilient facilities. Because structures designed today have an expected life span of 75 years, future changes in precipitation patterns, storm frequency, and stream flow are generally not accommodated for in the designs. In other words, in the latter part of a culvert's expected life, it will face different flow conditions. The discharge that corresponds to a 2% annual risk today will carry a higher risk in the future.

To that end, for this study we used a new tool developed to incorporate climate scenarios into transportation planning. This tool allows hydraulic designers to consider future risk conditions in structure designs, ensuring adequate stream flow capacity throughout a structure's design life.

Methods. A new, enhanced web-based tool developed by the USGS Troy, NY office, titled "StreamStats: Estimated Impact of Climate Change on Peak Flow Magnitudes", estimates the magnitude of future peak flows for streams and rivers in New York State and the Champlain Basin in Vermont. Methods are described briefly below and presented in detail in Appendix B.

To evaluate how future climate might affect peak flow magnitudes, data were applied from five climate models that were part of the most recent global climate assessment (5th Phase of the

5

Coupled Model Intercomparison Project (CMIP5); Taylor et al., 2012). These models were selected based on discussions with climate scientists as to which of the CMIP5 climate models best represented past trends in precipitation in the Lake Champlain basin (based on an analysis described in Guilbert et al., 2014).

Precipitation data were evaluated for two future scenarios that provide estimates of the extent to which greenhouse gas concentrations in the atmosphere are likely to change through the 21st century. These scenarios, RCP 4.5 and RCP 8.5, were evaluated for each of the five climate models we selected. RCP is an abbreviation for Representative Concentration Pathways, referring to potential future emissions trajectories of greenhouse gases such as carbon dioxide and others. RCP 4.5 is considered a mid-range emissions scenario, and RCP 8.5 a high emissions scenario.
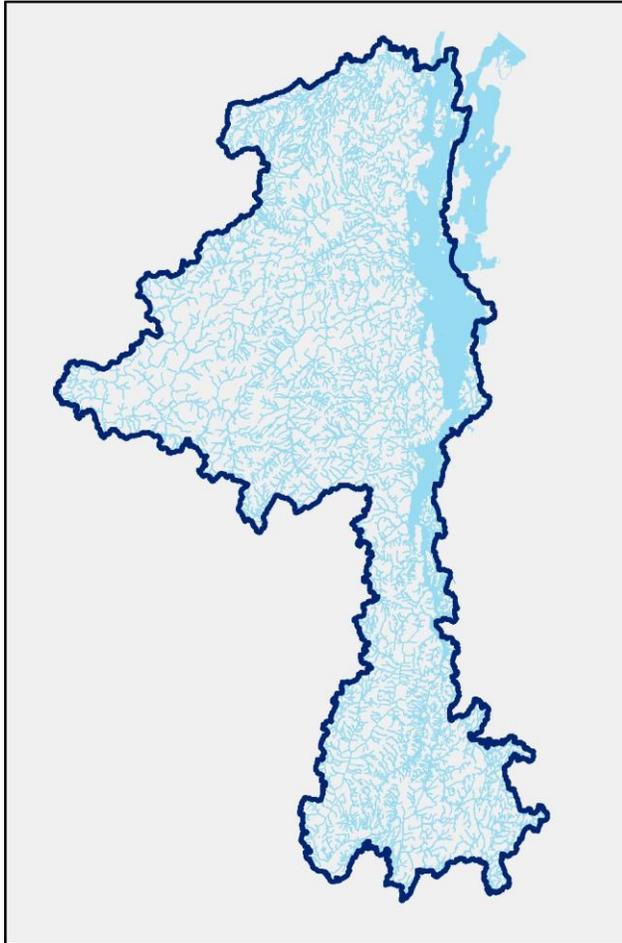
Results were averaged for three future time periods (2025-49, 2050-74, and 2075-99) following the approach used in the USGS Climate Change Viewer (http://www.usgs.gov/climate_landuse/clu_rd/nccv.asp). The downscaled precipitation data for each model and RCP scenario averaged over these 25 year time windows were obtained from the developers of the USGS Climate Change Viewer (Jay Alder, U.S. Geological Survey, personal communication, http://www.usgs.gov/climate_landuse/clu_rd/nccv.asp).

Findings. The combination of climate models, greenhouse gas scenarios, and time periods, can provide up to 30 sets of peak flow magnitude estimates for each stream watershed delineated. These results are meant to reflect a range of variation predicted among the five climate models and two greenhouse gas scenarios. Additional information on the models, greenhouse gas scenarios, and time periods is available in Appendix B; the StreamStats Climate Change Tool can be found here: http://ny.water.usgs.gov/maps/floodfreq-climate/ .

ECOLOGICAL CULVERT RANKING

Introduction. We developed a culvert prioritization methodology to identify culverts that have high ecological value. The methods were based on a previous analysis that identified about 150 high priority ecological culverts across NYS on state roads (TNC, 2010). The current assessment applied that methodology to the Lake Champlain Basin, which allowed us to use a more detailed stream database, roads data for state, county, and town municipalities, and new ecological data. The prioritization methodology consisted of three steps conducted in a geographic information system (GIS): data preparation, fragmentation analysis, and the development of ecological ranking models. The fragmentation analysis identified the most intact stream networks in the watershed by calculating how many miles of stream existed

between every dam and culvert in the analysis, and associated each barrier with that distance. The ecological ranking models incorporated 16 ecological inputs (including the results of the fragmentation analysis) and produced a tiered ecological ranking of all the road and stream crossings in the Lake Champlain watershed.

Methods

1. Data Preparation

Hydrology. The hydrology data set that was used for the analysis was the USGS National Hydrography Dataset (NHD) High Resolution 1:24,000 (Fig. 2). We verified the directionality of the stream flow and removed any bifurcations so all streams could flow to the outlet.

Unit of Analysis: potential barriers. There is no comprehensive database of culvert locations in the watershed. Therefore, we created a predicted culverts layer in GIS by intersecting the hydrology layer with roads. This produced a point dataset representing all potential road and stream crossings (Fig. 3). We cross-referenced this dataset with known bridge, dam, and waterfall locations (NYS bridge dataset, NYS DEC Inventory of Dams dataset).

Figure 2. Stream hydrography.

Throughout the report, the *potential barrier layer* refers to this dataset of culverts, dams, and waterfalls. These are considered potential barriers to aquatic organism passage.

2. Fragmentation Analysis

The Barrier Analysis Tool (BAT) was used to analyze the fragmenting effects of dams and culverts on streams. BAT is a GIS tool that evaluates overall watershed connectivity and the potential magnitude of each individual barrier's fragmenting effect (Hornby, 2010).

We updated the potential barrier layer with existing field data from previously completed culvert inventory projects. In other words, if we knew a culvert was not a barrier to aquatic organism passage, we included that information in the database. We assumed crossings on large rivers were bridges and did not consider them to be barriers to aquatic organisms.

We calculated several fragmentation metrics resulting from the BAT tool: upstream and downstream stream miles between each barrier (termed functional network) (Fig. 4), the absolute mileage gain upstream of each barrier (Fig. 4), and culvert density along a stream (Olivero and Jospe, 2006).
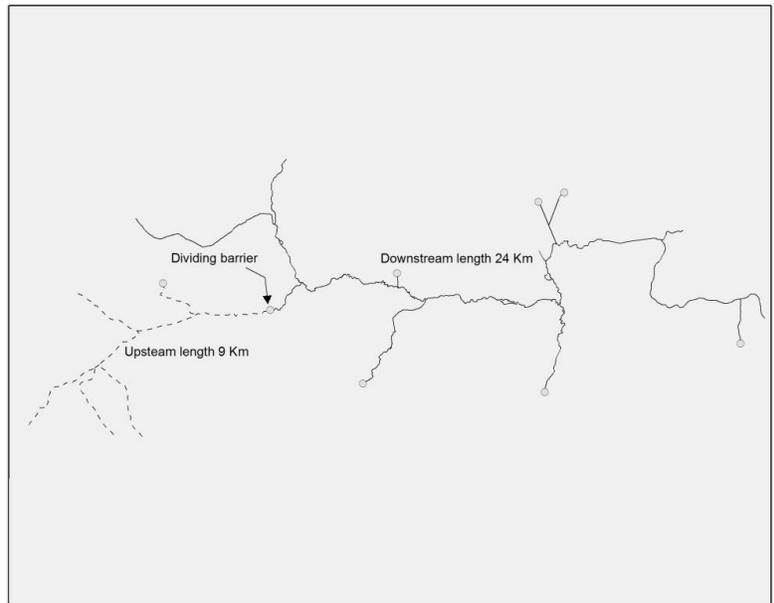
Figure 3 (above). Culverts, dams, and waterfalls in the Lake Champlain Basin.

Figure 4 (right). Barriers (gray points) serve as the dividing point between two networks (solid and dashed lines). The removal of a dividing barrier results in the solid stream network "gaining" the dashed stream network. This is termed "absolute gain." From Olivero and Jospe, 2006.

3. Ecological Ranking Model

The objective of the ecological ranking model was to identify culverts that were ecological priorities. We used 16 criteria to evaluate each culvert (Table 1; Fig. 5) and calculated a cumulative total score. The score for each culvert was ranked highest to lowest and grouped into four equal tiers of ecological value (Fig. 6). The criteria were determined by an expert team comprised of NYSDOT, NYSDEC, USFWS, SUNY Plattsburgh, and TNC.

The ecological ranking model allows users to select specific criteria for their needs. Table 1 illustrates the subset of criteria that our project team used to calculate ecological value, but any combination of criteria can be selected. Furthermore, users can weight each criterion according to its importance. This flexibility allows a user to apply this approach at multiple scales. For example, a user can select and weight criteria based on local importance or regional data availability.

Table 1. Criteria for identifying priority ecological culverts.

| Criteria	Data Source
Upstream culvert density	The Nature Conservancy
Downstream culvert density	The Nature Conservancy
Total length of upstream and downstream functional network from each culvert (miles)	The Nature Conservancy
Absolute gain in stream miles upstream of each culvert	The Nature Conservancy
Percent impervious surface in watershed upstream of culvert	US Geological Service
Percent natural land cover in riparian area of upstream functional network	US Geological Service
Percent natural land cover in riparian area of downstream functional network	US Geological Service
Percent conserved land within riparian area of upstream functional network	The Nature Conservancy
Percent conserved land within riparian area of downstream functional network	The Nature Conservancy
Number of rare fish in upstream functional network	NY Natural Heritage Program
Number of rare fish in downstream functional network	NY Natural Heritage Program
Number of rare mussel in upstream functional network	NY Natural Heritage Program
Brook trout locations in downstream functional network	NYS Dept. of Env. Conservation
Brook trout locations in upstream functional network	NYS Dept. of Env. Conservation
"Healthy" Eastern Brook Trout watersheds (HIC12) at each culvert	Eastern Brook Trout Joint Venture
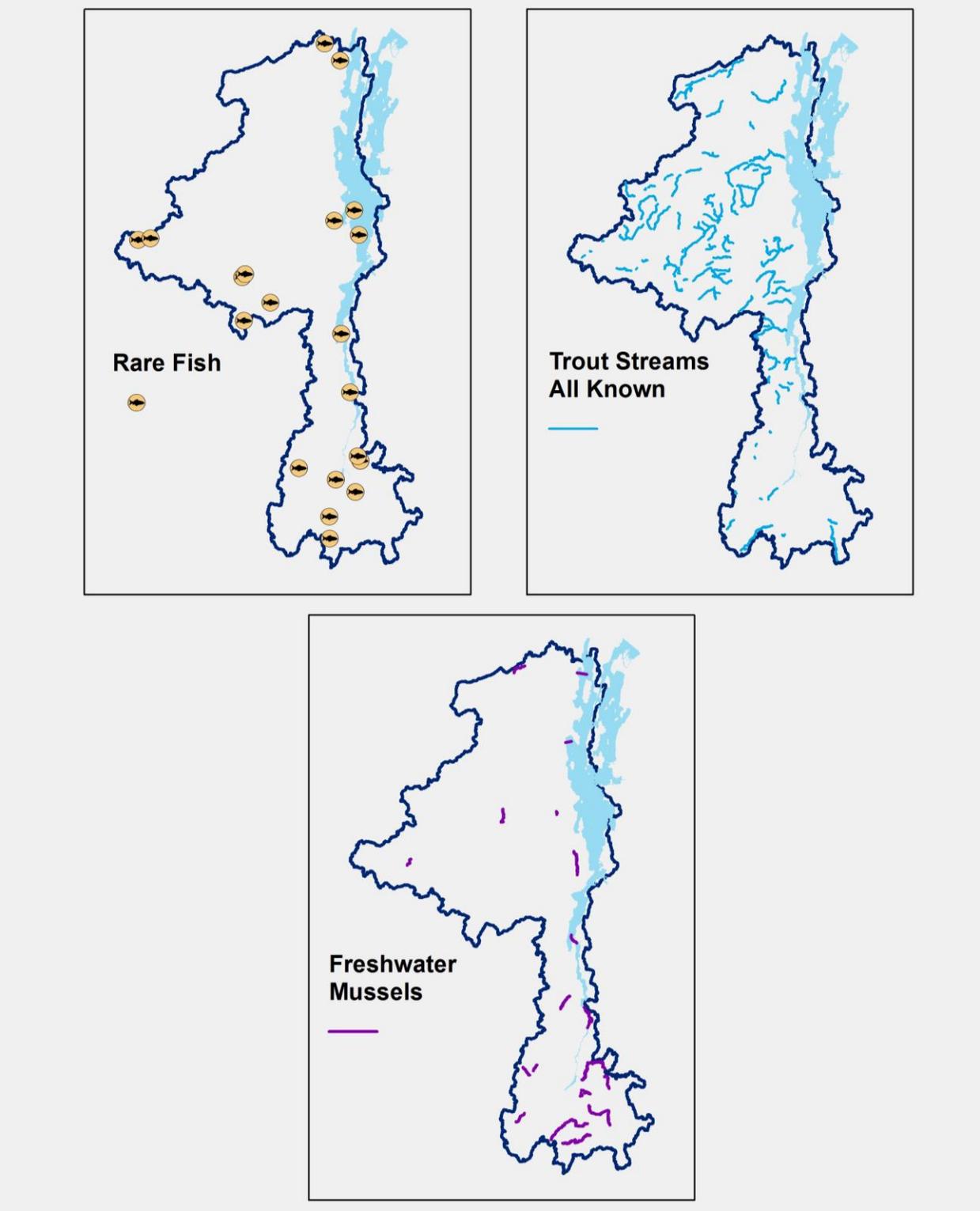
Figure 5. Criteria used to prioritize ecologically important culverts.

Key Findings. More than 4500 road stream crossings were assessed using the ecological prioritization method. A general trend emerged showing headwaters and streams upstream in the watershed as higher ranked ecological priorities (Fig. 6). In the Lake Champlain watershed, these areas tend to be higher gradient, proximate to protected lands, and less fragmented by roads. Our previous assessment also identified culverts where there was a large amount of unfragmented habitat upstream, but, due to the focus on state roads (versus municipal roads), these culverts were more likely on larger streams, lower in the stream network.

The flexible scoring framework creates an approach that is scalable for application in both towns and across New York State (Fig. 7). This is of critical importance, as towns often do not have access to ecological data. Using a consistent framework also allows for better communication and in some cases affords the towns access to state resources for project implementation (e.g., NYS Water Quality Improvement Program).

The ecological culvert rankings and all of the underlying data have been added to the NYSDOT statewide environmental viewer, which is available to NYSDOT employees. Several components of the analysis can be found here: http://nyanc-alt.org/gis/champlain/.
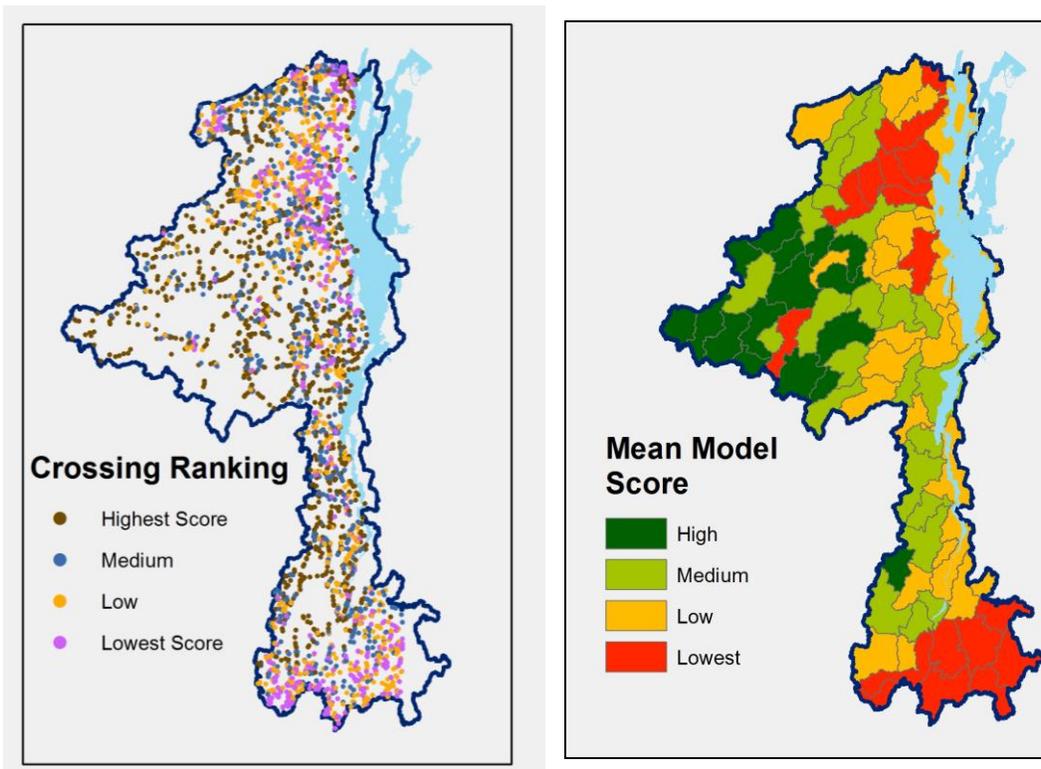
Figure 6. Stream road crossing ranks based on ecological criteria.
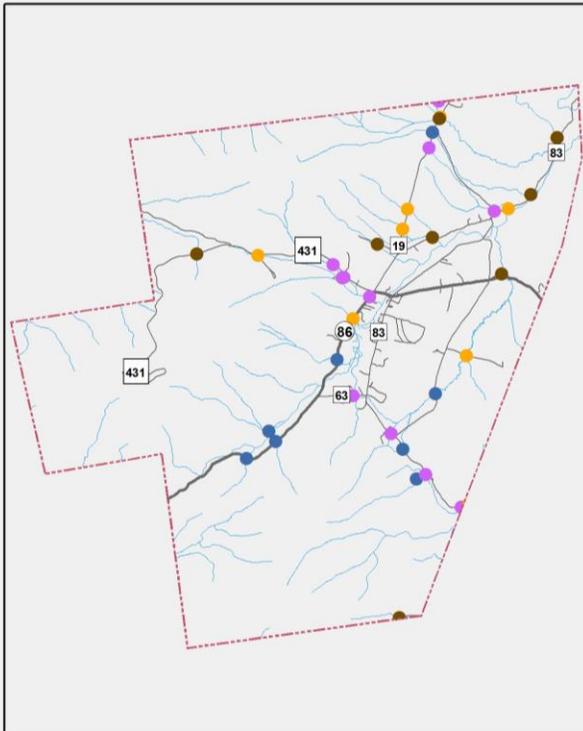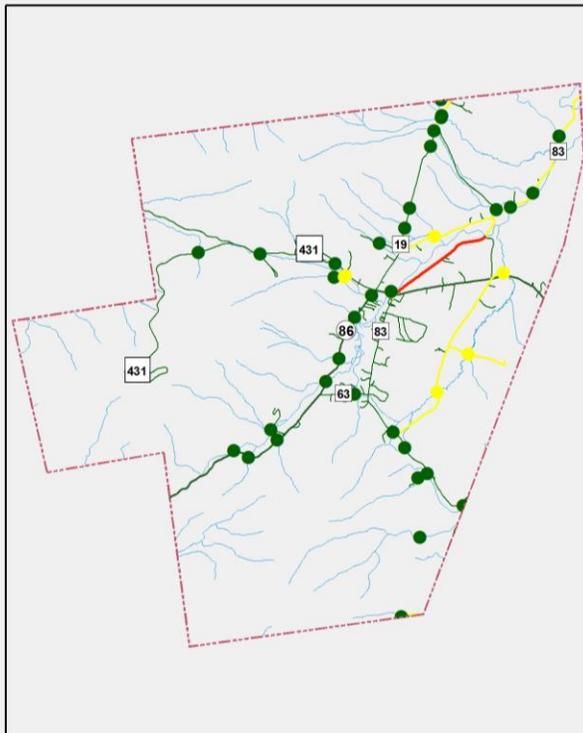
Figure 7. Example of the scalability of stream road crossing data for municipal use.

VULNERABLE, CRITICAL, AND AT-RISK CULVERTS

Introduction. As an additional component of objective 1, we developed and applied a methodology to identify the relative flood risk of road-stream crossings and road segments in the New York portion of the Lake Champlain Basin (Fig. 8). For this analysis, we determined that the two key components of flood risk are flood vulnerability and road criticality.

Methods

1. Vulnerability Assessment

We compiled information about vulnerable road-stream crossing and road segment data through direct outreach, via in-person meetings with staff from the following departments:

- Essex County Department of Public Works
- Clinton County Department of Public Works
- Town highway supervisors from Essex County and Clinton County

Flood vulnerability information was provided voluntarily by highway department engineers and directors.

On town and county roads, road-stream crossings (culverts and bridges) identified as vulnerable to flooding were mapped using GIS and those points were assigned a score of 10 (vulnerable) while all other crossings were scored with a 1 (not vulnerable). In addition, road segments containing vulnerable stream crossings are ranked as vulnerable between the two nearest intersections on either side of the crossing.

In a separate effort, a NYSDOT team created a statewide GIS data layer of flooding vulnerable locations based on information from in-house staff. To develop a qualitative statewide vulnerability assessment, in 2014, NYSDOT modeled an in-house effort after Washington Department of Transportation's (WSDOT) 2011 FHWA Climate Change Pilot Project (FHWA, 2014). Similar to WSDOT's FHWA pilot program, NYSDOT developed a structured, stakeholder-based approach to qualitatively assess facility risk. The NYSDOT team met with NYSDOT regional maintenance units and regional hydraulic engineers to solicit information on flood vulnerable locations on state roads, along with determining available detours, causes of concern, etc. We were able to use the state road vulnerability data extracted from NYSDOT's Flooding Vulnerability Assessment GIS Layers, which display bridges, culverts and road segments that are vulnerable to flooding as well as the bridges on the Statewide Flood Warning Bridge Watch list. Locations categorized as medium or high received a score of 10 (vulnerable) in the vulnerability assessment. Low vulnerability sites were not included in the analysis.

The vulnerability GIS layer shows all vulnerable road-stream crossings and segments with a score of 10.

2. Criticality Assessment

Using GIS, all road segments were assigned a criticality score from 1 (least critical) to 10 (most critical). Criticality scores were calculated as follows:

Criticality Score = Critical Facility Score + Functional Classification Score

a) *Critical Facility Score*
    The Critical Facility score indicates the presence of a critical facility, defined as hospitals, fire stations, police stations, and ambulance services. Road segments containing critical facilities received a critical facility score of 5 for the segment between the two nearest intersections on either side of the facility. Road segments without a critical facility received a critical facility score of 0. Stream crossings were scored based on the score of the road segment on which they are located.

b) *Functional Classification Score*
    The Functional Classification (FC) score indicates the role that a road segment plays in serving the flow of traffic through the road network. There is a general relationship between a road segment's functional classification and its usage. NYSDOT data was used for these scores. Using GIS, we assigned FC scores to road segments as follows:

Road Type	FHWA FC code	FC Score
Principal arterials	1, 2, 3	5
Minor arterials and major collectors	4, 5	3
Minor collectors and local roads	6, 7	2
All other local roads	-	1

3. Risk Assessment

Using GIS, we assigned a Risk Score to each road segment and road-stream crossing, using the following formula:

Risk Score = Vulnerability Score x Criticality Score

Risk values range from 1-100, with higher scores indicating higher risk. For visualization purposes, we created three categories of risk:

  High risk: scores of 50-100

  Medium risk: scores of 10-40

  Low risk: Scores less than 10

Key Findings. Through this analysis, we found that 98% of culverts in this region are low risk, less than 2% of culverts are medium risk, and less than 1% of culverts are high risk (http://nyanc-alt.org/gis/champlain/). This equates to seven high risk crossings. In most places in this rural region, there are easily accessible alternative routes and significant redundancy in the network, particularly for roads with critical services. This resulted in a low number of at-risk crossings. Similarly, less than 1% of all road miles are ranked as high risk. Due to the scoring framework, a road segment or culvert must be identified as vulnerable to be ranked high risk. This supports decision-makers focused on identifying the most critical and vulnerable facilities.

For the risk assessment, we deliberately chose methods that could be replicated in other places. To assess vulnerability, we utilized a low-tech but fairly time-intensive outreach approach because comprehensive vulnerability data are currently not available in NYS. The approach, which has been used in other places, such as Washington State, has the advantage of being repeatable but the disadvantage of being subjective, based on several factors: willingness to participate, knowledge of the roads/culverts in the jurisdiction, history with the department, locality-specific flood history, and perception of "vulnerable." Through this project, we advanced the state of knowledge and created new vulnerability data now available. We also developed a tool, the enhanced StreamStats tool, which could provide widespread vulnerability if comprehensively applied.

For the criticality assessment, we relied on data that is fairly easy to access for critical services. We excluded other facilities that may contain large numbers of people (e.g., schools, theaters, shopping centers) on the basis that flood events are typically forecast in advance (in contrast to events like earthquakes), allowing places likes schools to close in advance of major road flooding. We selected the functional classification code – a system that is widely used – as a suitable indicator of a road's importance and a likely indicator of relative road usage, rather than traffic data, which is absent for most of the rural roads in our project geography.
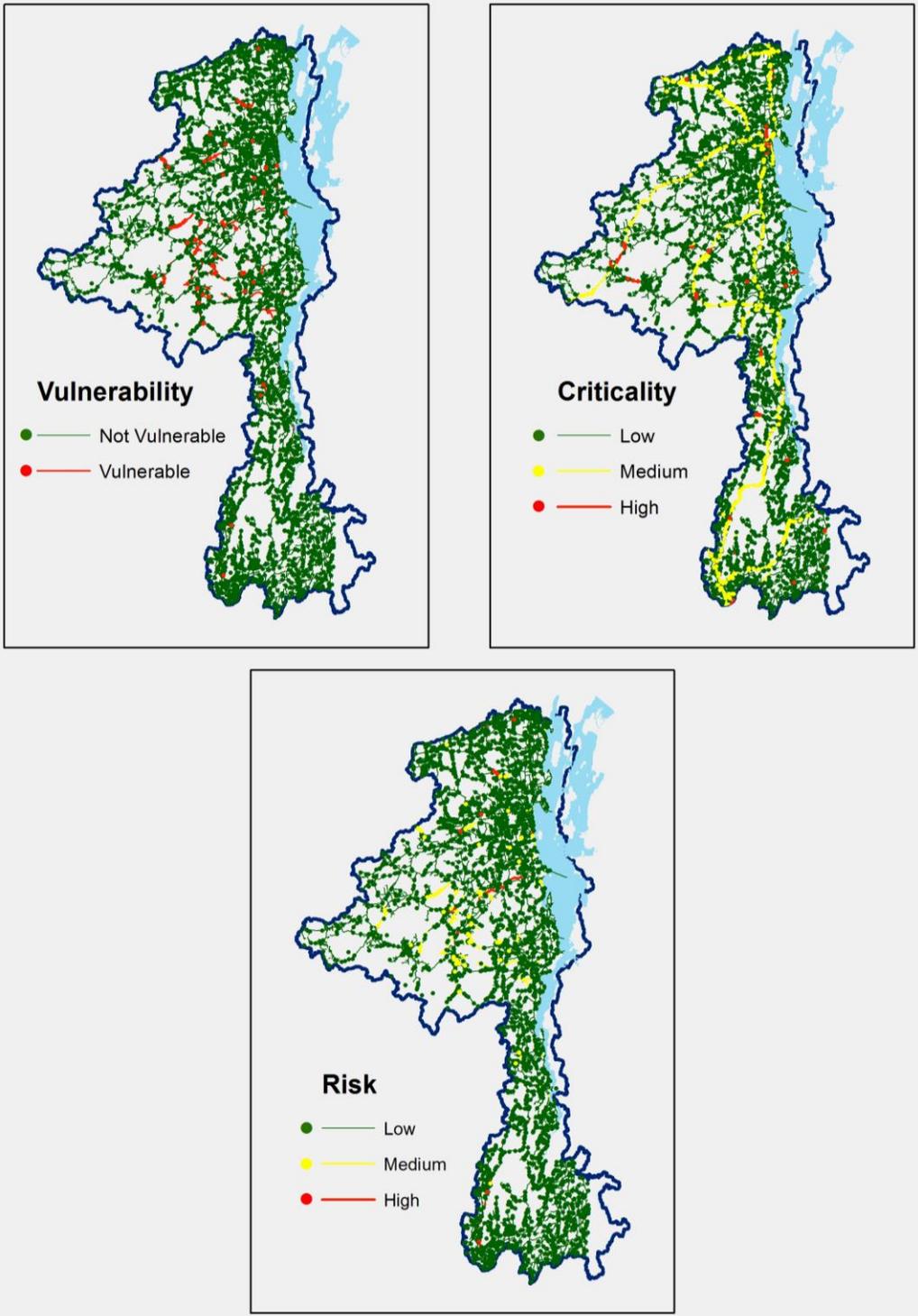
Figure 8. Vulnerability, criticality, and risk maps for the Champlain Basin.

OBJECTIVE 2: EVALUATE ENGINEERING-BASED DESIGN ADAPTATION OPTIONS FOR VULNERABLE ROAD-STREAM CROSSINGS

Introduction. A culvert is any enclosed channel open at both ends carrying water from a stream or water course through an artificial barrier such as a roadway embankment. This includes enclosed channels that are over 20 feet in length that are otherwise defined by NYSDOT as bridges (NYSDOT, 2010). Culverts (small-span structures) are distinguished from bridges (larger-span structures), with a simpler inspection procedure, and requiring less frequent inspection (minimum frequency is every 4 years for culverts, every 2 years for bridges).

In structural terms, a culvert might be distinguished from a bridge by its method of support. A culvert would be a stream crossing structure, which is self-supported, by distributing the load of its own weight, the fill and roadway above it, and traffic on the road over the bottom of the culvert, which is in contact with the soil. This makes closed culverts a good choice for use in soils with weak bearing capacity, as well as being simple and inexpensive. In contrast, a bridge must be supported on foundations, requiring either stronger soil (or rock), or piles, and adding to the expense.

The most common culvert shapes are circular pipes and rectangular boxes. Other shapes include elliptical pipes, arches (semi-circular, high- and low-profile), and pipe arches. Although generally closed, we now deal with what are termed open or bottomless culverts. Structurally, these more closely resemble bridges in that they are not self-supporting, but require foundations, which can add dramatically to the cost of the culvert crossing. There are also lower limits on the spans available, as well as structural limits on the span to rise ratio.

Culverts may be made of a variety of materials. Common materials for highway culverts are corrugated steel and concrete. Less commonly, corrugated aluminum is used, and plastic is often used for small culverts. Culverts may also be lined with other materials, like asphalt or concrete-lined metal pipe. Choice of material can depend on structural strength, hydraulic roughness, durability, corrosion or abrasion resistance, and cost.

BOX 1 - Culvert Terminology

barrel — the body of the conduit. It is the pipe or box through which the water flows. Culverts may be single-barrel or multiple-barrel.

headwall — retains the fill of the embankment above the culvert, and may serve to anchor the railing. The presence and configuration of a headwall also affects the efficiency of the inlet.

wingwalls — retains and protects from erosion the embankment fill adjacent to the culvert and may direct flow into the inlet

cutoff wall — extends below the outlet or inlet to protect from undermining

invert — the inside bottom of the culvert

span — the inside width of the opening, either perpendicular to the barrel or measured parallel to the centerline of the roadway

rise — the maximum inside height of the barrel

fish dish — a usually v-shaped depression in the bottom slab of a box culvert, to concentrate low flows.

improved inlet — any of a variety of inlet geometries (drop, side-tapered, slope-tapered) that improve the efficiency of flow into the culvert

design flow — the discharge (Q; the volume rate of flow past a point) that a hydraulic structure is designed to accommodate. As a policy guideline, it is generally expressed as a flood having a particular **recurrence interval**, e.g. the "50-year flood" (Q_{50}))
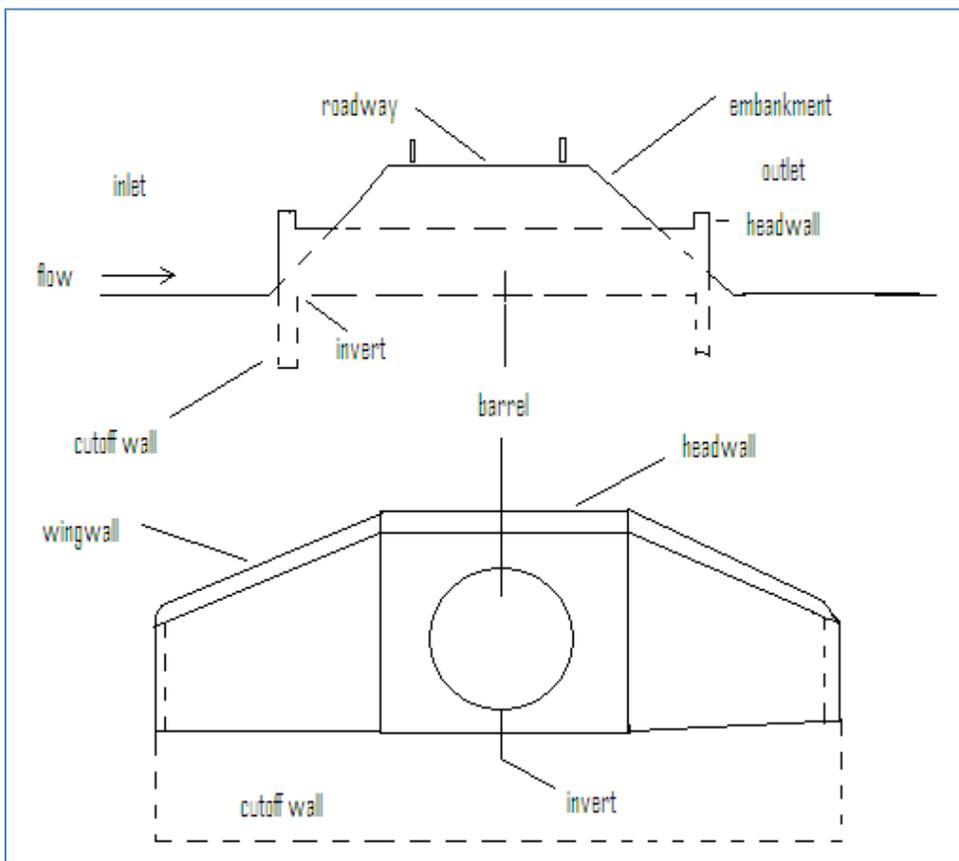
CULVERT HYDRAULICS

Culverts are designed and analyzed using empirical relationships. The material roughness, size and length of the barrel determine friction losses. The conditions at the ends are assigned inlet and outlet losses, and other minor losses are added up to determine how much energy in terms of hydraulic head is needed to push water through the culvert. This will be the difference between the water surface elevation downstream of the culvert (tailwater) and that upstream (headwater). To effectively convey water through an embankment or obstruction, the headwater elevation must be below the top of the embankment, or overtopping will occur. To prevent this, NYSDOT requires that culvert headwaters be no higher than 2 feet below the shoulder elevation of the roadway for the design flow. Headwater depth is further limited to less than or equal to 1.5 times the rise.

A culvert is said to be in inlet control when the culvert barrel is capable of conveying more water than the inlet will accept. Flow within the barrel of a culvert in inlet control will be supercritical for at least part of the barrel length. Where the flow is supercritical, the barrel will not be full, but will have a free surface. The inlet, the outlet, or both, may be submerged or not; if the outlet is submerged the hydraulic jump occurs inside the culvert, or typically just downstream if the outlet is unsubmerged. Inlet control is a hydraulically inefficient design, since the culvert barrel has "excess" capacity. Since the inlet controls the amount of water passing through the culvert, the barrel roughness, slope, length and area are irrelevant, so long as they are in a range to maintain inlet control.

Outlet control is the condition where the inlet does not limit the amount of water flowing through the culvert. Rather, it is controlled by the slope and characteristics of the barrel. Again, the inlet, the outlet, or both, may or may not be submerged. Flow in the culvert will be subcritical, and most often the outlet is unsubmerged.

The hydraulic capacity of a given culvert is the maximum discharge that the culvert is capable of conveying at the design conditions. The headwater depth will be at its allowable maximum (2 feet below the roadway shoulder, or lower as determined by upstream conditions such as flooding of developed areas). The hydraulic capacity is thus achieved assuming ponding upstream. For the most efficient and economical design, the culvert will be in outlet control, and flowing full for at least part of its length.

Methods. The objective of this assessment was to estimate the costs of different culvert types. NYSDOT developed a method for estimating the cost of culvert replacements based on span, rise, culvert type, depth of cover, culvert embedment, and length.

This methodology, described in Appendix C, allows a comparison of the costs of different design options. The design options considered are as follows:

 a) In-kind replacement of the existing crossing (in kind)
 b) Replacement crossing based on future streamflow projections (climate sized)
 c) Replacement crossing that meets the U.S. Army Corps of Engineers General Conditions and General Regional Conditions in New York, i.e. a crossing with a width of 1.25 times the stream's natural bankfull width and whose characteristics match the natural stream in terms of stream bed material and slope (stream sized)

Several sequential formulas were populated to produce the final costs:

Total depth of culvert = Rise + Depth of cover + Embedment + Floor + Crushed stone thickness

Total excavated Area in yd³ = (Culvert Box Area + Culvert Slope Area)/27

Total Excavation Cost = Total Excavated Area * Excavation cost per yd³

Subtotal Culvert cost = Culvert Cost + Total Excavation Cost

Total Culvert Cost = Culvert Cost + Total Excavation Cost + Maintenance and Protection of Traffic (MPT) Cost

---

Key Findings. Based on an analysis of ten recent NYSDOT culvert replacements, we found that the average increase in the 50 year flows between the current StreamStats and the new enhanced StreamStats was around 25 percent. The highest difference was 37 percent and the lowest was 9 percent.

Analysis of the data, as presented in Appendix C, shows that there is not much difference in the cost of culverts needed for climate change and from those needed to meet the US Army Corps of Engineers regional conditions for nationwide permits that address aquatic passage. Because the "climate sized" and "stream sized" culvert sizes are close (or the same), the costs associated with them are also close. The cost of the concrete box itself is a minor component of the total project costs relative to other construction costs such as maintenance and protection of traffic, which is not affected by culvert size.

It is important to keep in mind that replacement culverts cost, on average, 4 to 6 times more than preservation practices, such as culvert linings or invert pavings. Service life of new culverts is approximately 75 years versus approximately 40 years for repaired culverts, making culvert

repairs a desirable option. This is especially true for culvert replacements on interstates or other major arterials with deep cover, which may cost millions of dollars to replace. Maintenance and protection of traffic (MPT) decisions affect costs, with the use of detours being more cost effective than staged construction. Excavation costs are more a function of depth than width. For every foot down, there has to be a three foot width. Depth of cover was not an issue in the set of culverts we explored.

It is promising that, based on this initial assessment, the conditions for addressing aquatic passage appear to address future predicted increase in stream flows. Further study is warranted to explore this hypothesis. Understanding infrastructure criticality and risk of culverts will help asset managers justify replacement of high risk culverts in appropriate situations to accommodate aquatic organism passage and projected discharges that consider climate scenarios.

OBJECTIVE 3: CREATE AN ECONOMIC TOOL THAT EVALUATES THE FULL BENEFITS AND COSTS OF ADAPTATION OPTIONS TO HELP DOTS PRIORITIZE ADAPTATION INVESTMENTS AND EVALUATE ALTERNATIVE DESIGN OPTIONS.

Introduction. Schwartz (2011) stresses that "planned adaptation must balance the risks with benefits and costs in a rational manner." He goes on to state "applying risk analysis techniques to climate change and reaching sound adaptation conclusions is a very complex process. It is truly decision making under circumstances of great uncertainty."

Koetse and Rietveld (2009) recognize that, in addition to the costs of flooding related to infrastructure damages, indirect costs due to network effects such as delays, detours, and trip cancellation, may also be substantial. They discuss several values related to climate change impact on global transport. Noteworthy values that are associated with roadways, bridges and culverts include passenger transport: pattern in tourism; freight transport: shifts in agricultural production; accident frequency and severity; congestion, travel time and travel reliability.

For objective 3, we researched the benefits of stream crossings and developed an initial approach to value selected social, economic, and environmental benefits. This approach is intended to enable transportation departments to weigh the benefits and costs of stream crossing alternatives in light of current conditions and projected future stream flow scenarios.

While improved road-stream crossings and other resiliency infrastructure improvements (e.g., raising the profile of a road segment) typically have longer life spans and deliver a broader range of benefits than more traditional designs, they have a higher up-front cost. This initial cost presents a challenge for transportation departments as they allocate often limited resources for infrastructure repair and replacement. The benefits valuation approach developed for this project seeks to quantify benefits over an appropriate time frame.

We developed this benefits valuation approach with the New York portion of the Lake Champlain Basin as the primary geography, but the intention is to propose a methodology that can be applied more broadly across New York and other parts of the Northeast, with some alterations based on data.

Methods
   1. Review of Existing Guidance Documents and Reports

With the intent to develop an approach for economic valuation of stream crossing designs, we reviewed a wide range of existing economic analysis tools, guidance documents and supporting

literature. We also consulted with transportation experts and environmental economists. Appendix D presents an assessment of existing relevant research and tools, as well as discussion on its application or limitations relative to this study.

The literature review spanned the domains of transportation economic analysis, environmental valuation, and natural hazard mitigation valuation. While each of the guidance documents reviewed provides useful information for economic valuation, none alone adequately covers the range of benefits and costs that should be considered when evaluating different stream crossing designs. Many of the studies and tools reviewed were location specific, and while they provided useful context and information, the primary tools selected are relevant at larger geographic scales.

Table 2 below provides an overview of the general guidance documents reviewed. More detail about these documents is provided in Appendix D. Specific guidance documents, such as the National Cooperative Highway Research Program's report on the economic impacts of freight disruption, were also reviewed in developing specific benefit recommendations.

Table 2. General Guidance Documents Reviewed

Author	Title	Relevance
U.S. DOT	Economic Analysis Primer	Discusses key concepts and decision points for project economic analysis.
FHWA	Operations Benefit/Cost Analysis Desk Reference	Provides detailed guidance on how to conduct benefit-cost analysis of operations strategies for transportation departments.
U.S. DOT	TIGER Benefit-Cost Analysis Guidance Documents	Recommends methodology for calculating multiple benefits, such as emissions reductions, operating cost savings, travel time savings, and safety; provides monetized values for several benefits.
Transportation Research Board	Benefit-Cost Analysis [Website]	Serves as useful resource for developing and conducting benefit-cost analysis for transportation projects.
FEMA	Benefit-Cost Analysis Tool	Provides formulas and standard values associated with the mitigation of damage from a range of natural hazards, including floods.

In addition, we reviewed existing case studies comparing the installation and life cycle costs of road-stream crossings with different designs. Given the wide variety of crossing materials, designs and sizes, we found considerable disparity among these studies. Appendix D provides more information about these case studies.

> 2. Review and Selection of Benefits

Stream crossings have social, economic, and environmental impacts on stream health, fish populations, local communities, and road users. Some of the benefits of improved crossings, compared to more traditionally designed crossings, are summarized in Table 3 below.

Table 3. Benefits of Improved Road-Stream Crossings

Type of Benefit	Outcomes
Social	- Improved safety - Improved mobility (avoided travel delays) - Improved accessibility
Economic	- Avoided flood repair costs: - Repair of damaged infrastructure - Repair and replacement of damaged property - Lost business income from road closures - Avoided disruption of freight movement - Avoided costs to repair environmental degradation (e.g., water quality)
Environmental	- Healthier populations of fish and wildlife - Improved river habitat for in-stream and river-dependent species - Decreased erosion of stream banks - Improved water quality - Avoided water quality impacts from storm-related failure - Enhanced river-related recreation

In developing our recommended valuation approach, we considered the importance of each benefit as well as the extent to which each can be quantified and monetized. We reviewed valuation literature, both peer reviewed and gray, and consulted with economists about potential methodologies. We also explored existing benefits values in the literature, and we determined that they are not sufficiently similar to justify using benefits transfer in this context. Additional information about the rationale for selecting particular benefits and omitting others is described in Appendix D.

Key Findings. Many of the potential benefits of improved crossings result from *avoided* flooding and/or stream crossing failure. Significant flooding can disrupt the operations of the transportation system. Suarez et al. (2005) describe how a storm that causes significant flooding can cause disruption to travelers wherein:

- Some trips will be canceled because either the origin location or the destination location is flooded. For example, some work trips will not occur because either the employees' homes or places of work are flooded. Shopping trips may be canceled because either the shoppers' homes or the shopping center is flooded.

- Some trips will not occur because flooding of links has made it impossible for the traveler to get from origin to destination.

- Many trips that occur despite the flooding will take much longer. This may occur either because travelers are forced to take circuitous routes from origin to destination to avoid impassable links, or as a result of traffic congestion on passable links that is caused by the diversion of traffic away from impassable links.

These disruptions have economic costs because trips have value. This may be expressed in terms of lost work-days, lost sales, or lost production. Traveler's time also has value and, thus, lost time due to circuitous travel or traffic congestion has significant cost (Suarez et al., 2005).

APPROACHES FOR VALUING BENEFITS – SOCIAL AND ECONOMIC
The selected primary social benefits of improved crossings include: safety (reduction in potential injuries and fatalities due to road flooding and culvert failure); mobility (avoided travel delays/detours due to road flooding and culvert failure); and access to critical services (ability to reach critical facilities such as hospitals and fire stations when roads are flooded or closed due to culvert failure).

Selected primary economic benefits of improved crossings include resiliency/avoided flood damage; and avoided freight disruption (in terms of detour cost, delay cost and inventory cost).

While established methodologies exist for the monetization of many benefits, availability of data may be a limiting factor in using these methodologies.

Tables 4 and 5 outline a menu of approaches for valuing a range of types of social and economic benefits associated with improved stream crossings. The proposed approach for environmental benefits is discussed separately.

Table 4. Approaches for Benefit Valuation: Social Benefits

Benefit ($/year)	Formula (Required data inputs are indicated in **bold italics**)
Mobility: additional travel cost from road closure	Annual travel cost = ***Detour length (miles)*** x Standard mileage rate ($0.565/mile[1]) x ***Average daily traffic count*** x ***Duration of road closure (days)*** x ***Annual probability of road-closing flood***
Mobility: additional travel time from road closure	Annual travel time = ***Time to travel detour (hours)*** x Travel time cost ($30.69/vehicle-hour[2]) x ***Average daily traffic count*** x ***Duration of road closure (days)*** x ***Annual probability of road-closing flood***
Access to critical services: loss of access to fire station	Annual cost of inaccessible fire station = *Daily cost of inaccessible fire station[3]* x ***Duration of road closure (days)*** x ***Annual probability of road-closing flood***
Access to critical services: loss of access to EMS	Annual cost of inaccessible EMS = *Daily cost of lost access to EMS[4]* x ***Duration of road closure (days)*** x ***Annual probability of road-closing flood***
Access to critical services: loss of access to hospital	Annual cost of loss of access to hospital = *Daily cost of lost access to hospital[5]* x ***Duration of road closure (days)*** x ***Annual probability of road-closing flood***
Safety: avoided fatalities*	Annual cost of fatalities = ***Expected number of fatalities from road flooding*** x ***Annual probability of road-closing flood*** x Value of a statistical life ($6.8-$9.2 million[6])
Safety: avoided injuries*	Annual cost of injuries = ***Expected number of injuries per AIS value*** x ***Annual probability of road-closing flood*** x Value of injuries per AIS value[7]

---

[1] Source: U.S. IRS, 2013$.

[2] Source: FEMA, 2013$.

[3] Refer to FEMA Benefit-Cost Analysis Toolkit to calculate daily cost of inaccessible fire station. Required data for calculation: 1) distance between inaccessible fire station and nearest temporary replacement fire station; 2) population served by inaccessible fire station.

[4] Refer to FEMA Benefit-Cost Analysis Toolkit to calculate daily cost of lost access to EMS. Required data for calculation: 1) distance between inaccessible EMS and nearest temporary replacement EMS; 2) population served by inaccessible EMS.

[5] Refer to FEMA Benefit-Cost Analysis Toolkit to calculate daily cost of lost access to hospital. Required data for calculation: 1) distance between inaccessible hospital and nearest temporary replacement hospital; 2) population served by inaccessible hospital; 3) population served by replacement hospital.

[6] Source: FEMA, U.S. DOT, 2013$.

[7] AIS 1 = $27,600; AIS 2 = $432,400; AIS 3 = $966,000; AIS 4 = $2,447,200; AIS 5 = $5,445,600; Source: U.S. DOT, 2013$.

Note: The safety benefits of improved crossings are the potential reduction in driver and passenger fatalities and injuries caused by road flooding (due to undersized culverts) or culvert failure. As discussed in Appendix D, the currently available data cannot be used to estimate the likelihood of a flood-related injury or death, and as such, it does not provide the specific information needed for a safety benefits valuation. Since we are unaware of specific accident data for our region, we do not propose including safety benefits at this time.

Table 5. Approaches for Benefit Valuation: Economic Benefits

Benefit ($/year)	Formula (Required data inputs are indicated in **bold italics**)
Avoided flood damage	Annual flood damages to be calculated with FEMA BCA tool using Damage Frequency Assessment (DFA) module; data needs: flood damage value for at least three storm events, year of storm events, year structure built, return period for storm events
Avoided freight disruption: detour cost	Annual detour cost = ***Annual probability of road-closing flood*** x ***Duration of road closure (days)*** x ***Daily number of truck trips*** x Direct transport cost per vehicle-mile ($1.39/truck-mile[8]) x ***Length of detour (miles)***
Avoided freight disruption: delay cost	Annual delay cost = ***Annual probability of road-closing flood*** x ***Duration of road closure (days)*** x ***Daily number of truck trips*** x Direct transport cost per vehicle-hour ($59.03/truck-hour[9]) x ***Increase in delivery time (hours)***
Avoided freight disruption: inventory cost	Annual inventory cost = ***Annual probability of road-closing flood*** x ***Duration of road closure (days)*** x ***Daily number of truck trips*** x ***Average payload (lbs)***[10] * 1 ton/2000 lbs. x ***Increase in delivery time (hours)*** x Average truck freight value/ton-hour ($0.98/ton-hour[11])

APPROACHES FOR VALUING BENEFITS – ENVIRONMENTAL

While the environmental benefits of stream crossing improvements are substantial, valuation of these benefits is extremely difficult. Our research indicates that the environmental benefits associated with improved stream crossings cannot be satisfactorily valued at present, and, as noted earlier, benefits transfer is not practical for this unique context. In light of the absence of

---

[8] Source: NCHRP 2012, 2009$.
[9] Source: NCHRP 2012, 2009$.
[10] Average payload may be estimated based on the number of trucks on the road in each vehicle classification; see http://faf.ornl.gov/fafweb/ for the most up-to-date freight information.
[11] Source: NCHRP 2012, 2009$.

useable values, we propose the use of a multiplier to include environmental benefits in the overall benefits value. This approach utilizes the results of the ecological culvert ranking, described under objective 1. The approach is described below and summarized in Table 6 below.

As presented in Table 6, there are four steps needed to apply an environmental benefits multiplier to monetary values. Recall the approach above describes how to calculate social and economic monetary benefits (e.g., Tables 4 and 5). Here, we will calculate a multiplier in order to apply environmental benefits to high priority sites without determining a monetary value for the environmental benefits. First, the user must decide how much of an effect the multiplier will have on the other benefits. The example in Table 6 illustrates a maximum bump of 20%. This means that where ecological value is the highest, the other benefits (i.e., social and economic) will be inflated by 20%. Step 2 determines how to apply the environmental multiplier to the full range of ecological data available. In this pilot study, recall we summarized our ecological scores in four tiers: high to lowest (Fig. 6). Here, we determined that the highest tier sites will receive a 1.20 multiplier, medium tier sites a 1.15 multiplier, low tier sites a 1.10 multiplier, and the lowest tier sites will not receive any environmental multiplier (1.0). This is illustrated in Step 3, Table 6. Finally, simply multiply the total social and economic values by the environmental multiplier.

Table 6. Environmental Benefits Approach

Step	Example
1. Determine maximum amount that environmental benefits may inflate other benefits.	User determines that environmental benefits may inflate other benefits up to a maximum of 20%.
2. Determine range of environmental benefit multiplier values.	Range of environmental benefit multiplier values is 1.0 (min, no benefit) to 1.20 (max, highest benefits).
3. Assign environmental benefit multiplier value to each of 20 ecological tiers to fit within multiplier range.	Tier 1 (highest ecological value) sites receive value of 1.20, tier 2 sites receive value of 1.15, tier 3 sites receive value of 1.10, etc., and tier 4 sites (least ecological value) receive value of 1.
4. Use environmental benefit multiplier to "inflate" the total benefits value.	For each site, multiply total social and economic benefits value by environmental benefit value.

We present two scenarios to provide illustrative examples of how benefits values can be calculated using two roads in our study area.

The first road segment we explored is NYS Route 9N between Ausable Forks (pop. 559) and Keesville (pop. 1,780), near the intersection of Interstate 87 (the Adirondack Northway) at Exit 34. NYS Route 9N is a principal arterial - other, traveling along the Ausable River. It has annual average daily traffic (AADT) (two-way) of 2,251 with 5.3% trucks, so AADTT would estimate as 119.

The Ausable River is a high priority watershed with a large percentage of natural cover and a robust native trout population, thus this road segment has the highest environmental score. The road is considered vulnerable to flooding and has the highest risk rating. If the road became flooded, there is a potential detour that adds 1.1 miles to a trip. However, this detour route would require crossing the Ausable River and traveling on a parallel road that may be affected by the same flood occurrence. In that event, the alternate detour route would add 3.7 miles to the trip. We explored both scenarios for this road.
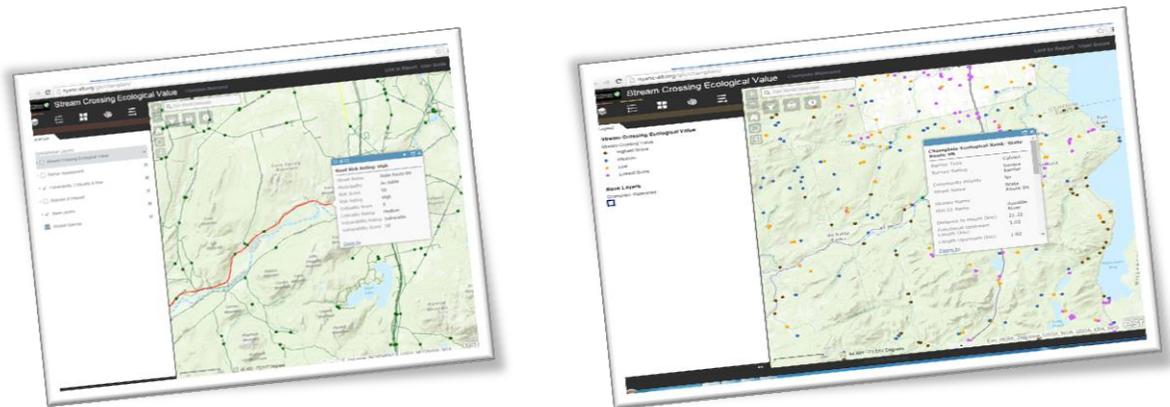
The second road segment we explored is NYS Route 3 between Plattsburgh (pop. 19,898) and Morrisonville (pop. 1,545) in the area where it intersects with Interstate 87 (the Adirondack Northway) at Exit 36. NYS Route 3 is a principal arterial – other, with an AADT of 16,348 with 5.79% trucks, or 947. This road segment is near the State University of New York Plattsburgh campus, shopping malls, and downtown in a developed watershed with relatively low biodiversity values, thus has a low environmental score. Due to the redundancy in the road system, the detour would only add 0.65 miles in travel distance.
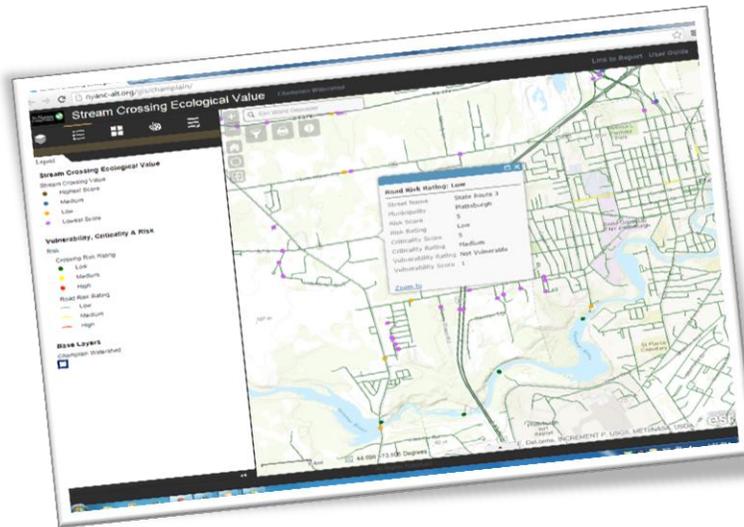
In example 1 (data rich), a user has monetary benefits for economic and social values. In example 2 (data poor), a user does not have monetary benefits calculated for economic and social values. For these two scenarios, the data values for the roads are as outlined below.

Data Value	NYS 9N, Ausable (1.1 mi detour)	NYS 9N, Ausable (3.7 mi detour)	NYS Route 3, Plattsburgh
AADT (two-way)	2,251	2,251	16,348
Detour length (miles)	1.1	3.7	0.65
Duration of road closure (days)	3	3	3
Probability of road closing flood (percent)	15%	15%	15%
Time to travel detour (hours @ 40 mph)	0.025	0.093	0.016
Daily number of truck trips	119	119	947
Increase in delivery time (hours)	0.025	0.093	0.016

Risk Value	NYS 9N, Ausable	NYS Route 3, Plattsburgh
Vulnerability Score	10	1
Critical Facility Score	0	0
Functional Classification Score	5	5
Criticality Score	5	5
Risk Score	50	5
Risk Value*	1.2	1

*Risk Value – High = 1.2; Medium = 1.1; Low = 1.0

Example 1:

Sample benefit valuation (data rich)

Benefit ($/yr)	NYS 9N, Ausable (1.1 mile detour)	NYS 9N, Ausable (3.7 mile detour)	NYS 3, Plattsburgh
Social Values			
mobility benefit (additional travel cost)	$629.55	$2,117.57	$2,701.71
mobility benefits (additional travel time)	$777.19	$2,875.59	$3,668.83
Economic Values			
avoided freight disruption (detour cost)	$82.09	$276.11	$384.84
avoided freight disruption (delay cost)	$79.23	$293.14	$408.58
Environmental Values			
environmental benefits value	1.2	1.2	1

Total annual benefits = (social benefits + economic benefits) * environmental benefits:

NYS 9N, 1.1 mile detour	=($629.55 + $777.19 + $82.09 + $79.23)*1.2	$1,881.66
NYS 9N, 3.7 mile detour	=($2,117.57 + $2,875.59 + $276.11 + $293.14)*1.2	$6,674.89
NYS 3	=($2,701.71 + $3,668.83 + $384.84 + $408.58)*1	$7,163.97

Though we only applied a few of the social and economic values for this illustration, it is worth noting that the lower volume road (Route 9N) with the longer detour and high environmental benefits value had nearly the same annual benefits value as the higher volume road (Route 3) with a short detour and low environmental benefits value. Without an understanding of the vulnerability and the high environmental benefits, culvert work on NYS 9N would likely focus on repair rather than replacement. However, considering the flood risk and the environmental benefits, culvert replacement is warranted and preferred. Alternatively, though NYS Route 3 serving downtown Plattsburgh has high economic benefits for the area, the risk is low, there is redundancy in the network, and the environmental benefits are low, thus culvert repair is a cost-effective option.

Example 2:

Sample benefit valuation (data poor)

Benefit ($/yr)	NYS 9N, Ausable (1.1 mi detour)	NYS 9N, Ausable (3.7 mi detour)	NYS 3, Plattsburgh
Social Values			
	----	----	----
Economic Values			
	----	----	----
Environmental Values			
environmental benefits value	1.2	1.2	1
Risk Value			
risk rating	1.2	1.2	1

Total annual benefits = (environmental benefits score * risk score):

NYS 9N, 1.1 mile detour	= (1.2*1.2)	1.44
NYS 9N, 3.7 mile detour	= (1.2*1.2)	1.44
NYS 3	= (1.0*1.0)	1

In this case, the high risk and high environmental benefits of NYS Route 9N, regardless of the detour length, support culvert replacement to reduce flood risk and improve ecological conditions and aquatic organism passage. Conversely, the low risk and low environmental benefits of NYS Route 3 support culvert repair as a cost-effective option if deemed appropriate based on the life and condition of the culvert.

The differences between the two examples are rooted in data availability. In example 2, data for monetary benefits are not available and therefore economic data is not included. Here, we use the risk map and score (calculated by assessing criticality and vulnerability) (Fig. 7) in combination with the environmental benefits score to prioritize between two roads. In example 1, risk is inherently included in the social and economic benefits calculations so we do not apply the risk multiplier.

USING BENEFITS VALUATION

The approach above considers the social, economic, and environmental benefits of prioritizing road segments and culverts for infrastructure redesign. One key consideration of this process is the condition of the culvert. The reality of addressing over a million culverts requires the

replacement of culverts only when their condition warrants it. We developed the following decision tree to help a user determine when to consider full culvert replacement or repair, and when to apply the benefits valuation approach considering culvert condition as a key factor.

Does culvert condition warrant replacement or repair?

Yes
Is the culvert high or medium risk?

No
Do not replace or repair culvert

Yes
Apply benefits valuation data.

Consider culvert replacement

No
Apply environmental benefits.
Is environmental benefits score high?

Yes

Consider culvert replacement

No

Consider culvert repair
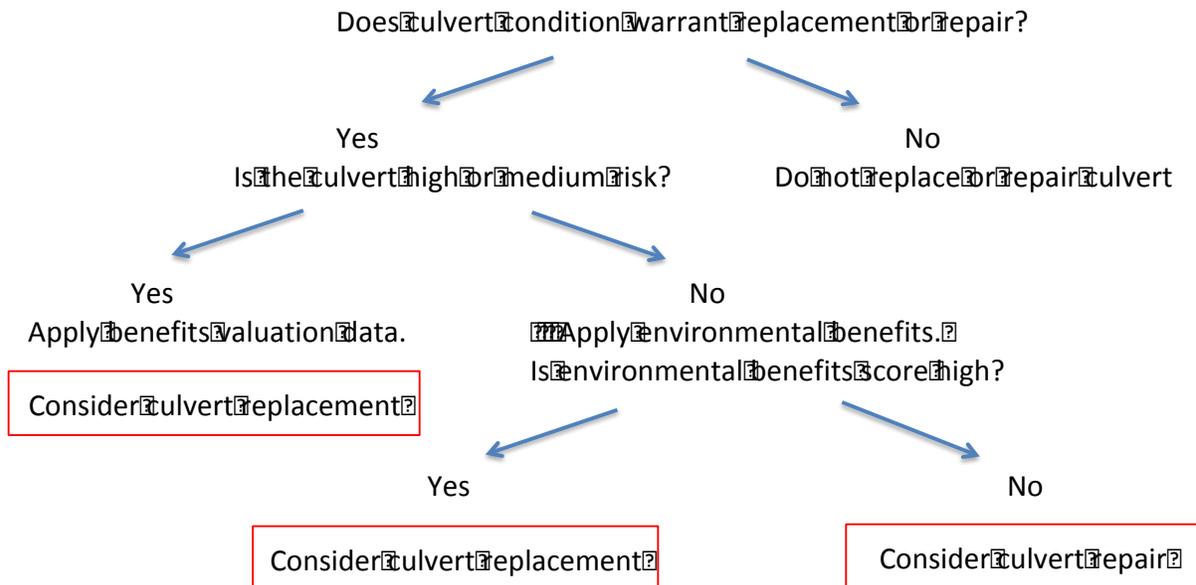
Applying the decision logic to the two road segments discussed:

For data rich example:

NYS Route 9N -> condition warrants replacement or repair -> high risk -> moderate to low benefits valuation -> high environmental benefits score -> **replace**

NYS Route 3 -> condition warrants replacement or repair -> low risk -> low environmental benefits score -> **repair**

For data poor example:

NYS Route 9N -> condition warrants replacement or repair -> high risk -> high environmental benefits score -> **replace**

NYS Route 3 -> condition warrants replacement or repair -> low risk -> low environmental benefits score -> **repair**

BENEFIT-COST ANALYSIS

To evaluate the costs and benefits of different stream crossing designs, several key decisions will need to be made. While a benefit-cost analysis was beyond the scope of this project, we provide the following recommendations for development of the benefit-cost analysis based on what we learned in our research. Appendix D contains more detail about these values and recommendations.

	Range of values in literature reviewed	Recommendation
Time Period of Analysis	20 – 100 years	50 years
Discount Rate	2% - 7%	3% and 7%; 4% for single value
Summary Measures	• Benefit-cost ratio • Net present value • Cost-effectiveness • Payback period • Internal rate of return	• Benefit-cost ratio for each design option • Net Present Value for each design option

LIMITATIONS OF STUDY

There were several limitations to our current study. First, benefits data are severely lacking. While data from other geographies can often be found, we determined that it was rarely appropriate to transfer benefits to our pilot region. Second, several benefits, such as environmental benefits, do not have credible tools or methods available for valuation. In our study we developed an environmental benefits multiplier to avoid applying monetary valuation methods. Third, the risk score is only as good as the vulnerability data that underlies it. We did not have comprehensive vulnerability data available for our region, but we were able to make several advances including the development of an enhanced StreamStats tool, and local and regional data collection through outreach. The latter method is labor intensive. Finally, the overall scoring framework needs to be tested in other areas of the state. Our pilot area is in a rural part of New York and we need additional examples from around the state to ensure it applies equally in all regions. Stratifying priorities by region or watershed might help in a statewide application. Finally, the environmental benefits score and risk score are relative scores. This means they are good for prioritization, but they do not work for direct monetary valuation.

SUGGESTIONS FOR FUTURE STUDY

Based on our current research, we have several ideas that could help improve the economic approach for valuing benefits of different stream crossing design options in future study. The primary challenge was data availability and as such, our primarily recommendation is for improved data collection. For social benefits it would be useful to improve data collection around safety and accidents at road stream crossing sites, including the systematic compilation of data about accidents related to road flooding and culvert failure. For economic benefits, improved collection and retention of flood damage data by road managers and FEMA would be a great advancement, including damage data by site (rather than event) and public sharing of data about private flood damages. For environmental benefits, the development and deployment of a survey to assess public values (willingness to pay) for stream crossing replacements projects would provide a first look at economic values for environmental benefits and risk. Finally, accessing all of these data is a challenge and the development of accessible databases is sorely needed at all municipal levels.

OBJECTIVE 4: INCORPORATE CLIMATE VULNERABILITY RESULTS INTO EXISTING NYSDOT STANDARDS, GUIDELINES, AND TOOLS

Through its recent asset management efforts, NYSDOT is taking steps to incorporate climate vulnerability considerations into NYSDOT decisions. As noted in Nelson and Krekeler (2013), in today's fiscally constrained times, it is clear that funding will not meet all transportation infrastructure needs. Therefore, it is crucial for transportation agencies to think critically about how they invest their limited resources in a way that fulfills the social (community), economic and environmental needs of the present without compromising the needs and opportunities of future generations. Findings from this pilot project will help support efforts to address this need.

To that end, NYSDOT has institutionalized an asset management framework that incorporates the Sustainability "Triple Bottom Line" of economic competitiveness, social equity and environmental stewardship in its investment decisions.

ASSET MANAGEMENT FRAMEWORK

As described in FHWA's June 2014 *Successes in Stewardship* newsletter (FHWA 2014a), NYSDOT created an Asset Management Framework in order to advance more sustainable programming, generate more consistent decision making, and ensure greater accountability throughout the agency. The framework creates Asset Management Teams at three levels of the organization. These Asset Management Teams are charged with making sure investments support and advance the long-term goals and short-term objectives of the agency, delivering the right project at the right time (FHWA 2014a).

NYSDOT formed Statewide and Regional Asset Management Teams in all asset areas to address Pavement, Structures, Safety, and Sustainability needs. Consistent with the approach of this FHWA pilot project, NYSDOT's capital programming efforts are working to consider economic, social and environmental benefits in making decisions on projects and overall program selections. Specifically, the findings from this research project will provide valuable insights in how we can approach asset prioritization in light of climate vulnerability and resiliency.

SPATIAL DATABASES

Spatial databases have been developed by NYSDOT to assist in capital programming and asset management; it is intended that these databases will continue to be expanded as data becomes available and as resources allow.

The Comprehensive Asset Management/Capital Investment (CAMCI) Viewer was created as an interactive GIS map that provides NYSDOT users easy access to enterprise transportation

information. As noted on NYSDOT's internal website, "originally created to support the goals of the Capital Program Update process, the CAMCI Viewer is a useful resource for any planning, asset management, operations or safety analysis workflow."

The CAMCI Viewer provides the latest data from the Department's business systems for a wide variety of transportation layers including pavement condition, bridges, large and small culverts, highway and bridge projects on the Capital Program, highway safety, traffic volume, functional class, important facilities (airports, rail stations, hospitals, businesses, etc.), and accessibility (ramps, sidewalks, bike/walk potential).

Additionally, flooding vulnerability information is included and is particularly relevant to assist in factoring resiliency into project and programming decisions. Data layers include flooding vulnerability for culverts and bridges, flood watch bridge list, and flooding vulnerability for roads.

As noted above, the system map includes important facilities such as hospitals, airports, passenger rail stations, businesses, universities, major shopping locations, intercity bus stations, and truck access routes. This information is relevant in determining criticality as discussed in objective 1 and the project benefit valuation as described in the objective 3.

NYSDOT also has an environmental viewer that includes a multitude of environmental layers (e.g., air quality, cultural resources, hazardous waste, wetlands, water, ecology, stormwater, etc.) as well as capital program data and bridges and culverts. In the culverts layer, information on environmental priority culverts has been added on a statewide scale. This model could be scaled to provide environmental priority culverts on a watershed level as described in objective 1.

CAPITAL PROGRAMMING

To ensure that New York State's transportation system can support future commerce, personal travel demands, and address emergencies and unforeseen circumstances, NYSDOT's upcoming metropolitan and statewide Transportation Improvement Program (TIP/STIP) update process will continue to encourage strong asset management practices.

The statewide asset management teams are working together to develop capital programming guidance that considers the *condition* of the assets, the *location* and the project's context in the transportation system and local geography, and the *function* of the roadway. A roadway's function reaches beyond its functional class and serves people and society in many ways including supporting economic vitality, employment and livability. When making transportation investment decisions, the condition/location/function approach allows transportation

infrastructure that supports these societal functions to be evaluated along with the roadway's importance.

The primary focus of a sustainable Comprehensive Program is to preserve critical linkages using appropriate preservation treatments for highways and bridges. Consistent with the objectives of this pilot project, it is important for transportation asset management decisions to consider community needs and context as well as the natural environment. Paramount to these decisions is the premise of selecting the right project at the right time in the right location.

The right time relates to the condition of the infrastructure. As described in Nelson et al. (2011), NYSDOT has an established Pavement Preservation Model (PPM) that enables managers to make system-wide economically sustainable decisions for pavement preservation. The PPM considers pavement conditions and other criteria to prioritize project-specific locations for work over a ten-year period based on a treatment selection matrix and available funding. Similarly, the Structures model develops a scaled bridge index considering condition rating, structural deficiency, load posting, detour length, hydraulic vulnerability, and other factors. Condition of the infrastructure is the primary criteria for selecting appropriate preservation/maintenance treatments for roads, bridges and culverts.

When looking at projects that go beyond maintenance treatments, the asset management teams are collaborating to develop an approach that considers infrastructure conditions, as well as location (using a corridor importance factor), and function (including safety, mobility, accessibility, and resiliency). Similar to the criticality factor discussed in objective 1, the corridor importance factor considers a combined employment and population value for the corridor, proximity to an agricultural area, how the corridor serves freight (as determined by truck traffic (AADTT)), and the functional class of the road.

The benefit valuation findings from this pilot project, particularly the economic and social factors, can provide a framework for NYSDOT to draw upon as it develops criteria to balance the multiple functions of **S**afety, **M**obility, **A**ccessibility, **R**esiliency and **T**ransportation partnerships (SMART) in its upcoming TIP/STIP update. The working-draft SMART approach to select statewide priority renewal projects attempts to balance the multi-purpose projects considering:

- **S**afety (to address crashes, fatalities, injuries),
- **M**obility (through intelligent transportation systems (ITS) technologies, system optimization, Emergency Transportation Operations (ETO)/Traffic Incident Management (TIM) facilities),

- **A**ccessibility (pedestrian and bicycle facilities, transit access and operations improvements, freight access and economic development),
- **R**esiliency (flood/scour risk, emergency route redundancy, green infrastructure), and
- **T**ransportation partnerships (leveraging funds, environmental protection or enhancement).

Consistent with the approach described in this research project, NYSDOT is taking action to incorporate the "Triple Bottom Line" of sustainability in its programming and investment decisions, factoring economic, environmental and social aspects into its comprehensive program, asset management and capital investment decisions. This includes addressing climate vulnerability and resiliency building from what was learned in this FHWA pilot project.

SUMMARY OF FINDINGS

This FHWA Climate Change Resilience Pilot project reinforces the need and value of a risk-based approach to mainstreaming the consideration of the effects of climate change and extreme weather events, particularly flooding, into transportation decisions to most effectively focus our investments.

The scale of NYSDOT's highway culvert program requires tools to prioritize and evaluate when increased costs are warranted for culvert replacement or repair. The findings described in objective 1, particularly the identification of vulnerable, critical and at-risk infrastructure, will enable transportation decision makers to focus on the greatest needs. Vulnerability alone is not enough to make sound decisions. We propose a Risk Score based on a Vulnerability Score and a Criticality Score (derived from a critical facility score + functional class score).

Where we invest matters. A strong asset management strategy focuses our funds on the right treatment at the right time in the right place, considering the *condition* of the assets, the *location* and the project's context in the transportation system and local geography, and the *function* of the roadway. The right place considers public benefits such as safety, access/proximity to emergency services, businesses, schools, modal choices as well as corridor services such as freight movement and transit. The benefits valuation approach captures many of these values.

The culvert cost comparisons for ten recent culvert replacements found that culvert size is not the driving factor in total cost. The decision is more dependent on whether culverts require replacement or repair; if replacement is warranted due to condition and/or risk (vulnerability times criticality), the culvert should be sized to address aquatic organism passage and future climate flow projections. In many cases, we found that culverts designed to facilitate future climate flow projections was similar to designs needed to meet the US Army Corps of Engineers regional conditions for nationwide permits that address aquatic passage. While needing more study, this suggests that meeting the regional conditions may often meet future climate needs.

Culvert replacement projects (and other infrastructure capital projects) should consider not just the spot location, but the context of the transportation system in connecting communities and in the value of the natural landscape. It is the cumulative values and benefits of a corridor, system, and intersection of systems (as in road-stream crossings) that will help guide decision makers in asset management decisions and determine benefits and tradeoffs.

Finally, it is important to contextualize and prioritize projects in a manner that assesses them as key components or critical links within the larger transportation and natural systems. A systems perspective will create more efficiencies for both natural and capital resources.

REFERENCES

Federal Highway Administration (FHWA). 2014. FHWA Climate Change Vulnerability Assessment Pilot Project: Washington State Department of Transportation. FHWA-HEP-14-004.

Federal Highway Administration (FHWA). 2014a. New York State Asset Management Framework Encourages Preservation and Sustainability. In *Successes in Stewardship Newsletter.* June 2014. https://www.environment.fhwa.dot.gov/strmlng/newsletters/jun14nl.pdf

Greco, B. and D. A. Nelson. 2009. Interagency Partnering for the Development of Stream Crossing Standards in New York State. *In Proceedings of 2009 International Conference on Ecology and Transportation, Duluth, MN.*

Guilbert, J., B. Beckage, J.M. Winter, R.M. Horton, T. Perkins, and A. Bomblies. 2014. Impacts of projected climate change over the Lake Champlain basin in Vermont: Journal of Applied Meteorology and Climatology, v. 53, p. 1861-1875.

Hayhoe, K., P.W. Cameron, T.G. Huntington, L. Luo, M.D. Schwartz, J. Sheffiled, E. Wood, B. Anderson, J. Bradbury, A. DeGaetano, T.J. Troy, and D. Wolfe. 2007. Past and future changes in climate and hydrological indicators in the US Northeast, Climate Dynamics, 28: 381-407.

Hornby, D. 2010. Barrier Analysis Tool (BAT) User Guide, Geodata Institute of the University of Southampton.

Huntington, T.G., A.D. Richardson, K.J. McGuire, and K. Hayhoe. 2009. Climate and hydrological changes in the northeastern United States: recent trends and implications for forested and aquatic ecosystems. Canadian Journal of Forest Research. 39: 199-212.

Hyman, R., R. Lupes, and D. Perlman. 2011. Federal Highway Administration Activities Related to the Adaptation of Transportation Infrastructure to Climate Change Impacts. *Transportation Research E-Circular*, (E-C152).

Jenkins, J. 2010. Climate Change in the Adirondacks. Comstock Publishing Associates, Ithaca, NY, 183 p.

Koetse, M. J. and P. Rietveld. 2009. The impact of climate change and weather on transport: An overview of empirical findings. *Transportation Research Part D: Transport and Environment*, *14*(3), 205-221.

Lambert, J. H., Y.J. Wu, H. You, A. Clarens, and B. Smith. 2013. Climate change influence on priority setting for transportation infrastructure assets. *Journal of Infrastructure Systems*, 19(1), 36-46.

Major, D. C., R. Zimmerman, J. Falcocchio, K. Jacob, R. Horton, M. O'Grady, D. Bader, J. Gilbride, and T. Tomczyszn. 2011. *Mainstreaming Climate Change Adaptation Strategies into New York State Department of Transportation's Operations: Final Report* (Research Project No. C-08-09).

Meyer, M. 2006. Design Standards for the U.S. Transportation Infrastructure: Implications of Climate Change. Discussion document prepared for the Transportation Research Board Committee on Climate Change.

Meyer, M., M. Flood, C. Dorney, K. Leonard, R. Hyman, and J. Smith. 2011. Climate Change and the Highway System: Impacts and Adaptation Approaches. *NCHRP #20-83(5) Task 2.3 Synthesis Report: Review of Key Climate Impacts to the Highway System, and Current Adaptation Practices and Methodologies.* National Cooperative Highway Research Program.

Nelson, D. A., and P. Krekeler. 2013. Building Coalitions and Leaders In Sustainability: NYSDOT's Actions to Interweave Sustainability and Asset Management. In *Proceedings of 2013 International Conference on Ecology and Transportation, Scottsdale, AZ.*

Nelson, D. A., P. Krekeler and M. Rossi. 2011. Incorporating Sustainability into NYSDOT Decisions. In *Proceedings of 2011 International Conference on Ecology and Transportation, Seattle, WA.*

NYSDOT. 2010. Engineering Instruction (EI) 10-028. Guidance for Complying with US Army Corps of Engineers Regional Conditions for Nationwide Permits. Issued 11/1/10.

Olivero, A. P. and A. Jospe. 2006. Fragmentation analysis in the Connecticut River watershed. Boston, MA, The Nature Conservancy, Eastern Conservation Science Office.

Schwartz Jr., H. G. 2011. Adapting to Climate Change - Another Challenge for the Transportation Community. *Transportation Research E-Circular*, (E-C152).

Stager, C. and M. Thill. 2010. Climate Change in the Lake Champlain Basin: What natural resource managers can expect and do. Keene Valley, NY and Montpelier, VT: The Nature Conservancy.

Suarez, P., W. Anderson, V. Mahal, and T. R. Lakshmanan. 2005. Impacts of flooding and climate change on urban transportation: a systemwide performance assessment of the Boston Metro Area. *Transportation Research Part D: transport and environment*, *10*(3), 231-244.

Taylor K.E., R.J. Stouffer, and G.A. Meehl. 2012. An overview of CMIP5 and the experiment design: Bulletin of the American Meteorological Society, v. 93, p. 485–498.

The Nature Conservancy (TNC). 2010. Incorporating aquatic Species of Greatest Conservation Need requirements and conservation objectives into state transportation planning. The Nature Conservancy, Keene Valley, NY. Final Report to New York State Department of Environmental Conservation, State Wildlife Grant Program.

Trenberth, K.E., A. Dai, RM Rasmussen, D.B. Parsons. 2003. The changing character of precipitation. Bulletin of the American Meteorological Association. 84: 1205-1217.

APPENDICES

Appendix A: Future Rainfall and River Discharge in the Adirondack-Champlain Region

Appendix B: A Web-Based Tool that uses Climate Model Forecasts to Estimate the Magnitude of Future Peak Flows in Streams and Rivers of New York State and the Champlain Basin of Vermont

Appendix C: Methodology for Culvert Sizing and Cost Estimation

Appendix D: An Initial Approach for Economic Valuation of Road-Stream Crossings in the Context of Climate Change

Appendix D-1: FEMA Methodology for Calculating Benefits of Improved Access to Critical Services

APPENDIX A: FUTURE RAINFALL AND RIVER DISCHARGE IN THE ADIRONDACK-CHAMPLAIN REGION

Curt Stager

INTRODUCTION

Although warming trends over the next 50-100 years are anticipated by all downscaled climate model projections for the Adirondack-Champlain region, the nature of future precipitation remains less certain. This is partly due to the limited ability of existing models to fully simulate the complexity of mechanisms that produce rainfall, and partly due to inherently unpredictable aspects of rainstorms. Nonetheless, general predictions can still be made regarding the direction of future changes in rainfall that have serious implications for the management of rivers and their associated infrastructure in this region.

This preliminary study examines several factors that will help to determine that future:

1. Patterns of rainstorm intensity over the last century in the Adirondack-Champlain region

2. Relationships between extreme rainstorms and river discharge

3. Likely changes in regional rainstorm intensity and discharge during the next 50-100 years

The findings of this study point to one major conclusion of obvious relevance to highway management: damaging flood events that are now considered to be highly unusual are likely to become more common and more intense in coming decades.

MATERIALS AND METHODS

The analyses conducted for this study center primarily on century-long rainfall records from three weather stations of the United States Historical Climatology Network (USHCN), which are distributed along the western rim of the Champlain Basin: Dannemora, Lake Placid, and Indian Lake. Because a key focus of this study is the relationship between extreme rainfall events and river discharge, only warm-season data (May-October) were examined, and data from months during which freezing and/or thawing complicates precipitation-runoff dynamics were excluded.Daily discharge data from river gages on the Ausable and upper Hudson (at North Creek) were obtained (waterdata.usgs.gov). Seasonal- and annual-scale precipitation projections for the western Champlain Basin were obtained from the outputs of 16 regionally-downscaled climate models through Climate Wizard (www.climatewizard.org). More

qualitative projections regarding the likely future of extreme rainfall events in this region were obtained from recent peer-reviewed literature.

RESULTS

Rainstorm intensity

Total annual rainfall experienced an aburpt step-increase of ca. 3 inches per year around 1970, not only in the Champlain Basin (Stager & Thill, 2011), but also along much of the East Coast (REF). This wetter-on-average setting naturally primes this region for somewhat greater-on-average runoff during storm events, but a much greater change is readily apparent in the nature of the storms themselves.
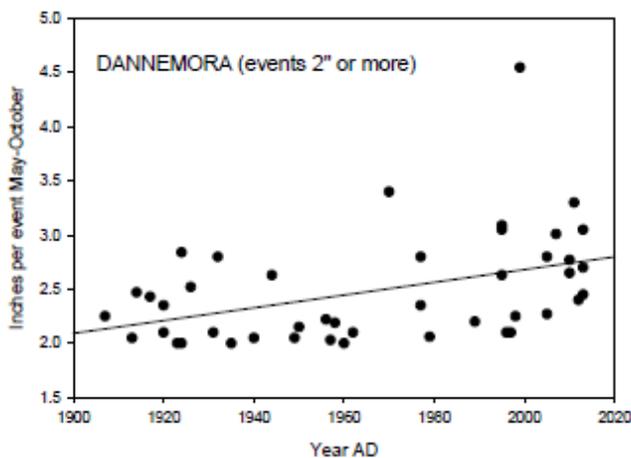
The average amount of rain falling during storms that dropped 2 inches or more within a single day has increased significantly during the last century in most of the weather records examined. Records from Dannemora display one of the most dramatic rises in rainstorm intensity (*see figure to the left*). The trend is also statistically significant but less intense in the records from Indian Lake.

However, the Lake Placid records show no significant trend in the intensity of extreme rainstorms (*see figure to the right*).

There are several possible reasons for this variability among records. The location of the Lake Placid station equipment was recently moved, which might have affected results, and the methodologies and nature of equipment can change over time within and among stations.
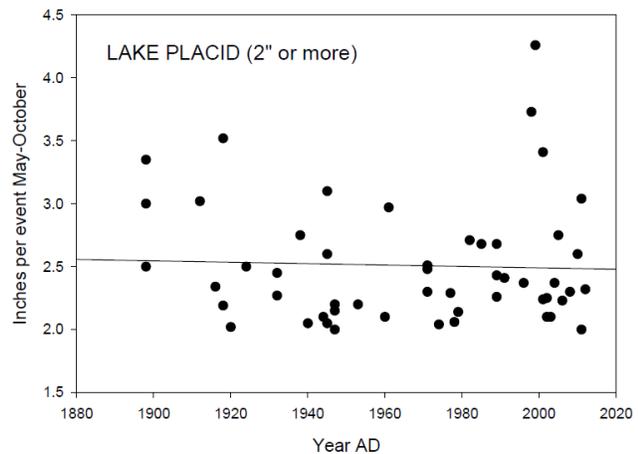
Furthermore, the amount of rain that falls from any given storm varies a great deal from place

to place; Tropical Storm Irene dropped nearly a foot of rain at Johns Brook Lodge but relatively little at the Lake Placid weather station just a few miles away. Finally, the nature of rain systems themselves causes great local variability: a large-scale frontal system is likely to drop more consistent rainfall amounts than smaller thunderstorms.

Flash flooding associated with intense downpours from thunderstorms and hurricanes can suddenly overwhelm storm-water infrastructure with or without a long-term wetting trend. Although there is as yet little evidence that the frequency and/or paths of Atlantic hurricanes are changing or even likely to change predictably in response to global warming, an unusual climate record from Cranberry Lake shows that thunderstorms have recently become more common in the Adirondacks. Three decades of twice-daily weather observations were made there by Robert Simon, a retired engineer, starting in 1959 and ending in 1991, the year of his death. Analysis of his journals by Paul Smith's College students (*see figure below; showing the years for which observations were made consistently*) reveals a statistically significant increase in the number of thunderstorms at Cranberry Lake during those three decades, during which the region also warmed significantly. This is consistent with theory and models that link greater atmospheric moisture and convection to global warming (REFS), and points to more thunderstorms and associated heavy downpours in a warmer future.


Thunderstorm Frequency May-September (1965-1990)

R^2= 0.3952
P- One- Tail= .000758

—Thunderstorm Frequency
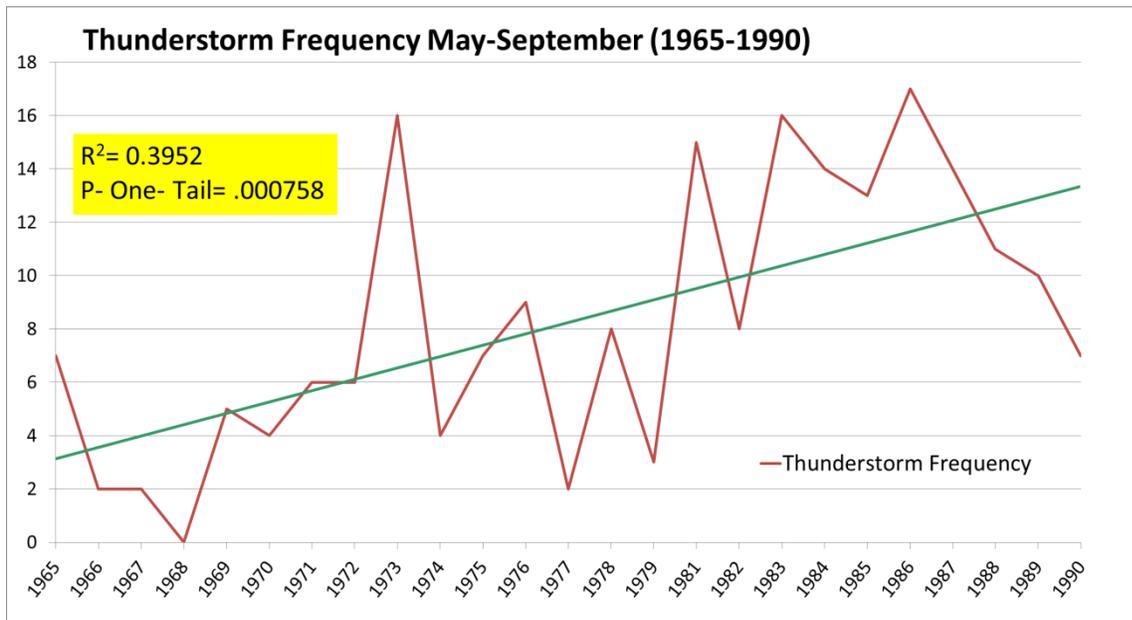
There are several important points to take away from these records:

1. The general direction of change in precipitation over decades and large areas is more useful for future planning than any single year or locale. The great variability of rainfall patterns, particularly over complex terrain such as the Adirondack-Champlain region, makes broad generalities far more reliable predictors of the future than more detailed but less reliable short-term, small-scale patterns. One's own limited personal observations, in other words, may not be a reliable basis for decision-making.

2. The spatial-temporal variability of rainfall makes hydrological modeling of climatic effects on local flooding difficult. This, along with other inherent complications, means that model predictions of river discharge should be regarded as general illustrations of possible future conditions rather than statements of fact. In such situations, the wisest response is to employ the precautionary principle, taking particular note of the extremes in a range of scenarios rather than optimistically assuming that "the worst will not occur."

CONCLUSION: the intensity of "extreme" rainfall events has increased significantly in the Adirondack-Champlain region during the last century.
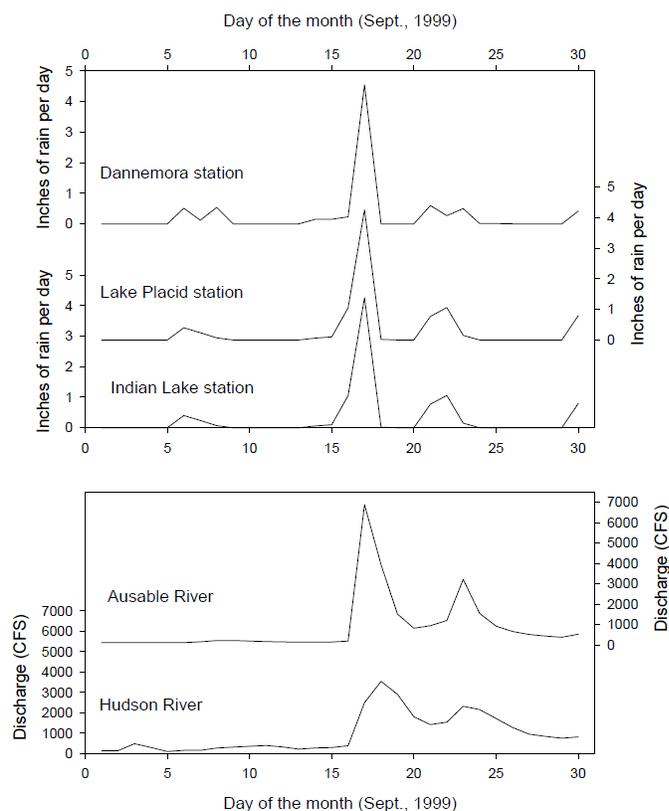
Rainstorms and River Discharge

Stream gage data from the upper Ausable and Hudson Rivers (waterdata.usgs.gov) were examined in relation to four extreme rainfall events of the last century as recorded at Dannemora, Lake Placid, and Indian Lake. Several important conclusions can be made from these records.

First, the rainfall data illustrate the extreme spatial variability described earlier. In some instances, all three stations registered heavy precipitation on the same day (Sept., 1999; see figure to left), and in others the downpours were far more localized. ***This variability shows that the number and locations of weather stations in relation to stream gages can strongly affect the accuracy of hydrological models.*** In the case of this study, the

small number and scattered distributions of available weather and gaging stations precludes exact modeling of rainfall-runoff relationships. However, the Ausable gage did register strong discharge pulses within a day of heavy rainfall events at the Lake Placid station, which is located in the upper Ausable watershed.

Using the Lake Placid and Ausable records for illustrative purposes, one can reasonably conclude that - not surprisingly - heavy rainfall events do indeed produce heavy discharge events in the Adirondack-Champlain region. One can also estimate that an inch of rainfall at Lake Placid was typically soon followed by an increase of roughly 1500 cubic feet per second at the Ausable gage. These values, of course, are specific to these locations and would vary quite a bit spatially, and even such simple estimates of rainfall-runoff relationships in the Ausable watershed have limitations. One of the four rainfall events was associated with a much larger discharge pulse in the Ausable than the data from the other three events might suggest. It is possible that the Lake Placid station was bypassed by the zone(s) of heaviest rainfall in the Ausable watershed as a whole during that particular event.

In any case, the occurrence of this much-larger-than-expected runoff pulse serves as a reminder of the complexity of local climate-landscape connections. It also favors careful consideration of potentially dangerous extremes when interpreting future scenarios.

Future projections of rainfall and runoff

Most of the models employed by Climate Wizard anticipate a generally warmer and wetter future in the Adirondack-Champlain region, which is consistent with most global-scale models as well as basic principles of physics; more greenhouse gases mean a warmer atmosphere, more evaporation from the oceans, and more convective storm activity on average.

As most such studies suggest, these climatic changes will play out over time scales that will make them difficult to detect without long-term perspectives. Inevitable shifts in various aspects of the climate system will further obscure underlying trends; for example, unstable ocean currents are now temporarily shunting extra heat into the deep sea and leading some to mistakenly think that "global warming is over." In general, however, noticeably different climatic conditions are expected to arrive by the middle of this century and become increasingly different from those of today over coming centuries, with the magnitudes of change depending upon future trends in our fossil fuel emissions.

Climate model projections for this region do not agree on how much rain will fall, what form the rainstorms will take, or what seasons will become wetter or drier. As a result, hydrological models can only take us so far in anticipating what the intensities and frequencies of future floods will be.

In spite of these limitations, enough can be concluded with a high degree of certainty to warrant serious consideration by those responsible for the management of flood-sensitive infrastructure.

1. We can't know exactly when the next extreme rainstorm will occur... but all available evidence indicates that more are coming, and that we are wise to expect more of them to strike in coming decades than were seen during the early 20th century. A baseball analogy may help to illustrate this principle: We can't say that steroids caused any given one of the home runs that Barry Bonds hit, but we know that they helped him to hit more of them and to hit them farther. We now have weather on steroids.

2. We can't know exactly how much rain will fall in the larger storms to come... but all available evidence indicates that downpours of the future will be heavier on average than they are today. This conclusion is strongly supported by multiple public and private weather records from this region as well as by the scientific literature and physical principles. A simplistic extension of current trends suggests that the amount of rainfall in an average extreme rainstorm could rise by half an inch in mid-century and an inch by 2100 AD. However, individual storms could well exceed anything seen within the last century.

3. We can't predict exactly how extreme future floods will be at any given location... but we can be sure that heavier downpours in the future must result in heavier flooding, as well. The shifting nature of what constitutes "normal" weather requires that the magnitudes of future flood events should be assumed to be shifting towards higher intensities than were anticipated in the past. This, in turn, suggests that it is wise to anticipate severe flood damage to become more frequent and more extreme, on average, in coming decades.

APPENDIX B: A WEB-BASED TOOL THAT USES CLIMATE MODEL FORECASTS TO ESTIMATE THE MAGNITUDE OF FUTURE PEAK FLOWS IN STREAMS AND RIVERS OF NEW YORK STATE AND THE CHAMPLAIN BASIN OF VERMONT

Douglas A. Burns, Martyn J. Smith, Douglas A. Freehafer
U.S. Geological Survey
425 Jordan Rd.
Troy, NY 12180

INTRODUCTION

A new web-based tool, titled "StreamStats: Estimated Impact of Climate Change on Peak Flow Magnitudes", allows the user to apply a set of regression equations to estimate the magnitude of future peak flows for streams and rivers in New York State and the Champlain Basin in Vermont. This tool excludes the outlet of Lake Champlain, the Hudson River downstream of Hastings-on-Hudson, and all basins in Long Island. Additionally, the tool should not be applied to urban basins and to rivers with extensive regulation. The regression equations that are the basis of the current application were developed and are described by Lumia and others (2006) for New York and by Olson (2014) for Vermont. These regression equations include several landscape metrics that quantify aspects of watershed geomorphology, basin size, and land cover as well as a climate variable, generally either annual precipitation or annual runoff. The approach used to develop peak flow magnitudes for various recurrence intervals is described more fully in a report titled, "Guidelines for Determining Flood Flow Frequency" (Interagency Advisory Committee on Water Data, 1982) as well as in the most recent New York and Vermont reports that describe the regressions for estimating peak flows (Lumia and others, 2006; Olson, 2014).

STREAMSTATS PROGRAM

The existing set of regression equations are implemented in a web-based stream analysis tool titled, "The StreamStats Program" (hereafter referred to as StreamStats, that is available for streams and rivers in New York (http://water.usgs.gov/osw/streamstats/new_york.html) and Vermont (http://water.usgs.gov/osw/streamstats/Vermont.html). The current version of Vermont StreamStats, however, does not apply the most recently available regression equations from Olson and other (2014); therefore, these have been added in the current application. StreamStats allows the user to delineate a watershed at any point on the stream

channel within these two states, and to then obtain information about the stream and watershed. Available peak flow information for New York includes the magnitudes of peaks with recurrence intervals of 1.25, 1.5, 2, 5, 10, 25, 50, 100, 200, and 500 yrs (corresponding to an annual probability of 80, 67, 50, 20, 10, 4, 2, 1, 0.5, and 0.2 percent, respectively). Available peak flow information for Vermont includes the magnitudes of peaks with recurrence intervals of 2, 5, 10, 25, 50, 100, and 200 yrs (corresponding to an annual probability of 50, 20, 10, 4, 2, 1, 0.5, and 0.2 percent, respectively). New York is divided into six regions for the purposes of this analysis, and separate regression equations were developed for each of these regions. A single set of regressions was developed for the whole state of Vermont.

CLIMATE CHANGE APPLICATION

In the current application described here, the regressions are applied with a new climate variable (either precipitation or runoff) substituted into each equation. To evaluate how future climate might affect peak flow magnitudes, data are applied from five climate models that were part of the most recent global climate assessment (5th Phase of the Coupled Model Intercomparison Project (CMIP5); Taylor and others, 2012). These models were selected based on discussions with climate scientists as to which of the CMIP5 climate models best represented past trends in precipitation in the Lake Champlain basin (based on an analysis described in Guilbert and others, 2014).

Precipitation data from these climate models were obtained from downscaled projections at a spatial resolution of 30-arc-seconds that are available from the National Aeronautics and Space Administration as described by Thrasher and others (2013). Precipitation data were evaluated for two future scenarios (termed Representative Concentration Profiles (RCP) in CMIP5) that provide estimates of the extent to which greenhouse gas concentrations in the atmosphere are likely to change through the 21st century.

These scenarios, RCP 4.5 and RCP 8.5, were evaluated for each climate model in CMIP5 (Taylor and others, 2012). RCP is an abbreviation for Representative Concentration Pathways, referring to potential future emissions trajectories of greenhouse gases such as carbon dioxide and others. RCP 4.5 is considered a mid-range emissions scenario, and RCP 8.5 a high emissions scenario. Finally, results were averaged for three future time periods, 2025-49, 2050-74, and 2075-99 following the approach used in the USGS Climate Change Viewer (http://www.usgs.gov/climate_landuse/clu_rd/nccv.asp). The downscaled precipitation data for each model and RCP scenario averaged over these 25 year time windows were obtained from the developers of the USGS Climate Change Viewer (Jay Alder, U.S. Geological Survey, personal communication, http://www.usgs.gov/climate_landuse/clu_rd/nccv.asp).

Together the combination of climate models, greenhouse gas scenarios, and time periods, can provide up to 30 sets of peak flow magnitude estimates for each stream watershed delineated. These available results are meant to reflect a range of variation predicted from among the five models and two greenhouse gas scenarios. Information on the models, greenhouse gas scenarios, and time periods is shown in Table 1.

ASSUMPTIONS

The application of these regression equations involves a space-for-time substitution approach because these equations were derived to account for spatial variation in peak flows across each hydrologic region of New York and across the state of Vermont. A space-for-time approach has proven useful in other investigations that have explored how hydrologic measures may respond to climate change in individual watersheds (Sing and others, 2011; Sivapalan and others, 2011). According to this approach, the key variable that will govern the change in peak flows is the exponent of either precipitation or runoff in the regression equations. If this exponent is greater than one, then peak flows will increase by a relative amount that is greater than the relative increase in precipitation or runoff. The opposite will occur if the exponent is less than one. For example, if precipitation in Region 1 of New York increases by 10% in a future climate scenario, then the 50-yr recurrence interval peak flow will increase by 11.38% because the exponent of the precipitation variable for this region and flow is 1.131 (Table 1, Lumia and others, 2006).

Several additional simplifying assumptions were made in the development of this web-based tool. A broad assumption is that the relation between annual precipitation or runoff and the magnitudes of peak flows will in the future as these values were over the time periods for which the regressions were developed. These relations were developed based on an analysis of all pertinent and available streamgage discharge data in New York through 1999 (Lumia and others, 2006), and in Vermont through 2011 (Olson, 2014). Discharge data from surrounding states and Canadian provinces were also used in these analyses. Several analyses of historical climate data and projections of future climate based on model output have indicated that the magnitude and frequency of large precipitation events is increasing (Groisman and others, 2005; Hodgkins and Dudley, 2011) and likely to further increase in the future; (Toreti and others, 2013; Jannssen and others, 2014). These and other analyses suggest that the relation between annual precipitation and runoff and the size and intensity of large precipitation events may change in the future (Silliman and others, 2013). The development of this web-based tool necessitated the use of the available regression equations, which consider only annual values of precipitation or runoff.

Another important assumption made in the development of this web-based tool is applicable to the regressions developed for hydrologic regions 2, 3, 4, and 6 in New York, which use annual runoff as the climatological variable. These annual runoff values are based on the hydrologic analysis of Randall (1996) for the period 1951-80. Annual runoff is the difference of annual precipitation and annual evapotranspiration (ET) in the absence of major human alteration of the water cycle and resulting changes in storage in a basin. Recent reports have indicated that ET is increasing in the Northern Hemisphere, and continued increases are likely during the 21st century (Miralles and others, 2014), but some conflicting evidence has also been shown suggesting that changes in ET are complex, of high spatial variability, and likely to be influenced by multi-decadal climate oscillations (Jung and others, 2010). In this web based tool, ET/precipitation was held constant, and future changes in annual runoff are governed by changes in precipitation and resulting changes in ET. The effects of future changes in ET on the magnitude of peak flows are not well known at present and are the subject of ongoing research.

A final assumption is pertinent only to the regression equations for Region 3 in New York. In this region, the 38 yr median maximum seasonal snow depth is one of the predictive variables in the regression (Lumia and others, 2006). Future snowfall and snowpack depth for Region 3, which includes the Catskill Mountains, is expected to decline during the 21st century as the climate warms (Matonse and others, 2013). The effects of a decreasing snowpack on peak flows in this region are not well known, and were not considered in the development of this web-based tool.

Table 1. Names, abbreviations, and references that describe the climate models, greenhouse gas scenarios, and time periods that are included in the web-based tool that provides estimates of future peak flow magnitudes for streams and rivers in New York State and Champlain basin of Vermont.

Name/Description	Abbreviation	Reference
Climate Models		
Beijing Normal University Earth System Model	BNU-ESM	Ji and others, 2014
Community Earth System Model with Biogeochemical Cycling Model, Version 1.0	CESM1-BGC	Lindsay and others, 2014

Centre National de Recherches Météorologique Climatological Model 5	CNRM-CM5	Voldoire and others, 2012
Institut Pierre Simon Laplace Climate Model 5A, Low-Resolution	IPSL-CM5A-LR	Dufresne and others, 2013
Norwegian Earth System Model, Intermediate Resolution	NorESM1-M	Bentsen and others, 2013
Greenhouse Gas Scenarios		
Representative Concentration Profile 4.5	RCP 4.5	Thomson and others, 2011
Representative Concentration Profile 8.5	RCP 8.5	Riahi and others, 2011
Time Periods		
Average of the years 2025 - 49	2025-49	USGS Climate Change Viewer (http://www.usgs.gov/climate_landuse/clu_rd/nex-dcp30.asp)
Average of the years 2050 - 74	2050-74	USGS Climate Change Viewer (http://www.usgs.gov/climate_landuse/clu_rd/nex-dcp30.asp)
Average of the years 2075 - 99	2075-99	USGS Climate Change Viewer (http://www.usgs.gov/climate_landuse/clu_rd/nex-dcp30.asp)

LIMITATIONS AND UNCERTAINTY

The regression equations in StreamStats are not readily applicable to two types of watersheds: (1) those that are greatly affected by stream regulation such as reservoirs and/or withdrawals or additions for water supply or irrigation, and (2) those where urban land use exceeds 15% of basin area (Lumia and others, 2006). None of the basins in Vermont were considered urbanized

(Olson and others, 2014). The user of this web-based tool is encouraged to first obtain a table of basin characteristics from StreamStats prior to considering how climate change may affect peak flow magnitudes. Regression-based estimates of current peak flow magnitudes for any basin with substantial regulation or diversion, or urban land exceeding 15% of basin area are considered to have unacceptably high uncertainty, indicating that estimates of future peak flow magnitudes in such basins will also have unacceptably high uncertainty. Methods for estimating peak flows in ungaged urban watersheds are described by Sauer and others (1983).

 Another reason to explore the characteristics of a delineated basin in StreamStats before applying this new web-based tool is that some basins have geomorphic or land cover characteristics, including basin drainage area, that are outside of the linear range used to develop the peak flow regressions in each New York region or in Vermont. StreamStats provides a warning when an out-of-range basin has been delineated, and estimated peak flow magnitudes from such basins are considered to be poorly defined and should be used with extreme caution (Lumia and others, 2006).

There are several sources of uncertainty in the use of a regression-based approach to estimate peak flow magnitudes, especially when the role of future climate is being considered. Uncertainty of current peak flow estimates can be obtained by using the standard error of prediction of the regression equations for each region of New York as described by Lumia and others (2006) and Olson and others (2014). Other sources of uncertainty arise from inaccuracies in the basin delineation and those of the predictive variables. A major source of uncertainty is the application of these regression equations to future climate conditions that are likely to be much different than those for which they were developed. Future changes in air temperature and ET along with those of snowfall and snowpack development are likely to affect peak flows in a manner that cannot be well represented by an analysis of current and past data. Ongoing climate change provides an impetus to periodically re-assess these regressions with updated data, and also suggests that improved peak flow forecasts could be provided through the application of deterministic rainfall-runoff models that can explore different combinations of climate factors that are likely to affect peak flows.

Considerable uncertainty also results from the assumptions and calculations embedded in each climate model and greenhouse gas scenario. This source of uncertainty is difficult to evaluate, however, one approach has been to examine the "ensemble" of results available from the various climate models and greenhouse gas scenarios. An ensemble-like approach can be explored with this tool by examining the variation in the results of all 30 sets of results available for future 21st century peak flow magnitudes available for each delineated basin. A final major source of uncertainty derives from the approach used for downscaling results from global

climate models that have a spatial resolution of about 50 – 500 km (Taylor and others, 2012) to the scale of 30 arc-seconds for the data used in this application. This source of uncertainty is potentially large, but difficult to quantify (Mearns and others, 2014). The downscaling approach used to derive the NEX DCP-30 downscaled data set can be broadly described as a statistical approach, and is described by Thrasher and others (https://cds.nccs.nasa.gov/wp-content/uploads/2014/04/NEX-DCP30_Tech_Note_v0.pdf; Thrasher and others, 2013).

HOW TO USE THE WEB-BASED TOOL

The user is advised to first delineate the basin of interest in the StreamStats Program for New York (http://water.usgs.gov/osw/streamstats/new_york.html) or Vermont (http://water.usgs.gov/osw/streamstats/Vermont.html). Check the delineated basin to be certain it does not: (1) exceed either 15% urban land area or is highly altered by impoundment or withdrawal, and (2) have basin characteristics outside the range used for the regression in the region of interest. If the basin is acceptable for evaluation with the regressions, then proceed to the new web-based tool (http://ny.water.usgs.gov/maps/leaflet-streamstats/).

The computer mouse can be used to navigate around the map of northeastern states that appears when the tool is first implemented. The default zoom level is 7. To delineate a stream basin, the zoom level must be at 15 or greater. Use the + button in the upper left hand side to increase the zoom level. Once the zoom level has reached at least 15, the dark blue grids representing stream channels will become visible. Move the appropriate stream location near the center of the map, and click on the green button in the upper right hand side to activate the delineation function. Then navigate to the appropriate stream location, center the cross over the dark blue grid and click to delineate a basin. Wait for the basin delineation and calculate basin characteristics functions to complete (the average time is about 1.5 to 2 minutes). Click on the Output button to see the StreamStats parameters used to evaluate the current regressions. Select a greenhouse gas scenario, climate model, and time period. Then click the "Update climate parameter" button. New estimates of runoff, precipitation, and evapotranspiration for a future climate will appear in the output table. Next, click on Estimate flows to calculate the peak flow values. The values for current and future peak flow magnitudes for the various recurrence intervals will appear in the table in units of cubic feet per second. To change the greenhouse gas scenario, climate model, or time period, click the Output tab, enter the new choices, update the Climate parameters, and then click the Estimate flows button again to see the revised peak flow magnitudes. Once the user is finished with calculations for a given basin, the Start Over button can be used to delineate a new basin.

REFERENCES CITED

Bentsen, M., Bethke, I., Debernard, J.B., Iversen, T., Kirkevag, Seland, O., Drange, H., Roelandt, C., Seirstad, I.A., Hoose, C., and J.E. Kristjansson, 2013, The Norwegian Earth System Model, NorESM1-M – Part 1: Description and basic evaluation of the physical climate: Geoscientific Model Development, v. 6, p. 687-720.

Dufresne, J.-L., and 60 others, 2013, Climate change projections using the IPSL-CM5 Earth System Model: From CMIP3 to CMIP5: Climate Dynamics, v. 40, p. 2123-2165.

Groisman, P.Y., Knight, R.V., Easterling, D.R., Karl, T.R., Hegerl, G.C., and Razuvaev, 2005, Trends in intense precipitation in the climate record: Journal of Climate, v. 18, p. 1326-1350.

Guilbert, J., Beckage, B., Winter, J.M., Horton, R.M., Perkins, T., and Bomblies, A., 2014, Impacts of projected climate change over the Lake Champlain basin in Vermont: Journal of Applied Meteorology and Climatology, v. 53, p. 1861-1875.

Hodgkins, G.A., and R.A. Dudley, 2011, Historical summer base flow and stormflow trends for New England rivers: Water Resources Research, v. 47, W07528, doi:10.1029/2010WR009109.

Interagency Advisory Committee on Water Data, 1982, Guidelines for determining flood flow frequency: Bulletin 17B of the Hydrology Subcommittee, 194 p.

Jannssen, E., Wuebbles, D.J., Kunkel, K.E., Olsen, S.C., and Goodman, A., 2014, Observational-andmodel-based trends and projections of extreme precipitation over the contiguous United States, Earth's Future, v. 2, p. 99-113.

Ji, D., and 15 others, 2014, Description and basic evaluation of Beijing Normal University Earth System Model (BNU-ESM) version 1: Geoscientific Model Development, v. 7, p. 2039-2064.

Jung, M., and 32 others, 2010, Recent decline in the global land evapotranspiration trend due to limited moisture supply: Nature, v. 467, p. 951-954.

Lindsay, K., Bonan, G., Doney, S., Hoffman, F., Lawrence, D., Long, M., Mahowald, N., Moore, J., Randerson, J., and Thornton, P., 2014, Preindustrial control and 20th century carbon cycle experiments with the Earth System Model CESM1 (BGC): Journal of Climate, v. 27, p. 8981-9005.

Lumia, R., Freehafer, D.A., and Smith, M.J., 2006, Magnitude and Frequency of Floods in New York: U.S. Geological Survey Scientific Investigation Reports 2006-5112, 152 p.

Matonse, A.H., Pierson, D.C., Frei, A., Zion, M.A., Anandhi, A., Schneiderman, E., and B. Wright, 2013, Investigating the impact of climate change on New York City's primary water supply: Climatic Change, v. 116, p. 437-456.

Mearns, L.O., Bukovsky, M.S., Pryor, S.C., and Magana, V., 2014, Downscaling of climate information, in: Climate Change in North America: Regional Climate Studies, Ohring, G. (Ed.), Springer, p. 201-250.

Miralles, D.G., and 11 others, 2014, El Niño–La Niña cycle and recent trends in continental evaporation: Nature Climate Change, v. 4, p. 122-126.

Olson, S.A., 2014, Estimation of flood discharges at selected annual exceedance probabilities for unregulated, rural streams in Vermont: U.S. Geological Survey Scientific Investigation Reports 2014-5078, 27 p.

Randall, A.D., 1996, Mean annual runoff, precipitation, and evapotranspiration in the glaciated northeastern United States, 1951–80: U.S. Geological Survey Open-File Report 96-395, 2 pls.

Riahi, K., Rao, S., Krey, V., Cho, C., Chirkov, V., Fischer, G., Kindermann, G., Nakicenovic, N., and Rfaj, P., 2011, RCP 8.5—A scenario of comparatively high greenhouse gas emissions: Climatic Change, v. 109, p. 33-57.

Sauer, V.B., Thomas, W.O., Jr., Stricker, V.A., and Wilson, K.V., 1983, Flood characteristics of urban watersheds in the United States: U.S. Geological Survey Water-Supply Paper 2207, 63 p.

Silliman, J., Kharin, V.V., Zwiers, F.W., Zhang, X.,, and Bronaugh, D., 2013, Climate extremes indices in the CMIP5 multimodel ensemble: Part 2. Future climate projections, Journal of Geophysical Research: Atmospheres, v. 118, p. 2473–2493.

Singh, R., Wagener, T., van Werkhoven, Mann, M.E., and Crane, R., 2011, A trading-space-for-time approach to probabilistic continuous streamflow predictions in a changing climate – accounting for changing watershed behavior, Hydrology and Earth System Science, v. 15, p. 3591-3603.

Sivapalan, M., Yeager, M.A., Harmon, C.J., Xu, X., and Troch, P.A., 2011, Functional model of water balance variability at the catchment scale: 1. Evidence of hydrologic similarity and space-time symmetry, Water Resources Research, v. 47, W02522, doi:10.1029/2010WR009568.

Taylor K.E., Stouffer R.J., and Meehl G.A., 2012, An overview of CMIP5 and the experiment design: Bulletin of the American Meteorological Society v. 93, p. 485–498.

Thomson, A.L., and 10 others, 2011, RCP4.5: A pathway for stabilization of radiative forcing by 2100: Climatic Change, v. 109, p. 77-94.

Thrasher, B., Xiong, J., Wang, W., Melton, F., Michaelis, A., and Nemani, R., 2013, Downscaled climate projections suitable for resource management, Eos, v. 94, p. 321-323.

Toreti, A., Naveau, P., Zampieri, M., Schindler, A., Scoccimarro, E., Xoplaki, E., Dijkstra, A., Gualdi, S., and Luterbacher, J., 2013, Projections of global changes in precipitation extremes from Coupled Model Intercomparison Project Phase 5 models: Geophysical Research Letters, v. 40, p. 4887-4892.

Voldoire, A., and 25 others, 2012, The CNRM-CM5.1 global climate model: description and basic evaluation: Climate Dynamics, v. 40, p. 2091-2121.

APPENDIX C: METHODOLOGY FOR CULVERT SIZING AND COST ESTIMATION

METHODOLOGY FOR HYDROLOGIC ANALYSIS TO SIZE CULVERT
Step HA-1: Guidance document – Highway Design Manual
As noted in NYSDOT Highway Design Manual (HDM), a hydrologic analysis is required for culvert replacement or relining (see HDM Chapter 8 – Highway Drainage) (https://www.dot.ny.gov/divisions/engineering/design/dqab/hdm/hdm-repository/chapt_08.pdf).

HDM Section 8.3.2 - Hydrologic Analysis presents the overall process which should be used to conduct the hydrologic analysis for a given project. This analysis is done for the drainage area that flows to the culvert to determine the design flows for a 50 year storm event.

Step HA-2: Select method for design flows
Design guidance from the NYSDOT Highway Design Manual (HDM) indicates that one of three methods or a combination of is used to determine the design flows.   As explained in HDM Section 8.3.2.4 - Flow Rate Determination, "recommended methods, which are briefly explained in sections A through D, include:

> 1. Rational Method. Computes a peak discharge.
> 2. Modified Soil Cover Complex Method ("Urban Hydrology for Small Watersheds", NRCS TR-55, is the basis for this method). Computes a peak discharge directly using a formula and by plotting a hydrograph.
> 3. Regression Equations. Computes a peak discharge.
> 4. Historical Data."

The method used depends on the drainage area. Regression Equations (e.g., StreamStats) are used for drainage areas over 1 square mile; the Modified Soil Cover Complex Method (TR-55) is used for drainage areas between 200 acres and 1 square mile, and the Rational Method is used for drainage areas up to 200 acres. The culverts in this project were designed using a combination of StreamStats and TR-55.

Step HA-3: Derive design flows for three scenarios
1. *In-kind culvert design flow*

2. *Climate-sized culvert design flow* - To derive the predicted future design flows, this project used the updated StreamStats tool that USGS is developing (current url: http://ny.water.usgs.gov/maps/floodfreq-climate/). This tool allows the user to apply a

set of regression equations to estimate the magnitude of future peak flows for streams and rivers in New York State and the Champlain Basin in Vermont (with some exceptions and caveats).
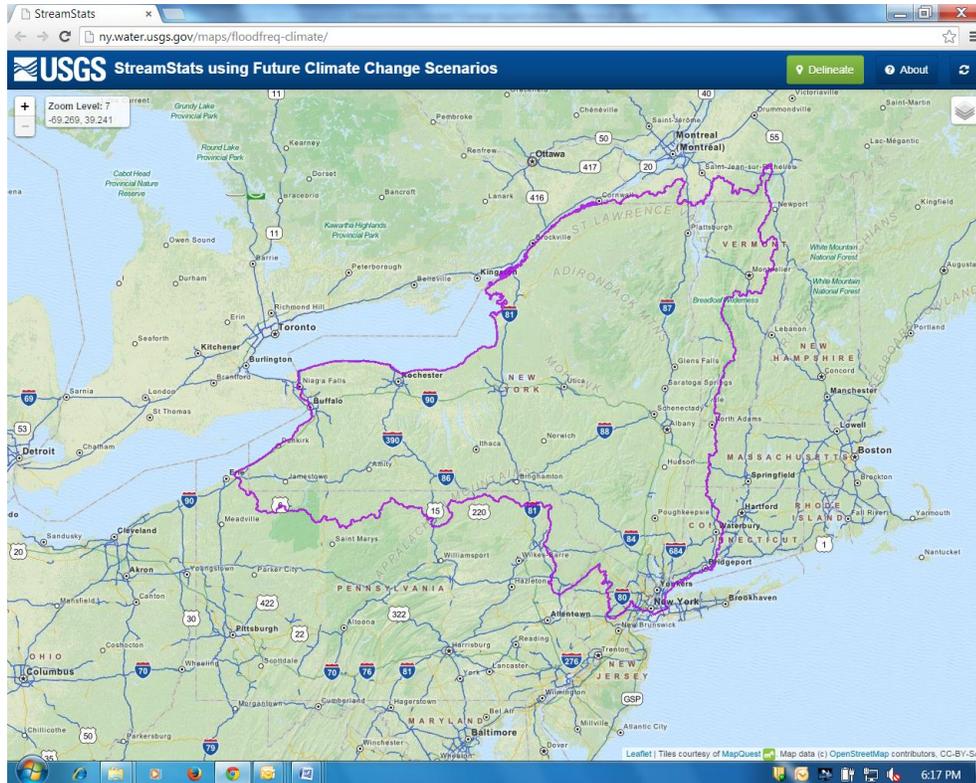
- o The tool gives three options for greenhouse gas scenarios, three time frames and five climate models. For this study, one time frame (2050-74) and one greenhouse gas scenario (8.5) were selected in conjunction with the five different climate models (BNU-ESM, CNRM-CM5, CESM1-BGC, IPSL-CM5A-LR and NorESM1-M). Use the average of the predicted 50 year discharge (cfs) from the five climate models to size the culvert for future predicted flows.

3. *Regulatory conditions (1.25 bankfull) culvert design flows*

Step HA-4: Confirm adequate hydraulic capacity

Confirm adequate hydraulic capacity by inputting the predicted flows for each of the design scenarios (in-kind, climate-sized, and regulatory conditions) into HY-8, Culvert Hydraulic Analysis Program (http://www.fhwa.dot.gov/engineering/hydraulics/software/hy8/).
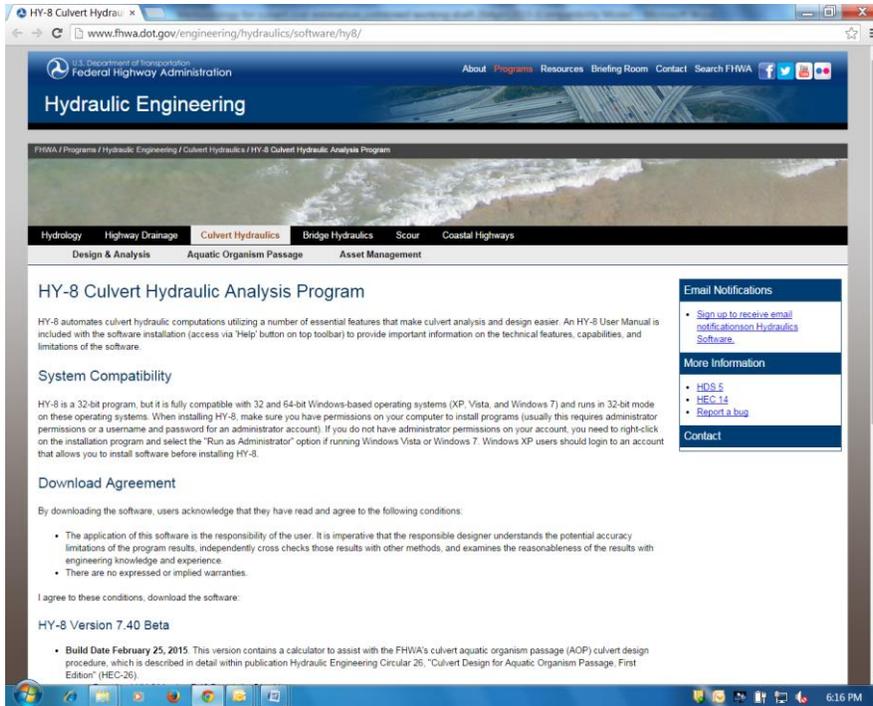
Step HA-5: Determine geometry of the culvert

For each of the scenarios, determine the geometry of the culvert that will allow the culvert to pass the design flows (for a 50-year Storm Event) while meeting the design criteria for allowable headwater as described in HDM Section 8.6.1 Hydraulic Design Criteria, subsection 8.6.1.1 Allowable Headwater:

8-42   **HIGHWAY DRAINAGE**

The most controlling of the following criteria should determine the allowable headwater:

1. Water should be kept 2 ft. below the outside edge of the lowest shoulder.
2. Water should be allowed to pass through the culvert without causing damage to upland property or increase the water surface elevation upstream of the culvert above that allowed by floodplain regulations, generally 1.0 ft.
3. The ratio of the headwater to pipe height, or diameter, (H_w/D) should be limited as follows:

Diameter or Rise	Maximum H_w/D Ratio
‹ 5 ft	1.5
≥ 5 ft	1.0

Pipes smaller than 5 ft with a H_w/D ratio greater than 1.0 should be discussed in the drainage report with regard to flooding conditions, velocities, scouring, economy, future maintenance (e.g., installing a smaller pipe within the original pipe or structure), etc. If damage to the culvert is possible, or if adverse flooding conditions will be caused upstream (from the accumulation of ice and debris at the culvert's inlet), the H_w/D ratio shall be reduced. The H_w/D ratio shall also be reduced to allow an increase in the design flow capacity, and freeboard (if needed) at the entrance of the structure, to eliminate flood damage or to reduce it within acceptable limits.

a. To determine "climate sized" culverts using future predicted flow, change the cfs value in the HY-8 formula to reflect the future climate flows determined in step 4.
b. Because the culverts used as illustrative examples for this project were in the design phase, HY-8 calculations were previously developed by the design engineer to meet the USACE regulatory condition (1.25 bankfull) ("stream-sized").

METHODOLOGY FOR CULVERT COST ESTIMATIONS

Determine culvert cost estimates for the various scenarios (in-kind, climate-sized, and stream-sized).

Step CE-1: Getting Started

To calculate the estimates, use the DOT Standard Specification for Construction and Materials book for the **Item Number** of a typical trench and culvert. The item number is specific to each culvert based on the *span, rise of the culvert, type of culvert, and the depth of culvert*.

Go to *DOT.NY.gov*, and click on the *"Business Center"* that is at the top of the webpage. Then click on the *"doing business with NYSDOT",* scroll down to the **Engineering** section and click on the *"Specifications and Standard Sheets"*.
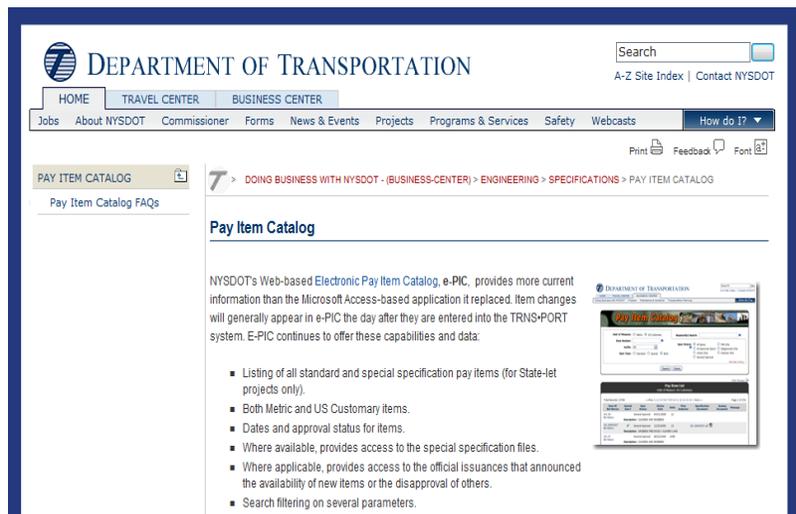
This will take you to the Specifications page through which you can enter to the *"Pay Item Catalog"* page and to the *"Electronic Pay Item Catalog (e-PIC)"*. The website is https://www.dot.ny.gov/pic

Step CE-2: Pay Item Catalog

Provide the **Item Number** that you have from the Standard Specification book into the catalog and click on **Search**. The Pay Item List shows at the bottom of the page. Click on the *Specific Item Number* **Bid History** and it will take you to the **Pay Item Bid History Information** page.
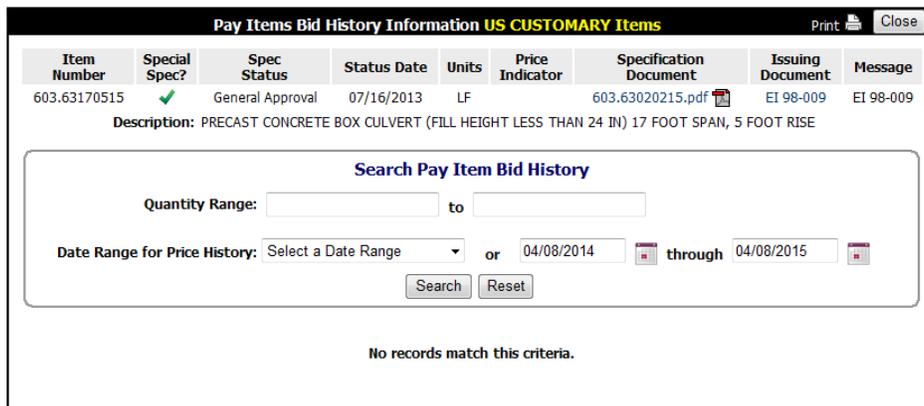
Change the date range according to your specifications and needs. For example, looking at the image above, the start date was changed from 2014 to 2000. Once the Date Range is entered, click **Search** and we get the details of the project below on the webpage.

Pay Items Bid History Information US CUSTOMARY Items								Print Close
Item Number	Special Spec?	Spec Status	Status Date	Units	Price Indicator	Specification Document	Issuing Document	Message
603.63170515	✔	General Approval	07/16/2013	LF		603.63020215.pdf 📄	EI 98-009	EI 98-009

Description: PRECAST CONCRETE BOX CULVERT (FILL HEIGHT LESS THAN 24 IN) 17 FOOT SPAN, 5 FOOT RISE

Search Pay Item Bid History

Quantity Range: [   ] to [   ]

Date Range for Price History: Select a Date Range ▼ or 04/08/2000 📅 through 04/08/2015 📅

[Search] [Reset]

Region	Number of Projects	Quantity	Weighted Average Price	
⊟ Statewide	1	80.00	$1,662.47	Export Data 📊 Print 🖨

D Number	Pin Number	Let Date	Project Description	Qty	Awarded Price	Extended Amt
D262401	180925	12/05/2013	THIS IS A CULVERT REPAIR / REPLACEMENT CONTRACT TO ADDRESS	80.00	$1,662.47	$132,997.60
			Total: 80.00			$132,997.60

⊞ 1		1	80.00	$1,662.47	Export Data 📊 Print 🖨

Gather the details for the following;

> **D Number** is the Contract Number
>
> **Pin number** is the Project Number
>
> **Let Date** is the date the project was awarded
>
> **QTY** is the length of the culvert in feet (Units in **LF**, Linear Foot)
>
> **Awarded Price** is the cost per length to the culvert
>
> **Extended Amount** is the total cost on the entire length of the culvert

If the number of bids in the above image box is just one you can assume the **culvert cost** amount given as the actual amount. Most of the projects will have a list of variable bids, in which case we take the average of the bids. The culvert cost varies depending on the span, rise, culvert type and the depth of cover. The item number is specific to each culvert, therefore for each different scenario the cost can be noted down.

Step CE-3: Culvert excavation cost estimation
The following are the formulae used for the calculations of the trench and culvert excavation costs:

Stream Size (ft)

> *Note down Span, and length.*
>
> *Offset   = Wall thickness + Lane*
>
>   *= 1 ft + 3 ft = 4 ft*

Total depth of culvert = Rise + Depth of cover + Embedment + Floor + Crushed stone thickness

C-6

Excavation (ft³)

Culvert Box Area = (Span + Offset) * Total depth of Culvert * Length

Culvert Slope Area = 2 * [1/2 * Total depth * (1.5 * Total depth)] * Length

= 1.5 * (Total depth) ² * Length

1.5 Depth

Depth
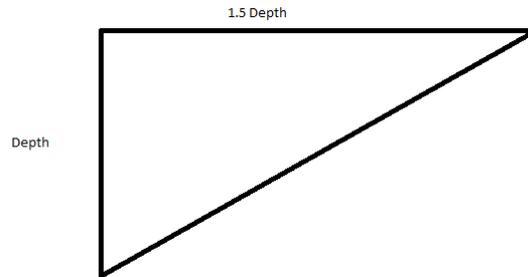
Fig: Slope gradient is 1:1.5

Total excavated Area in yd³ = (Culvert Box Area + Culvert Slope Area)/27

Total Excavation Cost = Total Excavated Area * Excavation cost per yd³

Subtotal Culvert cost = Culvert Cost + Total Excavation Cost

This cost estimation can be carried out for the in-kind, climate sized, and stream sized, by entering the appropriate dimensions for each scenario.

Step CE-4: Additional cost
The maintenance and protection of traffic (MPT) costs are determined based on bid history for those particular items. The calculations can be carried out by adding the maintenance and protection related cost. These costs can often be significant, especially when a detour is not feasible. In those cases, the necessity to keep one lane open can require the installation of structural support such as a GRES wall, sheet piling or a soldier pile lag wall. These costs do not vary with the size of the culvert.

The remainder of the costs includes items that would not increase if the culvert was upsized, such as cofferdams, the base and binder coarses of road material, guiderail and survey.

Other Cost = Total Cost – (MPT Cost + Subtotal Cost)

ILLUSTRATIVE EXAMPLES OF CULVERT COST COMPARISONS

C9-25

		In-Kind	Climate Sized	Stream Sized
Culvert Size	Span	5	14	12.5
	Rise	5	6	6
	Depth of cover	3	3	3
	Embedment	1	1.3	1.3
	Length	54	70	70
Trench & Excavation Cost		$ 19,470	$ 38,697	$ 37,262
Culvert cost per LF		$ 1,000	$ 1,400	$ 1,200
Culvert Cost		$ 54,000	$ 98,000	$ 84,000
Sub Total		$ 73,470	$ 136,697	$ 121,262
MPT		$ 55,000	$ 55,000	$ 55,000
Other Construction Items		$ 263,330	$ 280,335	$ 286,538
Total Cost		$ 391,800	$ 472,032	$ 462,800

C9-54

		In-Kind	Climate Sized	Stream Sized
Culvert Size	Span	10	10	10
	Rise	6	6	7.5
	Depth of cover	2.5	2.5	2.2
	Embedment	1.5	1.5	1.5
	Length	70	70	70
Trench & Excavation Cost		$ 33,600	$ 33,600	$ 38,808
Culvert Cost per LF		$ 1,100	$ 1,100	$ 1,150
Culvert Cost		$ 77,000	$ 77,000	$ 80,500
Sub Total		$ 110,600	$ 110,600	$ 119,308
MPT		$ 70,000	$ 70,000	$ 70,000
Other Construction Items		$ 267,000	$ 267,000	$ 264,792
Total Cost		$ 447,600	$ 447,600	$ 454,100

C9-55

Culvert Size		In-Kind		Climate Sized		Stream Sized
	Span	11		10		12.5
	Rise	6		5		6
	Depth of cover	4		4		4
	Embedment	1.3		1.3		1.3
	Length	53		60		60
Trench & Excavation Cost		$ 30,507	$	29,889	$	35,866
Culvert Cost per LF		$ 1,050	$	1,050	$	1,175
Culvert Cost		$ 55,650	$	63,000	$	70,500
Sub Total		$ 86,157	$	92,889	$	106,366
MPT		$ 65,000	$	65,000	$	65,000
Other Construction Items		$ 347,499	$	332,007	$	337,850
Total Cost		$ 498,656	$	489,896	$	509,216

C9-72

Culvert Size		In-Kind		Climate Sized		Stream Sized
	Span	10		11		12
	Rise	4		5.5		6
	Depth of cover	1.2		1.2		1.2
	Embedment	1.5		1.5		1.5
	Length	28		32		32
Trench & Excavation Cost		$ 8,404	$	12,439	$	13,715
Culvert Cost per LF		$ 1,050	$	1,150	$	1,175
Culvert Cost		$ 29,400	$	36,800	$	37,600
Sub Total		$ 37,804	$	49,239	$	51,315
MPT		$ 53,000	$	53,000	$	53,000
Other Construction Items		$ 185,780	$	179,301	$	180,685
Total Cost		$ 276,584	$	281,540	$	285,000

C9-79

Culvert Size		In-Kind	Climate Sized	Stream Sized
	Span	12	18	18
	Rise	6	7	7
	Depth of cover	4	4	4
	Embedment	1.4	1.4	1.5
	Length	28	32	32
Trench & Excavation Cost		$ 16,717	$ 24,371	$ 24,618
Culvert Cost per LF		$ 1,175	$ 1,860	$ 1,860
Culvert Cost		$ 32,900	$ 59,520	$ 59,520
Sub Total		$ 49,617	$ 83,891	$ 84,138
MPT		$ 65,000	$ 65,000	$ 65,000
Other Construction Items		$ 434,585	$ 422,415	$ 422,168
Total Cost		$ 549,202	$ 571,306	$ 571,306

C9-17

Culvert Size		In-Kind	Climate Sized	Stream Sized
	Span	19	17	17
	Rise	8	7	8
	Depth of cover	2	2	2
	Embedment	1.6	1.6	1.6
	Length	38	43	43
Trench & Excavation Cost		$ 27,218	$ 26,428	$ 29,500
Culvert Cost per LF		$ 2,300	$ 1,500	$ 1,600
Culvert Cost		$ 87,400	$ 64,500	$ 68,800
Sub Total		$ 114,618	$ 90,928	$ 98,300
MPT		$ 60,000	$ 60,000	$ 60,000
Other Construction Items		$ 270,784	$ 271,380	$ 265,980
Total Cost		$ 445,402	$ 422,308	$ 424,280

C9-18

Culvert Size		In-Kind	Climate Sized	Stream Sized
	Span	18	18	17.5
	Rise	4	8	5
	Depth of cover	4	4	4
	Embedment	1	1	1
	Length	33	39	39
Trench & Excavation Cost		$ 17,142	$ 31,525	$ 22,620
Culvert Cost per LF		$ 1,855	$ 1,880	$ 1,850
Culvert Cost		$ 61,215	$ 73,320	$ 72,150
Sub Total		$ 78,357	$ 104,845	$ 94,770
MPT		$ 60,000	$ 60,000	$ 60,000
Other Construction Items		$ 516,457	$ 497,592	$ 501,505
Total Cost		$ 654,814	$ 662,437	$ 656,275

CA-71

Culvert Size		In-Kind	Climate Sized	Stream Sized
	Span	5	12	12
	Rise	5	6	5
	Depth of cover	4	4	4
	Embedment	1	1	1
	Length	37.7	55	55
Trench & Excavation Cost		$ 15,583	$ 31,381	$ 27,867
Culvert Cost Per LF		$ 1,000	$ 1,175	$ 1,150
Culvert Cost		$ 37,700	$ 64,625	$ 63,250
Sub Total		$ 53,283	$ 96,006	$ 91,117
MPT		$ 55,000	$ 55,000	$ 55,000
Other Construction Items		$ 554,393	$ 551,720	$ 559,359
Total Cost		$ 662,676	$ 702,726	$ 705,476

C1-29

		In-Kind	Climate Sized	Stream Sized
Culvert Size	Span	5	12	16
	Rise	4	4	4
	Depth of cover	1.2	1.2	1.2
	Embedment	0	0	0
	Length	40	40	40
Trench & Excavation Cost		$ 7,616	$ 9,856	$ 11,136
Culvert Cost Per LF		$ 1,000	$ 1,150	$ 1,450
Culvert Cost		$ 40,000	$ 46,000	$ 58,000
Sub Total		$ 47,616	$ 55,856	$ 69,136
MPT		$ 65,000	$ 65,000	$ 65,000
Other Construction Items		$ 296,592	$ 309,912	$ 328,128
Total Cost		$ 409,208	$ 430,768	$ 462,264

C1-58

		In-Kind	Climate Sized	Stream Sized
Culvert Size	Span	7.3	18	16.5
	Rise	3	4.5	4.5
	Depth of cover	1.5	1.5	1.5
	Embedment	1	1	1
	Length	33	80	80
Trench & Excavation Cost		$ 7,301	$ 31,600	$ 30,400
Culvert Cost Per LF		$ 1,000	$ 1,860	$ 1,700
Culvert Cost		$ 33,000	$ 148,800	$ 136,000
Sub Total		$ 40,301	$ 180,400	$ 166,400
MPT		$ 31,500	$ 31,500	$ 31,500
Other Construction Items		$ 461,184	$ 455,415	$ 458,585
Total Cost		$ 532,985	$ 667,315	$ 656,485

APPENDIX D: AN INITIAL APPROACH FOR ECONOMIC VALUATION OF ROAD-STREAM CROSSINGS IN THE CONTEXT OF CLIMATE CHANGE

Contents

INTRODUCTION

Road-stream crossings, which include culverts and bridges, are an essential element of our transportation networks, allowing roads to pass over rivers and streams. Our communities and our economies depend on functioning road networks with safe stream crossings.

We also depend on healthy rivers and streams for clean water, recreation, and a host of other benefits. Unfortunately, many road-stream crossings have negative impacts on the rivers and streams that pass beneath. Undersized or poorly designed crossings fragment streams and can prevent aquatic organisms from accessing the upstream habitat they need to survive and reproduce. Many of these crossings also disrupt the natural movement of water, sediment and debris, causing erosion and degraded habitat.

Undersized crossings may also create problems on the roads. During major storms, undersized crossings fill with water and clog with debris, resulting in flooding of roads and loss of access to essential critical services. Over time, water passing through these crossing scours away surrounding soil, which increases the likelihood of sudden failure. **Road flooding and culvert failure are expensive for transportation departments and communities, and they can create dangerous conditions.**

Crossings can be designed to avoid these problems, and improved crossings deliver a host of social, economic and ecological benefits, including:

- Healthier river and stream habitat,
- Improved safety and mobility on road networks,
- Avoided flood impacts,
- Improved water quality.

Despite the many benefits of improved crossings, a financial obstacle currently limits their widespread installation: the up-front cost of larger, fish-friendly stream crossings may be 50 or even 100% higher than a traditional crossing, and this may seem prohibitive to highway departments. **Yet over the long term, improved crossings may be a more cost-effective option.** Improved crossings often last longer and require less maintenance.

As the climate changes, adequately sized and well-designed stream crossings can play a key role for human communities and aquatic ecosystems. The northeastern United States has experienced a major increase in extreme precipitation: since 1958, the region saw more than a 70% increase in the amount of precipitation falling in very heavy storm events. Scientists predict that the frequency of these large storms will continue to increase (Horton et al. 2014). As extreme precipitation events increase in frequency, larger crossings that allow for the

natural movement offish, sediments, and other materials will better pass high flows and will sustain less damage. On the other hand, undersized crossings can exacerbate flood impacts and result in costly damage to infrastructure and unsafe conditions on roads. Thus improved crossings may prove to be a key element of adapting transportation infrastructure to changing climate conditions.

In the context of climate change, improved crossings are also important for aquatic organisms. Scientists predict that rising temperatures will reduce suitable habitat for cold-water fish such as brook trout (Horton et al. 2014). To survive in these warmer conditions, fish will need to move upstream to cold-water refugia. Adequately designed stream crossings allow unrestricted movement for fish and other aquatic organisms; these can help ensure access to the full range of their habitat to meet their needs under these new warmer conditions.

Facing the initially high up-front cost but potentially longer life span of improved road-stream crossings, and a range of potential, yet often site-specific benefits, transportation departments face difficult decisions in allocating their limited resources. **This report proposes an approach that transportation departments can utilize to compare alternative road-stream crossing design options and weigh, to the fullest extent possible, the benefits and costs over the long-term for each option, in light of current conditions and projected future stream flow scenarios**.

A variety of options exist for economic analysis. This approach focuses on the use of benefit-cost analysis because it is particularly useful for determining whether a project is a sound investment overall and for comparing different options. Moreover, this approach allows for the monetization of social and environmental benefits that may be overlooked by transportation departments focused primarily on their own expenditures.

It is well known that larger, "fish-friendly" stream crossings are more costly to install than crossings with more traditional designs, but how do different options compare when the benefits are included and when a longer time frame is used for analysis? Since each crossing is unique, there is no universal answer to this question. Drawing on existing studies, tools, and values, this report presents an approach that should be a useful starting point for departments of transportation.

Because each crossing site is different, benefit and cost values will vary greatly from place to place. The approach presented here is intended for assessing the benefits and costs of any number of stream crossing design options at a specific site and for comparing among the options at that site. To assess the benefits and costs of crossings for a group of sites or among a region, an assessment would be needed for each site.

The approach presented here was developed with the New York portion of the Lake Champlain Basin as the primary geography, but our intention is to propose an approach that can be applied more broadly across New York and other parts of the Northeast, with some alterations based on data. While the primary user of these results is the New York State Department of Transportation (NYSDOT), this approach is also relevant for local (town and county) highway departments. The scalability of the approach may be hindered by the absence of similar data in other states, or potentially helped by the availability of more detailed data.

In this report, we present and assess existing relevant research and tools for measuring the benefits and costs of stream crossing design alternatives. Based on this review, we provide a proposed approach for quantifying the benefits and evaluating costs. We also recommend future work to help refine and improve this approach in the longer term.

EXISTING GUIDANCE AND TOOLS

An initial step toward development of this approach for economic valuation of stream crossing designs was the review of a wide range of existing economic analysis tools, guidance documents and supporting literature. This review spanned the domains of transportation economic analysis, environmental valuation, and natural hazard mitigation valuation. The proposed approach draws on existing values, tools, and guidance as much as possible. Many of the studies and tools reviewed were location specific, and while they provided useful context and information, the primary tools selected for this approach are relevant at larger geographic scales.

While each of the guidance documents reviewed below provides useful information for economic valuation, none alone adequately covers the range of benefits and costs that should be considered when evaluating different stream crossing designs. Nonetheless, in combination they provide a foundation toward development of an economic valuation approach. The most pertinent of these general guidance documents and tools are described below.

U.S. DOT ECONOMIC ANALYSIS PRIMER

A useful overview document is U.S. Department of Transportation's Economic Analysis Primer (2003). The primer outlines key concepts and decision points for project economic analysis and helps identify the type of analysis for different situations. The primer covers basic information about several types of economic analyses relevant to transportation, including life cycle cost analysis, benefit-cost analysis, risk analysis, and economic impact analysis.

FHWA OPERATIONS BENEFIT/COST ANALYSIS DESK REFERENCE

A much more detailed guidance document, the FHWA [Operations Benefit/Cost Analysis Desk Reference](#) provides more detailed guidance on how to conduct benefit-cost analysis of operations strategies for transportation departments. The document accompanies a decision support tool, the Tool for Operations Benefit/Cost (TOPS-BC), a spreadsheet-based tool for conducting benefit/cost analysis for transportation system management and operations strategies. As defined by the Federal Highway Administration, transportation system management and operation strategies are focused on optimization of performance of existing infrastructure by implementing "specific systems and services that preserve capacity and improve reliability and safety." Activities in this realm include incident management, traffic signal timing, ramp metering, and road weather management (FHWA 2012).

While many of the concepts informed development of the approach in this document, the TOPS-BC tool itself is not useful for the assessment of road-stream crossing design options.

U.S. DOT TIGER BENEFIT-COST ANALYSIS GUIDANCE DOCUMENTS

The U.S. Department of Transportation (DOT) provides several useful benefit-cost analysis guidance documents for applicants for federal Transportation Investment Generating Economic Recovery (TIGER) grants. TIGER grants are awarded competitively to state, local, and Tribal governments, transit agencies, and metropolitan planning organizations for transportation projects that "have a significant impact on desirable long-term outcomes," such as improving the condition of existing transportation facilities or systems, improving economic competitiveness, improving energy efficiency, reducing greenhouse gas emissions, and improving transportation safety. Past awards have funded railroad upgrades, transit station improvements, bridge and road improvement projects, and transportation planning efforts, among many other projects.

These documents recommend a methodology for calculating a variety of benefits, such as emissions reductions, operating cost savings, travel time savings, and safety. The TIGER guidance also recommends monetized values for several important benefits, including reduction in fatalities and injuries, travel time savings, maintenance savings, and emissions reductions. Clearly, many of the benefits associated with TIGER grant projects are not applicable to the question of stream crossing costs and benefits. The values that are relevant are highlighted in future sections.

The current versions of these documents are on the US [DOT website](#). These include a concise guidance document about how to conduct a benefit-cost analysis and a resource guide with technical information, including recommended monetized values.

TRANSPORTATION RESEARCH BOARD BENEFIT-COST ANALYSIS WEBSITE

The Transportation Economics Committee of the Transportation Research Board maintains a [website focused on benefit-cost analysis](#) for transportation projects. This website contains a great deal of material on benefit-cost analysis, including links to recent literature. The website is intended to lead practitioners through the process of benefit-cost analysis. While not a tool or guidance document this website is a useful resource, as it raises key issues for consideration and covers a range of concepts and metrics related to benefit-cost analysis for transportation projects.

FEDERAL EMERGENCY MANAGEMENT ADMINISTRATION BENEFIT-COST ANALYSIS TOOL

Another set of resources for benefit-cost analysis are provided by the Federal Emergency Management Administration (FEMA). In evaluating proposed hazard mitigation projects, FEMA requires that a benefit-cost analysis be performed. Only projects that are deemed cost effective are eligible for hazard mitigation funds. FEMA has developed written materials and a software tool to calculate benefits and costs for hazard mitigation projects. These tools and materials provide formulas and standard values associated with the mitigation of damage from a range of natural hazards, including floods. They are relevant and useful for estimating the benefits and costs of different stream crossing designs because of the potential flood mitigation benefits of improved designs. The tool and documentation, provided in a BCA Reference Guide, are available on [FEMA's website](#).

GENERAL CONSIDERATIONS

TIME PERIOD OF ANALYSIS

In evaluating different stream crossing designs, an important decision to be made is the time frame of the analysis. Since different crossing design options have different lifespans, the benefit-cost analysis needs to extend over an appropriate number of years to capture these lifespans. Ultimately, the transportation department conducting the analysis needs to select the appropriate time period based on its own internal guidelines. This period should be sufficiently long to incorporate the life cycle of the different design option alternatives.

U.S. DOT's Economic Analysis Primer advises: "As a rule of thumb, the analysis period should be long enough to incorporate all, or a significant portion, of each alternative's life cycle, including at least one major rehabilitation activity for each alternative (typically a period of 30 to 40 years for pavements, but longer for bridges)." U.S. DOT's TIGER Benefit-Cost Analysis guidance documents states that a project should be evaluated at a time scale of *at least* 20 years.

FEMA's benefit cost reference document provides standard values for project useful life of 50 years for bridges and 30 years for culverts with end treatments (FEMA 2009b). A large scale

benefit-cost analysis, conducted for FEMA, of 5,500 hazard mitigation grants funded over a ten-year period, used a longer time period: 50 years for "ordinary structures" and 100 years for important structures and infrastructure (Rose et al. 2007).

In light of the flood mitigation and climate adaptation benefits of improved crossings, we propose that a period of at least 50 years be used for the benefit-cost analysis. When the time frame for analysis is inadequate, the cost savings of those structures that are designed to be longer lasting may not be obvious. Moreover, the benefits of climate adapted (flood resilient) designs may appear less significant.

DISCOUNT RATE

When conducting economic analyses where there will be a stream of costs and/or benefits in the future, a discount rate should be applied. A discount rate reflects the time value or opportunity cost of money, generally equal to the economic return that could be earned on the invested resources in their next best alternative use. Discounting allows a comparison of different alternatives by comparing their respective present values. There is not a decisive rule governing the choice of discount rate, several factors come into play that will help guide the decision-making. The choice of discount rate can significantly change the stream of cost or benefit values and thus can have a significant impact on decision-making. For reference, we identify several examples below.

U.S. DOT's TIGER Benefit-Cost Analysis guidance document instructs applicants to use a 7% discount rate, following guidance provided by the U.S. Office of Management and Budget (OMB). In cases where the funds dedicated to the project would be used for other public expenditures (rather than being invested privately) if the project would not take place, a discount rate of 3% is also permitted as an alternative.

Similarly, U.S. DOT's Economic Analysis Primer notes that the U.S. Office of Management and Budget requires U.S. federal agencies to use a discount rate of 7% for evaluating public investments and regulations but allows lower rates for life-cycle cost analysis.

In 2013, in its [funding availability announcement for the Passenger and Freight Rail Assistance Program](), NYSDOT instructed applicants to use a 7% discount rate and an optional alternative analysis with a 3% discount rate.

The California Department of Transportation (Caltrans) provides a list of [economic parameters for life-cycle benefit cost analysis](). Caltrans recommends use of a 4% inflation-adjusted discount rate.

FEMA's Benefit-Cost Reference Guide also refers to the discount rates in OMB Circular A-94, and the Benefit-Cost Tool uses a discount rate of 7% (FEMA 2009b).

The U.S. Environmental Protection Agency's (U.S. EPA) guidelines for economic analysis recommend using a 3% interest rate, which corresponds with the consumption rate of interest, as well as a 7% interest rate, which corresponds with the rate of return to private capital (US EPA 2010).

These guidance documents would suggest that discount rates of 3% and 7%, as recommended in OMB Circular A-4, be used. However, in light the long-term and sustained benefits of an improved stream crossing design – both for communities in terms of flood risk reduction and for the environment – a discount rate of 7% may be high.

An analysis of multiple projects funded through FEMA's Hazard Mitigation Grant Program used a discount rate of 2% and sensitivity tested the results with rates from 0-7% (Rose et al. 2007).

We propose that a discount rate between 3% and 7% be used, as recommended by the U.S. Office of Management and Budget, U.S. EPA, and NYSDOT in its recent funding announcement. If possible, analyses should be performed with a 3% rate and a 7% rate. If a single value is preferred, we recommend a 4% discount rate.

SUMMARY MEASURES

Once the benefits and costs are estimated, there are several different ways to summarize the results; these summary measures include benefit-cost ratio, net present value, cost-effectiveness, payback period, and internal rate of return. We suggest calculating the net present value for each design option, as well as a benefit-cost ratio.

Net present value is simply the sum of discounted benefits less the sum of discounted costs. The net present value of different design options can be compared fairly easily. We'd expect that many stream crossing designs will have negative net present values simply because the total cost may outweigh their benefits; this measure will be useful in this context because it allows the comparison of the net present values of various design options.

A benefit cost ratio is the total discounted benefits divided by the total discounted costs. Benefit-cost ratios for different design options should also be compared. Options with higher ratios are those where the benefits are greater relative to the costs, and options with a ratio of a value greater than 1 are those where the benefits outweigh the costs. Calculating a benefit-cost ratio for each design option and comparing these ratios will be a useful approach for comparing the different crossing design options.

COSTS

Overview

There are a range of design options for road-stream crossings. Larger crossings that simulate the natural conditions of the stream channel are almost always more expensive in the short term than traditional pipe culverts designed to meet a hydraulic standard. Over time, these larger crossings may require less maintenance and last longer because they are made with more durable materials. In addition to their durability and less frequent need for maintenance, crossings that are sized and designed to simulate the natural stream conditions better withstand large storms, passing water, sediment, and debris that might clog smaller crossings and even result in complete failure of a small structure.

In this approach, **costs are those resources incurred by the transportation department** in designing, installing, maintaining, and replacing stream crossings. These do not include costs to the public.

Stream Crossing Life Cycle Costs

There are various cost components to include in evaluating the total cost over time of a crossing design:

> Planning costs: design, engineering, permitting, environmental review

> Construction costs: materials (including crossing structure), labor (contractor or highway department staff), equipment, and management of traffic

> Routine maintenance costs: annual maintenance to keep the structure safe and functional

> Rehabilitation costs: repairs and improvements that are outside the scope of routine maintenance (including those caused by major storm events)

> Replacement costs at end of lifespan

Design Options

The cost of a road-stream crossing structure depends on its design and material, which are influenced by a variety of factors, including the width and flow in the stream, site topography and geology, the materials available, the volume and type of traffic on the road and potential constraints at the site including nearby landowners. The durability of different materials and designs is also important.

There are numerous types of materials and design options for stream crossings, including culverts and bridges. Types of culverts include pipe culverts, box culverts and bottomless

arches. Culverts can be made from concrete, steel, aluminum, and plastic. Culverts can be cylindrical, arch-shaped, elliptical, or rectangular in shape. Their bottoms may be open (mimicking the natural channel) or closed. Bridges are spanning structures with no structural bottom that are attached to two or more abutments. In New York State, a bridge is defined by its width, as any spanning structure with an interior width of 20 feet or more, whereas a culvert is a structure with an interior width of less than 20 feet.

For this project, NYSDOT identified three different road-stream crossing design options to consider at each site. While these are by no means the only options, these three options provide a spectrum of structure types and sizes. The first design option is the "base case" and the other two options are alternative designs. These three design options are described below.

a) In-kind replacement: The existing crossing is replaced with a crossing of the same size and design. This is the "base case" scenario.

b) Replacement crossing that meets U.S. Army Corps of Engineers General Conditions and General Regional Conditions: Projects that meet the U.S. Army Corps of Engineers General Conditions and General Regional Conditions in New York qualify for authorization under the Nationwide Permit program. The General Conditions pertinent to stream crossings include:

   i. GC2, Aquatic Life Movements, which states that no activity "may substantially disrupt the necessary life cycle movements of those species of aquatic life indigenous to the waterbody, including those species that normally migrate through the area" and that all "permanent and temporary crossings of waterbodies shall be suitably culverted, bridged, or otherwise designed and constructed to maintain low flows to sustain the movement of those aquatic species."

   ii. GC3, Spawning Areas, which states that "activities in spawning areas during spawning seasons must be avoided to the maximum extent practicable. Activities that result in the physical destruction (e.g., through excavation, fill, or downstream smothering by substantial turbidity) of an important spawning area are not authorized."

   iii. The relevant General Regional Condition is G-A.11, which provides the following construction and installation guidance for all new and replacement culverts:

iv.   Engineering is required to "ensure structures are sized and designed to provide adequate capacity (to pass various flood flows) and stability (bed, bed forms, footings and abutments)."

v.   "Site specific information (i.e. stream bed slope, type and size of stream bed material, stream type, existing natural or manmade barriers, etc.) should be assessed to determine appropriate culvert design and to ensure management of water flows and aquatic life movement."

vi.   Replacement culverts must "be evaluated for its impacts on: downstream flooding, upstream and downstream habitat (in-stream habitat, wetlands), potential for erosion and headcutting, and stream stability."

vii.   All culvert designs must "promote the safe passage of fish and other indigenous aquatic organisms."

viii.   "The dimension, pattern, and profile of the stream above and below the stream crossing should not be permanently modified by changing the width or depth of the stream channel."

c) Replacement crossing that is designed based on future streamflow projections: The size and design would be based not on past streamflow statistics but on future projections of streamflow that incorporate climate change. (For more information, refer to the description of USGS "climate-enhanced" StreamStats in Appendix B of the study report.)

Existing Studies on Crossing Initial Costs

The installation costs for different crossings are site-specific, depending on a range of factors including the size of the stream, topography, materials selected and structure design. Several studies have compared the costs of traditional crossings with "improved" stream crossings designed to create a channel through the crossing with similar function and structure as the natural channel. The improved crossings allow for aquatic organism passage, more than span the natural channel's bankfull width, and accommodate large flows. Given the wide variety of crossing materials, designs and sizes, there is considerable disparity in just how much more expensive upgraded culverts are. These comparisons vary based on what kind of crossing is in place and what kind of crossing is chosen as a replacement, as well as site characteristics and required construction practices.

The following table summarizes the cost of *installing* an improved stream crossing compared with the cost of an in-kind replacement of the existing crossing.

Location	Mean % capital cost increase for installing an improved crossing (range of values)	Notes	Reference
Green Mountain National Forest, Vermont	14% (9% - 22%)	Compares stream simulation culvert costs with cost of replacement based on hydraulic design	Gillespie et al. 2013
Minnesota (statewide)	10% (1% - 33%)	Compares cost of replacing existing culvert with improved "MESBOAC" design; costs considered are those of structures only	Hansen et al. 2009
Maine (statewide)	Mean not available (80% - 295%)	Improved culvert widths in this study are 200% to 300% that of existing culvert	New England Environmental Finance Center 2010
Tongass National Forest, Alaska	17% (-5% - 38%)	Compares stream simulation culvert cost with hydraulic design cost; stream simulation culverts are 25% - 83% wider than hydraulic design culverts; cost increase insignificant for streams of slope less than 3%	Gubernick 2012
Oyster River Watershed, New Hampshire	42% (24% - 75%)	Compares cost to upgrade undersized culverts for a range of climate change/ precipitation change scenarios and land use	Stack et al. 2010

		scenarios with cost of in-kind replacement	

Existing Studies on Crossing Life Cycle Costs

Thinking beyond installation costs, little information is currently available about life cycle costs. A research project (NCHRP 25-25/Task 93) funded by the National Cooperative Highway Research Program and currently underway may fill this gap. As described on the Transportation Research Board website, "The goal of this research is to quantify the long-term costs of road stream crossings that span the bankfull width of a waterway in order to provide an accurate picture of the total life-cycle cost of the structure. These costs will then be compared to the costs of structures that constrict stream flows. Understanding the true cost of each structure type would help project designers make the most cost-effective structure choice and better comply with state and federal environmental regulations."

One study from eastern Maine considered the costs of different stream crossing designs over the long term. In this study, the long-term costs of undersized round culverts were compared with two to four times wider arch shaped culverts that restore fish passage and more natural stream conditions at four sites. Assuming a 10-year lifespan for round culverts and at least a 50-year lifespan for the arch culverts, and factoring in the costs of installation, operation, maintenance (e.g., removing debris, controlling beavers, repairing the road bed due to storms), the average annual costs of the arch culverts were 22% and 26% lower than those of the round culverts for two of the four sites. At the other two sites, the estimated average annual costs of the arch culverts were 18% and 35% higher than the costs of the round culverts. This Maine study indicates that **at certain sites, even without major flood events and without quantifying any of the environmental or safety benefits, improved road-stream crossings can be less expensive than undersized crossings in the long term** (Long 2010; Long 2012).

As the climate changes and extreme precipitation events increase in frequency (impacts we are already experiencing), any long term cost analysis of stream crossings should consider the costs to repair and replace culverts that are damaged or destroyed because of high flows produced by these storms. The expenditures to repair and replace culverts following major storm events can be considerable. The impacts of climate change, particularly increased intense storms, have not yet been factored into cost analyses for road-stream crossings; once they are, we can expect that undersized crossings will become increasingly more expensive.

Several recent storms provide evidence of the potential long term costs of undersized crossings. In just four towns near Vermont's Green Mountain National Forest, 70 culverts were

damaged or destroyed due to high flows from Tropical Storm Irene. Rochester, one of these towns, sustained damage to or completely lost 25 culverts. In the town of Hancock, the repair cost for a single site – where a 12 foot -wide culvert became plugged with debris and floodwater overtopped the road – was estimated at about $1.1 million including road repair (Gillespie et al. 2013).

Delaware County in the Catskill region of New York also has experience with costly stream crossing repairs. The county has experienced frequent flooding in the last few decades, with 11 federally declared flood related disasters between 1996 and 2011. A single stream crossing in the town of Hancock is a compelling example of the potential long term costs of undersized structures. Three flood events between 1996 and 2005 caused damage to an undersized and perched pipe culvert on the Big Hollow Creek, a tributary to Fish Creek, which flows into the East Branch of the Delaware River. In those nine years, the County's Public Works department spent over $70,000 to repair damages to the culvert, road and adjacent ditches. Because of the rural location, travelers on this road had to take an 18-mile detour while the road was closed for these repairs. Late in 2005, with hazard mitigation funding assistance from FEMA, the county replaced the pipe culvert with a three-sided concrete culvert with a natural bottom, designed to convey a 100-year storm, for a cost of $143,000. Since the culvert was replaced, the county has experienced seven federally declared flood disasters, including Tropical Storm Irene, and the new stream crossing has survived all of these events without significant damage (W. Reynolds, personal communication, September 2012).

BENEFITS

Stream crossings have environmental, social, and economic impacts on stream health, fish populations, local communities, and road users. Some of the benefits of *improved* crossings, compared to traditionally designed crossings, are summarized in the table below.

Type of Benefit	Outcomes
Environmental	Healthier populations of fish and wildlife
	Improved river habitat for in-stream and river-dependent species
	Decreased erosion of stream banks
	Improved water quality
	Avoided water quality impacts from storm-related failure
	Enhanced river-related recreation

Social	Improved safety
	Improved mobility (avoided travel delays)
	Improved accessibility
Economic	Avoided flood repair costs:
	Repair of damaged infrastructure
	Repair and replacement of damaged property
	Lost business income from road closures
	Avoided disruption of freight movement
	Avoided costs to repair environmental degradation (e.g., water quality)

While there are a great number of benefits, the approach proposed in the following sections of this report focuses on those benefits that can be reasonably quantified and, when possible, monetized. These benefits comprise the effects of stream crossings on road users, the local community, and society at large. The rationale for selecting particular benefits and omitting others is described in further detail below.

Benefit Valuation
Some of the social and economic benefits associated with stream crossing replacements have been monetized through surveys and studies conducted in different locations. For sites where primary data about benefits and values are not available, economists sometimes rely on a technique called "benefit transfer." Using benefit transfer, values obtained from past studies are applied to similar sites lacking primary data to estimate the value of a resource.

In the context of proposing an approach for monetizing the benefits of different stream crossing types, we recommend against the use of benefit transfer. We have thoroughly explored relevant existing benefits values for similar kinds of studies – discussed in further detail in the relevant sections that follow – and have determined that they are not sufficiently similar to the context of this work. Moreover, after careful deliberation with economics and transportation experts, we decided that the methodology for calculating values used elsewhere was not transparent enough for us to adapt these values.

Despite its frequent use, the reliability of benefit transfer to estimate values is controversial among economists. There are a number of potential challenges associated with use of benefit transfer and many studies that discuss its limitations. For example, the methods used to derive the values, e.g. how questions in surveys are worded and how surveys are implemented, often influence the resulting values. More importantly, the values derived are highly context and location-specific, and we do not believe that appropriate studies exist for this context (stream crossing replacements in New York).

An alternative approach, when solid economic values do not exist, is to use a multiplier to incorporate a set of benefits into a calculation of benefits. The multiplier can be derived from solid environmental or social data, even when monetary values for those data do not exist. A transportation agency can assign a range of weights to the attribute or value according to its importance as a component of the overall set of benefits. We propose use of a multiplier for environmental benefits. Details on quantifying this multiplier are provided in the following sections.

Benefits and Flood Vulnerability

As noted above, many of these potential benefits of improved crossings will result from *avoided* flooding and/or stream crossing failure. Monetizing these social and economic benefits will require information about flood vulnerability, expressed as the probability of a flood severe enough to cause a road closure at a particular location with a particular structure in place. This vulnerability information can be elicited from the transportation engineers who provide the various stream crossing design options for analysis.

While a full discussion of methods for assessing the vulnerability of stream crossing designs to flooding and failure is beyond the scope of this economic report, recent work in New York's Hudson River Estuary provides a model for a vulnerability assessment. Researchers used GIS to determine soil characteristics, land cover, drainage area, and time of concentration (the amount of time needed for water to flow from the most remote point in a watershed to the culvert) for each culvert location in the project area. The project team modeled runoff for nine future storm return periods, ranging from 1 year to 500 year, for both present and future precipitation conditions. Peak storm runoff was calculated using the USDA Natural Resources Conservation Service (NRCS) TR-55 Graphical Peak Discharge Method for current and future conditions. Field data collected by New York State Department of Environmental Conservation (NYSDEC) and county Soil and Water Conservation Districts were used to estimate the peak capacity of each culvert. Finally, the peak capacity of each culvert was compared to the modeled peak storm runoff to determine the maximum return period (storm recurrence interval) that the culvert can pass, including the maximum return period based on future

precipitation predictions (Walter et al. 2015). An automated tool to calculate the runoff expected for a range of storm magnitudes across New York is currently under development (Meyer 2015).

Flood Vulnerability Estimation Approach

To estimate flood vulnerability, at each site of interest, engineers will first determine the peak capacity of the existing culvert and associate that capacity with peak storm runoff (as described above) to determine the maximum storm return period that the culvert can pass, and the return period for a storm event causing sufficient flooding to close the road.

These return periods should be calculated based on streamflow projections that include the impacts of climate change, as provided by the U.S. Geological Survey's future streamstats tool developed as part of this project.

This flood return period will then be converted to an annual probability of a flooding event that causes a road closure (where the probability is 1/recurrence interval).This is the "base case" annual flood probability. Any social or economic benefits associated with avoided flood damage will be compared to this base case. Finally, engineers will also need to estimate the average duration of a road closure (in hours or days) for closures due to road flooding.

For each of the three design alternatives, engineers will also estimate annual probability of a flooding event that causes road closure.

SOCIAL BENEFITS

Overview of Safety Benefits

The main social effects of stream crossings result from road flooding due to undersized or ill-designed crossings. While undersized crossings can exacerbate flooding of roads, and even fail entirely during large storms, as experienced during Tropical Storm Irene, adequately sized and designed crossings are less likely to experience local flooding and failure (Gillespie et al. 2013). Road flooding and culvert failure have a number of repercussions for road users.

The primary social benefits of improved crossings include:

> Safety: potential injuries and fatalities due to road flooding and culvert failure;

> Mobility: avoided travel delays/detours due to road flooding and culvert failure; and

> Access to critical services: ability to reach critical facilities such as hospitals and fire stations when roads are flooded or closed due to culvert failure.

While established methodologies exist for the monetization of all three benefits, availability of data may be a limiting factor in using these methodologies.

Existing Valuation Approaches
Safety
The safety benefits of improved crossings are the potential reduction in driver and passenger fatalities and injuries caused by road flooding (due to undersized culverts) or culvert failure.

Standard values for injuries and accidents are provided in the [U.S. Office of Management and Budget (OMB) Circular A-4](), which recommends a range of values for Value of Statistical Life (VSL). FEMA's Benefit-Cost Analysis (BCA) Re-engineering document advises using a VSL of $4.7 million in 1997 dollars and adjusting the value for inflation using the [Bureau of Labor Statistics CPI inflation calculator]() (FEMA 2011a). Based on this guidance, the 2013 VSL value would be $6.8 million. However, the TIGER BCA Resource Guide recommends using a value of $9.2 million ($2013), based on a [2014 U.S. DOT guidance document]() for estimating the value of a statistical life. Therefore, a reasonable dollar range for estimation is $6.8-$9.2 million.

Values of nonfatal injuries can be scaled in proportion to VSL. The TIGER BCA guide uses the Abbreviated Injury Scale (AIS) for values of avoided injuries or different levels of severity, ranging from AIS 1 (minor injuries), valued at $27,600 ($2013), to AIS 6 (fatal injuries), valued at $9.2 million ($2013). The TIGER guidance document provides a matrix for converting accident data from the "KABCO injury scale" of the National Safety Council, frequently used by law enforcement to classify injuries, to the AIS scale. FEMA's BCA tool also uses AIS to value the benefits of avoided injuries or different levels of severity.

In order to calculate any safety benefits, we would first need to know how many injuries and fatalities would be expected at particular sites given different crossing design alternatives. The benefit of avoided injuries and fatalities would be estimated by comparing the reduction in injuries and fatalities at the sites of improved crossings, given the annual flood probability, compared to expected number of injuries and fatalities at the site of the "in kind" crossing (base case).

One way to estimate these safety benefits would be to utilize transportation agency data or expert opinion on the likelihood of an injury or fatality due to road flooding and/or culvert failure. To date, we have been unsuccessful in our efforts to identify if this data exists for New York. There are various sources of information about injuries and fatalities resulting from natural disasters, including NOAA's National Climatic Data Center's Storm Events Database, which is searchable by county, year, and type of storm event: [http://www.ncdc.noaa.gov/stormevents/](). This database includes information about injuries,

deaths, and property damage, so it is a useful resource for estimating damages from specific events. On the other hand, the data cannot be used to estimate the likelihood of a flood-related injury or death, and as such, it does not provide the specific information needed for a safety benefits valuation. Since we are unaware of specific accident data for our region, we do not propose including safety benefits at this time.

Mobility

Mobility benefits include avoided costs of travel time and avoided costs of vehicle use due to road closures and detours resulting from road flooding. A study of culvert failures across the U.S. found that delay costs to users of the road made up a significant portion of the cost of replacing culverts in an emergency situation, rather than through routine and planned maintenance. In the cases analyzed, the emergency replacement costs ranged from 4 to 140 times greater than planned replacement costs, largely due to user delays. This suggests that waiting until culverts fail through emergencies can be very expensive when the impacts on road users are factored into the cost analysis, yet delay costs often are not considered because they are not borne by the highway department undertaking the work (Perrin and Jhaveri 2004).

Vehicle use costs can be estimated simply using the standard federal mileage rate. For travel time, several values are available.

The TIGER BCA Resource Guide provides values for personal and business travel, along with all-purpose weighted averages. Because we are unlikely to have data about whether trips are for personal or business purposes, the weighted averages are more useful. These weighted-average values (in 2013$) are $18.90/person-hour for non-local travel and $12.98/person-hour for local travel. Some challenges associated with using these values are that we may not know which trips are local vs. non-local and how many people are in each vehicle.

The FEMA Benefit-Cost Analysis toolkit uses a value of $29.63/vehicle-hour in 2011$, or $30.69/vehicle-hour in 2013$, for extra travel time. This value is simpler to use because it is incorporates an average for vehicle occupancy and does not require differentiating between business and personal travel. The value is based on the national average hourly wage, average number of people per vehicle, and U.S. DOT's methodology for per-hour value of time (FEMA 2011a).

To calculate values for mobility benefits, flood vulnerability information and the estimated duration of a road closure will be combined with the following data: average daily traffic count on the road, length of detour, and the time needed to travel the detour. This is described in greater detail in the proposed approach section that follows.

Access to Critical Services

When flooding at the site of an undersized culvert causes a road to close, there may be significant consequences in terms of community members' ability to access key emergency services, such as fire stations, emergency medical services, and hospital services. The cost of "loss of function" of a range of services can be monetized using FEMA's Benefit-Cost Analysis toolkit. The FEMA toolkit is used to calculate the benefits of potential hazard mitigation projects, such as the installation of a larger culvert, so the benefits that will be calculated for accessibility are focused on avoided road closure potential of improved crossings compared to the base case. The FEMA BCAR document describes the basis of the economic values generated by the toolkit.

The FEMA BCAR document provides a methodology for valuing the effects of a reduced police presence resulting from the loss of a station. Yet there are many situations in which typical police station activities can be reassigned to another station without any loss of service, and FEMA's methodology only provides values for potential increases in crime and those costs to society, due to the loss of police services. In the case of a road flood, it seems far-fetched to include a loss of police services in the analysis.

FEMA also provides methods for valuing the loss of electrical services, wastewater services, and water services. Because it is highly unlikely that undersized culvert flooding could result in the loss of such services (or more precisely, that an improved crossing could prevent this loss), we will not provide detail about these approaches.

RECOMMENDED VALUATION APPROACH

As noted earlier, the social benefits valuation approach requires flood vulnerability information for the base case design as well as each alternative crossing design. This information should be expressed as the annual probability of a flooding event significant enough to close the road. With these probabilities calculated, we can value mobility and access to critical services.

For all of the benefits described below, we need to first determine the value for the "base case," i.e. in-kind replacement of the existing structure is replaced, and then look at the differences between the base case and the "improved crossings" in terms of avoided flood impacts.

Mobility

We recommend calculation of two benefits for mobility, as described below.

Data needed:

Average daily traffic count on the road: The average daily traffic count is available for many roads in New York through the online [Traffic Data Viewer](). For those roads without daily traffic data, daily traffic counts can be estimated by local transportation departments.

Length (miles) of detour from road closure: The detour length can be calculated using a web-based mapping tool such as google maps by "dragging" a line around the segment of the road that will close if a culvert floods the road.

Estimated time to travel the detour: The extra travel time can be calculated using a web-based mapping tool such as Google Maps along with detour length.

Travel cost savings over base case, where travel cost is calculated for each design option as follows:

Annual travel cost (2013$) = detour length (miles) * [standard mileage rate]() ($/mile)* average daily traffic count (vehicles/day) * length of road closure (days) * annual probability of road-closing flood with selected crossing type

The annual travel cost for the base case should be calculated first, and the annual travel cost for the alternative designs should be calculated next. The annual benefit is the difference between the base case travel cost and the alternative crossing travel cost. Any travel cost savings are treated as benefits.

These benefits should be projected out with a discount rate, for the time period of the analysis.

Travel time savings over base case, where travel time is calculated for each design option as follows:

Annual travel time (2013$) = * time to travel detour (hours) * $30.69 /vehicle-hour * average daily traffic count (vehicles/day) * length of road closure (days) * annual probability of road-closing flood with selected crossing type

The annual costs of travel time for the base case should be calculated first and set at 0 in the economic analysis. The annual benefit is the difference between the base case travel time and the alternative crossing travel time. Any travel time savings are treated as benefits.

These benefits should be projected out with a discount rate, for the time period of the analysis.

Access to Critical Services

If a road closure due to flooding from an undersized culvert cuts off a community's access to a critical emergency service, we can calculate the benefit of improved access to that service

resulting from an improved crossing. These benefits should only be calculated if the loss of access to the service effectively causes the service to cease to function for the community. If the fire station is still operable because a fire truck has an alternative route from the station, these values should not be used.

Data needed:
Fire stations:
Distance between inaccessible fire station to nearest temporary replacement fire station

Population served by inaccessible fire station

Emergency medical services (EMS):
Distance between inaccessible EMS provides and nearest temporary replacement EMS provider

Population served by inaccessible EMS provider

Hospital services:
Distance between inaccessible hospital to nearest temporary replacement hospital

Population served by both inaccessible and replacement hospitals

The formulas for calculating the value for the loss of access to critical services are fairly complicated. The steps for these calculations are outlined in Appendix A, and the values can be automatically calculated with the FEMA Benefit-Cost Analysis Toolkit (which must be downloaded).

The values from these formulas are a daily cost per day of inaccessible services. The following steps should then be taken:

Annual cost of inaccessible services = daily cost per day (from FEMA) * length of road closure (days) * annual probability of road-closing flood with selected crossing type

As with the travel time and cost benefit calculations, the annual costs of lost access to services for the base case should be calculated first and set at 0 in the economic analysis. The annual benefit is the difference between the base case cost and the alternative crossing cost. A reduction in the number of days that a critical service is inaccessible to the community is treated as a positive benefit, and any additional days that a critical service is inaccessible are treated as negative benefits.

These benefits should be projected out with a discount rate, for the time period of the analysis.

Benefits from safety improvements have the potential to be significant, yet the data do not currently exist to calculate these benefits. Anecdotally, we are aware of four stream crossing-related deaths in recent years in the New York portion of the Lake Champlain Basin, including one case where a roadway over a river had washed away and a car washed into the river during Tropical Storm Irene in August 2011, and one case where a car went off the road and passengers were trapped in a scour pool below an undersized culvert during a period in November 2011.

Systematic compilation of data about accidents related to road flooding, particularly if the specific cause of flooding can be identified (e.g., whether or not the flooding is the result of an ill-designed stream crossing), would enable an initial monetization of safety benefits. We would need data about flooding as well as the consequences of any accidents in terms of lost life or injuries.

Data about culvert failure and any associated accidents would also be extremely useful. The flood vulnerability approach outlined above does not provide any assessment of the likelihood of culvert failure, but tools are being developed, by MassDOT and others, to begin to identify crossings that are particularly vulnerable to failure during large storms.

ECONOMIC BENEFITS

OVERVIEW OF ECONOMIC BENEFITS

Like social benefits, the economic benefits of improved stream crossings are linked to reduced road flooding and avoided damages. The primary direct economic benefit of improved crossings is avoided flood damage, while indirect benefits are the avoided impacts of a road closure that extreme flooding may cause; these indirect benefits include lost income for businesses, lost tourism revenue, and for roads that are important for freight, the avoided disruption of freight movement and even disruption in production chains.

The economic benefits described here comprise the economic effects of improved stream crossings on entities other than the responsible transportation department. Any costs to repair stream crossings after flood events should be treated as costs, since these are paid by the transportation department. On the other hand, avoided costs to repair damaged buildings and other infrastructure near the site of a crossing should be treated as benefits. The flood damage repairs costs of the in-kind (base case) stream crossing replacement is the default value, and any avoided flood damage at the site of improved crossings are counted as economic benefits of those crossing design alternatives.

There are many important benefits – economic, social, and environmental – associated with avoided flooding and road closures. Social and environmental benefits are captured in other sections of this report. Established methodologies exist for two types of economic benefits that we may see from improved crossings: avoided flood damage and avoided freight movement disruption.

When roads are closed from flooding, local economies often suffer because communities are cut off; accordingly, the benefits of flood reduction measures may include the avoided loss of tourism income and avoided loss of revenue for local businesses. While local data may be used to assess some of the economic effects, the economic impacts must be carefully linked to specific stream crossing sites. Often, when a road floods at a crossing site, many other nearby locations may experience flooding, and it can be problematic to attribute a broad range of economic impacts to flooding at a specific site.

EXISTING VALUATION APPROACHES

Avoided Flood Damage

There are several approaches from the fields of hazard mitigation and emergency management to assess how much flood damage could be avoided by an improved stream crossing.

FEMA's Benefit Cost Analysis tool includes two different modules for assessing the value of flood damage reduction: a "Flood module" and a "Damage Frequency Assessment module;" both can be used to compare flood damages before and after flood mitigation projects – which include improved drainage, elevation of buildings, and other structural measures – are undertaken.

The Flood module is primarily used to assess projects that help to floodproof buildings, as it analyzes projects based on "the effect a storm of a certain magnitude will have on buildings before and after a project is completed" (FEMA 2011b). It is useful when detailed flood hazard information and structural data – such as detailed flood profiles, streambed elevations, the elevations of structures, sizes and contents of buildings – are available. Since this type of detailed information is unlikely to be available for most culvert projects, and since the module is intended for projects that focus on specific private property flood damage mitigation, this module is unlikely to be easily useful for evaluating different stream crossing design options.

The Damage Frequency Assessment (DFA) module is more flexible, as it assesses past damages and future avoided damages (the economic benefits). It can estimate future damages based on historical or expected damage data. Use of the module is explained in detail in FEMA's 2011 Supplement to the Benefit-Cost Analysis Reference Guide, and a thorough description of the underlying methodology is the subject of a 2009 FEMA publication.

Calculating the economic benefits of avoided flood damage is complicated, because the extent of damage is a function of the severity of the storm. FEMA's DFA module relies on historic flood data and determining a relationship between the extent of flood damage and the return period of the storm. When stream flow records are available, the return period of large storms can be calculated, but when these records do not exist or do not cover a long enough period of time (a more common scenario), the return period must be estimated in order to establish this relationship. The DFA module uses a statistical analysis technique to estimate the return period of historic flood events (FEMA 2009a).

These are more complicated calculations than those required to estimate social benefits, since the social benefits hinge only on identifying the minimum storm magnitude that will result in road flooding (and the frequency of that storm). If past flood damage data is not available, an engineer must estimate expected damages for at least two storm events with different recurrence intervals.

Given the complexity of the approach and fairly extensive data requirements, it may not be feasible for transportation departments to estimate avoided flood damages at most crossings.

Avoided Freight Disruption

A road closure due to flooding may disrupt the movement of freight. The economic impacts of freight disruption can be significant on major freight pathways. The National Cooperative Highway Research Program (NCHRP) has published a report that provides an overview of available modeling tools to estimate the economic impacts of freight disruption (NCHRP 2012). The available disruption impact assessment methodologies include supply chain response models, which can be used to estimate the cost of diversion of cargo and also help aid in decisions about inventory levels and sourcing, as well as economic impact methodologies, which can be used to calculate direct and indirect impacts based on the assumption that disruption in goods movement leads to changes in supply, demand, output, and prices.

The economic impacts of freight disruption associated with a road closure in a single location due to flooding are not extensive enough to warrant use of an economic impact model. Economic impact models assume that disruptions in freight flows or other supply changes lead to economic damages and have a ripple effect across a regional economy; we would not expect to see these kinds of impacts from flooding at a single location.

Supply chain response models include network-based models, which can be used to estimate the additional cost of diversion of freight, and industry supply chain models, which can be used to optimize decisions about sourcing and route choice. While these models have a short-term

view of the impacts of freight disruption, this is more appropriate for the context of this economic approach.

Among the methodologies described in the NCHRP report, the cargo diversion models are the most relevant. One example is the Disruption Impact Estimating Tool-Transportation (DIETT) model. DIETT focuses on prioritizing transportation choke points (TCPs) based on the costs of their disruption. While the primary use of the tool (prioritization of TCPs) is not the primary focus of this economic approach, the algorithms from the tool may be useful. They can be used to calculate the increased cost of freight movement through a detour as well as increased business inventory costs resulting from increased truck time en route and risk (both real and perceived) of alterations in patterns of freight movement.

Based on their review of many disruption impact assessment methodologies, the authors of the NCHRP developed economic impact "rules of thumb" for calculating direct logistics cost increases (transportation cost increases and inventory cost increases) as well as estimating lost regional economic output (increased supply chain costs as well as wider regional impacts, such as disrupted production output, and sales). While the lost economic output impacts are not relevant for assessing the benefits of interest here, the logistics cost increase models provide a useful approach.

Recommended Valuation Approach
The approaches proposed below are fairly complex and require significant data. If these data are available, we recommend their use, but we are aware that in many cases, they will not be feasible.

Avoided Flood Damage
To estimate avoided flood damage, we suggest use of the Damage Frequency Assessment (DFA) module in FEMA's BCA tool. The module contains a calculator to estimate the storm return period and correlate past damages with return periods.

Data needed:
Amount of flood damage for residential and non-residential structures for at least three storm events that occurred in separate years: This can include repair receipts and/or data from [BureauNet](#), a searchable database of National Flood Insurance Program flood claims since 1978. If historical data are not available, an engineer must estimate expected damages from at least two storm events with different recurrence intervals.

Return period (recurrence interval) of each storm event: This should be determined using U.S. Geological Survey stream flow data, and a process is described in FEMA's Supplement to the Benefit-Cost Analysis Reference Guide.

If storm return period data is unavailable, FEMA's BCA tool can estimate the return period using an "unknown frequency calculator," which requires past damage values, event years, and the year the structure in place was built. At least three events must be included to use the unknown frequency calculator. (Details about the methodology behind the unknown frequency calculator are provided in FEMA's 2009 Damage-Frequency Assessment (DFA) (Limited Data Module/Unknown Frequency Determination) Methodology Report.

Estimated expected flood damage for improved stream crossing (called "residual damages").

The DFA module will use this data to estimate the expected annual damages for the existing stream crossing (called, "annual damages before mitigation"). The tool will also calculate the expected annual damages with the improved stream crossing ("annual damages after mitigation"). The difference between these values represents the annual flood damage reduction benefit of the improved crossing.

These benefits should be projected out with a discount rate, for the time period of the analysis.

Avoided Freight Disruption
If the road where the stream crossing is located is a significant corridor for freight trucks, and if data about truck volume is available, we suggest using the economic model proposed in the NCHRP report to estimate direct logistics cost increases (direct transport costs and inventory costs) associated with any road closures.

As with social benefits calculations, the economic benefit valuation approach requires flood vulnerability information for the base case design as well as each alternative crossing design. This information should be expressed as the annual probability of a flooding event significant enough to close the road.

Data needed:
Average daily traffic count for freight: The average daily traffic count is available for many roads in New York through the online Traffic Data Viewer. Once the road segment is located, clicking on the segment brings up links to "Most Recent Volume" and "Most Recent Class" reports. These reports indicate the traffic count of different vehicle classes, from motorcycles (class F1) to 7 or more axle multi-unit trucks (class F7). Classes F5 to F13 can be considered freight vehicles for this approach.

Note: If traffic data does not exist for the road where the stream crossing of interest is located, it is probably safe to assume that the road is not a significant route for freight vehicles, and this benefit need not be calculated.

Length (miles) of detour for trucks: The detour length can be calculated using a web-based mapping tool such as Google Maps by "dragging" a line around the segment of the road that will close if a culvert floods the road. It is important to note that not all roads are designed for freight, so the detour for freight may differ from the detour path for passenger vehicles.

Increase in delivery time: This is the estimated time to travel the detour: The extra travel time can be calculated using a web-based mapping tool such as Google Maps along with detour length.

Average truck freight value: The user will need to make assumptions about the type of freight along this route based on the four categories below, and use these percentages to calculate the average value of freight. Average freight values ($2009) for each category are as follows:

High-value manufacturing	$1.05/ton-hour
Low- to moderate-value manufacturing	$0.92/ton-hour
Low-value bulk commodities	$0.74/ton-hour
Perishable agriculture	$1.19/ton-hour

If data are not available about the nature of the freight, an average value of $0.98/ton-hour can be used.

Average truck payload: Payload is the weight of cargo carried by a truck. The user will need to estimate the typical truck payload for vehicles traveling this road. This can be done by referring to the average payload by vehicle class tables provided by the Federal Highway Association (FHWA). For New York, average payload (lbs) for each vehicle class is as follows:

NYS Classification	FHWA classification	Average payload (lbs)
F5	Class 1	6,515
F6	Class 2	12,015
F7	Class 3	28,448
F8	Class 4	13,109

F9	Class 5	15,347
F10	Class 6	24,919
F11	Class 7	15,529
F12	Class 8	17,328
F13	Class 9	25,252

Once these values have been established, the economic benefit can be calculated as follows:

Direct freight transport costs avoided: Two formulas will be used to calculate the direct transport costs: one for time (delay) and one for the mileage (detour).

Annual cost of freight disruption for detour ("detour cost") (2009$) = annual probability of road-closing flood with selected crossing type * duration of closure * number of truck trips per day * $1.39/truck-mile * length of detour (miles)

Annual cost of freight disruption for delay ("delay cost") (2009$) = annual probability of road-closing flood with selected crossing type * duration of closure * number of truck trips per day * $59.03/truck-hour * increase in delivery time (hours)

Annual direct freight transport cost = detour cost + delay cost

The annual freight transport disruption cost for the base case should be calculated first, and the annual freight transport disruption cost with improved crossing designs should be calculated next. The annual benefit is the difference between the base case transport disruption cost and the alternative crossing transport disruption cost. Any travel cost savings are treated as positive benefits, and any additional travel costs (e.g., for any design options that may be more likely to flood) are treated as negative benefits.

These benefits should be projected out with a discount rate, for the time period of the analysis.

Freight disruption inventory costs avoided: The following formula can be used:

Annual freight disruption inventory cost (2009$) = annual probability of road-closing flood with selected crossing type * duration of closure * number of truck trips per day * average payload (tons) * increase in delivery time (hours) * average truck freight value/ton-hour

The annual freight disruption inventory cost for the base case should be calculated first, and the annual freight disruption inventory cost with improved crossing designs should be calculated next. The annual benefit is the difference between the base case disruption inventory cost and the alternative crossing disruption inventory cost. Any travel cost savings are treated as positive benefits, and any additional travel costs (e.g., for any design options that may be more likely to flood) are treated as negative benefits.

These benefits should be projected out with a discount rate, for the time period of the analysis.

LONG-TERM RECOMMENDATIONS

More accurate valuation of the economic benefits of improved stream crossings will require systematic collection and retention of flood damage data by managers of local and state roads and organization of this data by location. For flood damage repair costs resulting from major flood events, FEMA Public Assistance worksheets may be available and could provide an estimate of damages at particular sites. Unfortunately, these worksheets are not easily accessible from FEMA, and transportation agencies are likely to organize them by event rather than site, which may make it difficult to extract the needed data about particular places. Moreover, these worksheets are not comprehensive, as they do not include the cost of damage to private property. Private flood damage costs are reimbursed through assistance to individuals and households, and this data is not publicly available.

ENVIRONMENTAL BENEFITS

OVERVIEW OF ENVIRONMENTAL BENEFITS

Well-designed and adequately sized stream crossings provide a range of important environmental benefits. Replacing undersized and/or perched stream crossings with structures that allow organisms, sediment and debris to pass naturally through the stream can lead to great improvements in aquatic habitat. This habitat improvement benefits fish and other organisms that depend on streams.

Because upgraded crossings are less likely to fail during major storms, the environmental benefits include a number of avoided failure-related impacts. For example, when culverts fail due to large storms, the road is also likely to be damaged, and the result may be a massive load of sediment to the stream. This high concentration of sediment, particularly following a single event, degrades water quality and can negatively impact the ecology of a stream and the ability of organisms, such as trout, to reproduce. Water quality impacts are experienced both locally, at the site of the failed culvert, and downstream.

While there are multiple environmental benefits related to the improvement of road-stream crossings, most are difficult to quantify and value in dollar terms. As noted earlier, valuation studies are site and context specific and the results are highly sensitive to the particular valuation technique that is used. In short, while the environmental benefits of stream crossing improvements are substantial, valuation of these benefits is extremely difficult. In the absence of this economic data, benefits calculations are likely be incomplete. It is important that any management decisions made on the basis of benefit-cost calculations recognize these limitations.

EXISTING VALUATION APPROACHES

Recreational Fishing

An improvement in the health and viability of fish populations is a benefit of restoring freshwater connectivity. We expect that this would result in improved opportunities for recreational fishing.

The economic value of recreational fishing is significant, as shown in a number of studies that estimate the value (by day or by year) of recreational fishing in different regions, including New York. These values are measured through surveys of anglers assessing how much they spend on fishing trips. These studies indicate that the benefits are significant. A few highlights of these "revealed preference" studies follow:

The U.S. Fish and Wildlife Service's New York report of the 2011 National Survey of Fishing, Hunting, and Wildlife Associated Recreation estimates that fishing-related expenditures in New York totaled $1.9 million in 2011, with an average expenditure per angler of $907 and per day of about $35 (US DOI 2011).

New York's 2007 Statewide Angler Survey Report provides estimates of expenditures per angler day in different regions of the state. The net economic value estimated through willingness to pay was about $331 million at the fishing site and $202 million en route to the site. This data is broken out by region of the state, type of water body, and even primary fishing target. The survey found that about $172 million was spent at location and en route to river and stream fishing sites, with an average expenditure per angler day of about $27 (Connelly and Brown 2009).

A meta-analysis considered 391 observations from 48 stated preference studies conducted between 1977 and 2001 of people's willingness to pay for improved recreational fishing. For trout outside of the Great Lakes region, people were willing to pay between $4 and $11 for each additional fish caught (Johnston et al. 2006).

A number of studies have been conducted that are specific to fishing in the Great Lakes Basin. A review of those studies (Poe et al. 2013) estimated that the net value of fishing in the Great Lakes is between $393 million and $1.47 billion, with daily values between $20 and $75 per day.

In addition to these studies, several tools may be used to estimate recreational fishing values across a broad geographic range. These include:

The Wildlife Habitat Benefits Estimation Toolkit (Kroeger et al. 2008). This toolkit synthesizes the results from a large number of natural resource valuation studies, so it is particularly useful in places where original studies do not exist. In terms of freshwater, the toolkit can be used to estimate the value of fishing per day based on target species and type of waterbody. The toolkit estimates that the value of trout fishing in rivers and streams per angler day is about $56 (in 2006 dollars).

The National Ocean Economics Program (NOEP) data: For coastal fishing, this is a valuable resource for market and non-market (valuation research) data. The database includes value estimates for fishing and other types of recreation as well as non-use values, organized by state and region. While not directly relevant in the focal geography for this project, this information is applicable to other regions of New York. The information and database are available online.

Despite a substantial body of literature documenting the benefits of recreational fishing in dollar values, we do not have the data needed to use these studies to estimate how recreational fishing benefits might improve with enhanced freshwater connectivity. In order to use any of these studies to estimate the value of improved fishing resulting from new/different stream crossing designs, significant and ecological and economic impact data would be needed to help answer the following questions:

How would the fish population change as a result of connectivity improvements?

How would the value of fishing per day change in response to these changes in fish populations?

How would the total number of recreational fishing trips change in response to these changes in fish populations?

Since the data do not currently exist to answer these important questions, it is not possible to monetize the value of recreational fishing changes at sites where stream crossing improvements are made.

Outside of New York and more closely related to stream crossing replacement projects, a literature review for the U.S. Fish and Wildlife Service (FWS) assessed the economic impacts of

aquatic habitat restoration and enhancement projects, including fish passage projects, in the U.S. The report estimated that the value of removal of barriers within river systems is $515,000 per river mile in 2010 dollars (Charbonneau and Caudill 2010). The FWS applies this value rather broadly to estimate the economic benefits of removing barriers to fish passage across the country. While this is an impressive figure, it is important to note that the value of $515,000 per mile of habitat opened to fish movement is derived from a single study of the economic impact of a dam removal in Maine and the associated restoration of anadromous (sea - run) fish, in terms of expenditures by anglers (Robbins and Lewis 2008). While this study presents a situation most similar to the focus of this economic approach, the context is simply too different to use this value in New York.

Water Quality

Stream crossings that are suitably sized and designed to pass high flows typically result in improvements to water quality. Right-sized and well-designed stream crossings are less likely to cause erosion and scour in the stream, and they are less likely to fail. Erosion, scour, and culvert failure all degrade water quality.

There are many studies that examine the economic value of improved water quality. The Wildlife Habitat Benefits Estimation Toolkit (2008), described above, contains a module for estimating the public's willingness to pay for specific water quality improvements in each state of the U.S. In order to use the module, we would need to estimate the change in water quality expected from a particular project.

Just as we lack suitable models of how fish populations would change from aquatic connectivity improvements, we also lack quantitative data about the degree to which different stream crossing designs may improve water quality. Without this information, the toolkit cannot be used to estimate the benefits of potential water quality improvements.

In short, despite a substantial number of studies that monetize water quality improvements, the environmental data for New York do not support use of these studies at present.

Freshwater Health

Since the benefits of a particular stream crossing design are both specific to a particular stream AND numerous (improved water quality, healthier fish populations), a survey approach that describes these benefits and estimates their net value to the public may result in more useful values of this range of benefits.

A recent survey undertaken by the U.S. Environmental Protection Agency provides a useful example. Using a "Bioindicator-Based Stated Preference Valuation method," developed to estimate ecological results that people may value even though they don't understand the full

ecological science behind the outcome, the study estimated the values that people hold for aquatic ecosystem improvements that are not tied to particular use of the resource for recreation. The preliminary data indicated that households in the northeastern U.S. are willing to pay $9.34 per year for a 1% improvement in "aquatic ecosystem condition" relative to the most natural waters in the region (Helm 2012).

A locally specific survey using this approach was conducted in Rhode Island to gauge public preferences associated with policies that affect rivers. The survey instrument provides useful background information about the impacts of dams on fish populations, the importance of migratory fish, and different options for improving fish passage. Results from a survey such as this can be used to estimate society's value for the full range of environmental benefits that result from different stream crossing replacement options.

RECOMMENDED APPROACH

The review of existing data and studies indicate that the environmental benefits associated with improved stream crossings cannot be satisfactorily valued at present. In light of the absence of useable values, we propose use of a multiplier to estimate environmental benefits.

The ecological model developed for this project (described in a separate document and online at http://nyanc-alt.org/gis/Champlain/) uses a number of criteria to assess the ecological value at each stream crossing site. The data incorporated into the prioritization include fifteen metrics, such as:

Upstream density of culverts

Absolute mileage gain if barrier was removed

Percent of natural land cover in active river area upstream of culvert

Brook trout locations in downstream functional network

Quality of brook trout habitat at stream crossing location

To estimate an environmental benefit for a particular stream crossing project, we recommend the following steps:

The tool user will determine an acceptable range of values for environmental benefits, understanding that the environmental value will be a multiplier, and as such, will "inflate" the other benefits up to a maximum amount.

For example, DOT may decide that environmental benefits can inflate the other benefits up to a maximum of 20%. The range of environmental benefits would then be 1.0-1.20.

Based on this range, the 20 ecological value tiers will be adjusted to fit within this range. Each tier will be assigned a multiplier value. The highest ecological value sites (tier 1) will be scored at the upper end of the range, and the lowest ecological value sites (tier 20) will be assigned the lowest value in the range.

In our example, tier 1 sites would have an environmental value of 1.20 (maximum environmental benefits), tier 2 sites would have a value of 1.19, tier 3 sites would have a value of 1.18, etc., and tier 20 sites would have a value of 1 (no environmental benefits).

The environmental benefit number will be multiplied with the other benefits to "inflate" the total benefits value accordingly.

LONG-TERM RECOMMENDATIONS

In the long term, we recommend development and deployment of a survey tool to assess willingness to pay for stream crossing replacement projects with specific anticipated outcomes such as improved fish passage and improved water quality. Specifically, we advise use of a survey with a "Bioindicator-Based Stated Preference Valuation" approach, as described by Johnston et al. (2009) in their working paper. This approach "provides a means to estimate values for ecological outcomes that individuals might value, even though they may not fully understand all relevant ecological science." In short, this type of survey would provide transportation agencies with useful data about public values for the environmental benefits of improved stream crossings.

CONCLUDING THOUGHTS

The approach presented in this report is a work in progress. Development of a more robust approach for valuing different road-stream crossing designs requires significant improvements to the base of information, particularly for benefits valuation. As we have seen, while improved stream crossings bring many benefits, the vast majority are very difficult to quantify, due largely to a lack of data. For example, we need better records of flood damages and costs in specific locations as well as accidents and injuries. In addition, we don't have quantitative ecological or economic data to estimate the substantial environmental benefits.

Because many of the social and economic benefits of improved crossings result from better resilience to more intense storms, additional data needs include improved modeling of those storms as well as the capacity of crossings with different designs. It is also important to monitor crossings in place to better understand their performance, especially maintenance requirements and structure conditions following major storms, as the climate changes.

Though there the many identified limitations and significant research needs, we still encourage use of the approach and findings from this project, dependent on data availability. Implementation of the approach and subsequent feedback will assist with further refinement and help illuminate the benefits and the costs of different stream crossing design options and encourage decision making with a longer-term view. While full benefit-cost analyses may be time intensive, a small and focused set of such analyses in different geographies and at different types of sites will be extremely valuable for highway department managers and decision makers.

Across the country, municipal and state transportation departments are grappling with limited resources and an urgency to make difficult decisions in the face of a changing climate. While road-stream crossings are just one element of a large and complex transportation network, there is a growing pattern of negative social and economic impacts due to flooding at undersized stream crossing sites during major storms. Improved crossings can help protect communities from severe flooding and also make our rivers and streams healthier. We look forward to continuing to refine this valuation approach into the future, in order to provide transportation departments and decision makers with a more complete understanding of the full benefits and costs of road-stream crossings as the climate changes.

REFERENCES

Charbonneau, J.J. and J.C. Caudill. 2010. Conserving America's Fisheries: An Assessment of Economic Contributions from Fisheries and Aquatic Resource Conservation. Business Management and Operations, Division of Economics, U.S. Fish and Wildlife Service, Arlington, VA.

Connelly, N.A. and T.L. Brown. 2009. New York Statewide Angler Survey 2007. New York State Department of Environmental Conservation, Albany, NY.

Federal Emergency Management Agency (FEMA). 2009a. FEMA Benefit-Cost Analysis Re-engineering (BCAR): Damage Frequency Assessment (DFA) (Limited Data Module/Unknown Frequency Determination) Methodology Report, Version 4.5.

Federal Emergency Management Agency (FEMA). 2009b. Final BCA Reference Guide. Washington, D.C., June 2009.

Federal Emergency Management Agency (FEMA). 2011a. FEMA Benefit-Cost Analysis Re-engineering (BCAR): Development of Standard Economic Values, Version 6.0.

Federal Emergency Management Agency (FEMA). 2011b. Supplement to the Benefit-Cost Analysis Reference Guide. Washington, D.C., June 2011.

Federal Highway Administration. 2012. Creating an Effective Program to Advance Transportation System Management and Operations: Primer. FHWA-HOP-12-003.

Gillespie, N., A. Unthank, L. Campbell, R. Guberick, D. Cenderelli, M. Weinhold, P. Anderson, D. McKinley, S. Roy, B. Austin, S. Wells, J. Rowan, C. Orvis, R. Kirn, M. Hudy, A. Bowden, J. Levine, A. Singler, and E. Fretz. 2014. Flood effects on road-stream crossing infrastructure: economic and ecological benefits of stream simulation designs. Fisheries 39(2): 62-75.

Gubernick, R. United States Forest Service, Duluth, MN. September 12, 2012. Personal communication.

Hansen, B., J. Nieber and C. Lenhart. 2009. Cost Analysis of Alternative Culvert Installation Practices in Minnesota. Minnesota Department of Transportation Research Services Section, St. Paul, MN.

Helm, E. 2012. 316(b) Stated Preference (SP) Survey – Survey Methods and Model Results. Memorandum to the Section 316(b) Existing Facilities Rule Record. Enviromental Protection Agency. http://water.epa.gov/lawsregs/lawsguidance/cwa/316b/upload/316bmemo.pdf. Accessed November 21, 2012.

Horton, R., G. Yohe, W. Easterling, R. Kates, M. Ruth, E. Sussman, A. Whelchel, D. Wolfe, and F. Lipschultz, 2014: Ch. 16: Northeast. Climate Change Impacts in the United States: The Third National Climate Assessment, J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 16-1-nn.

Johnston, R.J., M.H. Ranson, E.Y. Besedin, and E.C. Helm. 2006. What determines willingness to pay per fish? A meta-analysis of recreational fishing values. Marine Resource Economics 21: 1-32.

Johnston, R.J., E.T. Schultz, K. Segerson, and E.Y. Besedin. 2009. Improving the Ecological Validity of Non-Market Valuation: Development and Application of Bioindicator-Based Stated Preference Valuation for Aquatic Restoration. Working Paper No. 2009-06, Clark University.

Kroeger, T., J. Loomis, and F. Casey. 2008. Introduction to the wildlife habitat benefits estimation toolkit. National Council for Science and the Environment, Wildlife Habitat Policy Research Program.

Long, J. 2010. The Economics of Culvert Replacement: Fish Passage in Eastern Maine. Natural Resources Conservation Service, Maine.

Long, J., Natural Resources Conservation Service, Bangor, Maine. April 26, 2012. Personal communication.

Meyer, A. New York State Department of Environmental Conservation, Albany, New York. March 20, 2015. Personal communication.

National Cooperative Highway Research Program (NCHRP). 2012. Methodologies to Estimate the Economic Impacts of Disruptions to the Goods Movement System. NCHRP Report 732. Transportation Research Board, Washington, D.C.

New England Environmental Finance Center. 2010. Construction Cost Models. Prepared for the Maine Department of Transportation Office of Environmental Planning. http://efc.muskie.usm.maine.edu/docs/ld1725_cost_models.pdf. Accessed February 1, 2015.

Perrin, J. and C.S. Jhaveri. 2004. The Economic Costs of Culvert Failures. Prepared for the Transportation Research Board. University of Utah. Transportation Research Board 2004 Annual Meeting.

Poe, G.L., T.B. Lauber, N.A. Connelly, S. Creamer, R.C. Ready, and R.C. Stedman. 2013. Net benefits of recreational fishing in the Great Lakes Basin: A review of the literature. HDRU Publ. No. 13-10. Department of Natural Resources, N.Y.S. College of Agriculture and Life Sciences, Cornell University, Ithaca, N.Y.

Robbins, J.L. and L.Y. Lewis. 2008. Demolish it and they will come: estimating the economic impacts of restoring a recreational fishery. Journal of the American Water Resources Association 44(6): 1488-1499.

Rose, A. Z., K. Porter, N. Dash, J. Bouabid, C. Huyck, J. Whitehead, D. Shaw, R. Eguchi, C. Taylor, T. McLane, L.T. Tobin, P.T. Ganderton, D. Godschalk, A.S. Kiremidjian, K. Tierney, and C.T. West. 2007. Benefit-cost analysis of FEMA Hazard Mitigation Grants. Natural Hazards Review 8(4): 97-111.

Stack, L., M.H. Simpson, T. Crosslin, R. Roseen, D. Sowers and C. Lawson. 2010. The Oyster River Culvert Analysis Project. Syntectic International, Antioch University New England, Climate Techniques, the University of New Hampshire, and the Piscataqua Region Estuaries Partnership. Prepared for the Piscataqua Region Estuaries Partnership, Durham NH, and the EPA Climate Ready Estuaries Program.

U.S. Department of the Interior (US DOI), U.S. Fish and Wildlife Service, and U.S. Department of Commerce, U.S. Census Bureau. 2011 National Survey of Fishing, Hunting, and Wildlife-Associated Recreation.

U.S. Department of Transportation (US DOT). 2003. Economic Analysis Primer. U.S. Department of Transportation, Federal Highway Administration, Office of Asset Management.

U.S. Department of Transportation (US DOT). 2014. TIGER Benefit-Cost Analysis (BCA) Resource Guide. http://www.dot.gov/sites/dot.gov/files/docs/TIGER%20BCA%20Resource%20Guide%202014.pdf. Accessed March 1, 2015.

U.S. Department of Transportation (US DOT). 2014. Benefit-Cost Analysis Analyses Guidance for TIGER Grant Applicants. http://www.dot.gov/sites/dot.gov/files/docs/TIGER%20BCA%20Guidance%202014.pdf. Accessed March 1, 2015.

U.S. Environmental Protection Agency (US EPA). 2010. Guidelines for Preparing Economic Analyses. December 17, 2010. National Center for Environmental Economics, Office of Policy, U.S. Environmental Protection Agency.

Walter, T., A. DeGaetano, A. Meyer, and R. Marjerison. 2015. Determining Peak Flow Under
   Different Scenarios and Assessing Organism Passage Potential: Identifying and Prioritizing
   Undersized and Poorly Passable Culverts: year 2. New York State Water Resources Institute.
   http://wri.cals.cornell.edu/sites/wri.cals.cornell.edu/files/shared/2014-Walter-
   UndersizedCulverts-final-Feb2015.pdf. Accessed March 23, 2015.

APPENDIX D-1: FEMA METHODOLOGY FOR CALCULATING BENEFITS OF IMPROVED ACCESS TO CRITICAL SERVICES

Note: All text is from "FEMA Benefit-Cost Analysis Re-engineering (BCAR): Development of Standard Economic Values," version 6.0, dated December 2011.

Fire Stations:

The steps to estimate the loss-of-function impact of firefighting services are:

Determine the fire station that would temporarily replace the fire station that is out of service

Establish the distance between the two fire stations

Estimate the population served by the non-operating fire station (Fire Station A)

Determine the dollar loss expected due to the shutdown

To determine the expected dollar loss (Step 4), a series of calculations need to be performed.

Estimate the number of fire incidents (I) in the area served by the non-operating fire station (Fire Station A). The population served as determined in Step 3 is used to obtain this number. Since obtaining specific data for a fire station may be difficult, a national average is used. According to the National Fire Protection Association (NFPA), the total number of fires in the United States in 2006 was 1,642,500 (Hall 2007). The 2006 U.S. population estimate given by the U.S. Census Bureau is 298,754,819 (U.S. Census 2007). Therefore, the number of incidents per capita is equal to 0.0055 per year, or 5.5 incidents per 1,000 people.[12]

Estimate the average response time in the area before and after the fire station shutdown. For the situation before the fire station shut down, it is assumed that the response time is equal to the national average. According to the U.S. Fire Administration (2006), the median response time for structure fires is 5 minutes.[13] The extra response time will be approximated using the distance between the two fire stations established in Step 2. The following formula developed by the New York City Rand Institute in the 1970s (Chaiken et al. 1975) is used to determine the relationship between expected response time (RT) in minutes and the distance (D) in miles:

---

[12] No studies were found regarding how a natural disaster will affect the number of fire incidents.

[13] Since this value has a considerable impact on the benefit estimate, when available, reliable local data may be used instead; proper documentation to justify its use should be provided.

$$RT = 0.65 + 1.70D \tag{5}$$

Hence, the response time after the fire station shutdown (RT_{After}) will be estimated to be (in minutes):

$$RT_{After} = 5 + (0.65 + 1.70D) \tag{6}$$

Determine the probability of a no-loss incident before and after the fire station shutdown. This is the probability of an event having zero losses as a function of the response time. The estimate was obtained from *Air Force Protection Cost Risk Analysis* (Air Force Civil Engineer Support Agency 1994). The study used data from the National Fire Incident Reporting System (NFIRS) for 760,000 nationwide records from 1989 to investigate the effect of response time on dollar losses and the amount of damages.[14] The probability of a zero dollar loss (P_0) is given by the following formula:

$$P_0 = 0.456 - 0.00264RT \tag{7}$$

Determine the average property dollar loss per incident before and after the fire station shutdown. This is a function of the response time. The relationship was also obtained from the *Air Force Protection Cost Risk Analysis* study.[15] The dollar loss (DL), in 1993 dollars, is given by:

$$DL = 3,845 + 431RT \tag{8}$$

Calculate the increase in the property dollar loss due to the fire station shutdown. This is done using the following formula:

$$\Delta \$ \, property \, loss = \left[(1 - P_{0After})DL_{After} - (1 - P_{0Before})DL_{Before} \right] \times I \tag{9}$$

Where:

P_{0After} and $P_{0Before}$ are the probabilities of a no-loss incident after and before the fire station shutdown, respectively

DL_{After} and DL_{Before} are the average dollar loss per incident after and before the fire station shutdown, respectively

---

[14] Only data for fixed property was analyzed to obtain these estimates. According to NFPA data for 2006, even though structure fires only account for 32 percent of total fires, they represent 85 percent of property damage, 88 percent of civilian injuries, and 83 percent of civilian deaths.

[15] This relationship was calculated using data for residential structures. NFPA data show that residential structure fires represent 79 percent of all structure fires.

I is the number of fire incidents in the area served by the fire station. Since the number of incidents is in per-year terms, the increase in the dollar loss is also in per-year terms

Add indirect losses. NFPA adds 10 percent for indirect loss as a fraction of direct loss in residential fires (Hall 2008). Indirect losses refer to the costs of temporary housing, missed work, and lost business:

$$\Delta\$total\ property\ loss = \Delta\$property\ loss \times 1.10 \tag{10}$$

Estimate the losses related to mortality and human injuries. According to NFPA estimates, in 2005 direct and indirect property losses due to fire totaled \$12.7 billion, while the total dollar losses for deaths and injuries were estimated to be \$41.9 billion (Hall 2008).[16] That gives a ratio of \$3.30 in losses for deaths and injuries per dollar of property loss. The losses for mortality and human injuries can be obtained by multiplying the total property loss calculated in Step v by 3.3:

$$\Delta\$mortality\ and\ injuries = \Delta\$total\ property\ loss \times 3.3 \tag{11}$$

Update the values to current-year dollars. Since the relationships used to estimate the dollar losses are in 1993 dollars, it is necessary to adjust this value for inflation variation between 1993 to the current year.

Obtain the total dollar loss due to the fire station shutdown. This is done by adding the estimates obtained in Steps vi (total property loss) and vii (mortality and human injuries losses):

$$\Delta\$total\ loss = \Delta\$total\ property\ loss + \Delta\$mortality\ and\ injuries \tag{12}$$

Emergency Medical Services

The steps to estimate the impact of losing an EMS provider are the following:

Determine the EMS provider that will temporarily replace the EMS provider that is out of service

Establish the distance between the two

Estimate the population served by the non-operating EMS provider

Determine the dollar loss expected due to the shutdown

---

[16] This estimate was obtained using the values of \$5 million per death and \$166,000 per injury as 1993 values, inflated to 2008 dollars.

To determine the expected dollar loss (Step 4), a series of calculations need to be performed.

Estimate the number of cardiac arrests treated by EMS in the affected area. These numbers were obtained using the population served as determined in Step 3.[17] Since obtaining specific data for an area may be difficult, a national average was used instead. The American Heart Association estimates that in the United States, EMS treats 36 to 81 out-of-hospital cardiac arrests per 100,000 people (American Heart Association 2004).[18] The middle point of that estimate is 58.5 per 100,000 people. Therefore, the number of cardiac arrests treated in the affected area (e.g., the area served by EMS Provider A) can be approximated as:

$$Number\ of\ cardiac\ arrests\ per\ year\ treated\ by\ EMS =$$
$$\frac{population\ served_{Fire\ StationA} \times 58.5}{100,000} \tag{14}$$

Estimate the average EMS response time in the area before and after the shutdown. In the United States, response times are typically different for urban and rural areas. For the situation before the shutdown, it is assumed that the response time is equal to the national average. According to the National EMS Information System (NEMSIS 2008), the national median response time for cardiac arrest calls is 7 minutes for urban, 8 minutes for suburban, 8 minutes for rural, and 9 minutes for wilderness.[19] The extra response time will be approximated using the distance between the EMS providers established in Step 2. The following formula, developed by the New York City Rand Institute in the 1970s (Chaiken et al. 1975), is used to determine the relationship between expected response time (RT) in minutes and the distance (D) in miles:

---

[17] No studies were found regarding how a natural disaster will increase the mortality rate from cardiac arrests. Even if that data were available, it would need to be established how an increased distance to a hospital would affect the increase in the mortality rate.

[18] No national data could be obtained about EMS calls. In 2001, the National Association of State EMS Directors, in conjunction with the National Highway Traffic Safety Administration (NHTSA) and the Trauma/EMS Systems program of the Health Resources and Services Administration's (HRSA) Maternal Child Health Bureau created a national EMS database known as NEMSIS (National EMS Information System). It is expected that in future years national data related to EMS would be available through this system.

[19] The definition of each category is based on an "Urban Influence" coding system used by the United States Department of Agriculture (USDA) and the Office of Management and Budget (OMB). These codes take into account county population size, degree of urbanization, and adjacency to a metropolitan area or areas. The categories are defined as follows:
 Urban: counties with large (more than 1 million residents) or small (less than 1 million residents) metropolitan areas.
 Suburban: micropolitan (with an urban core of at least 10,000 residents) counties adjacent to a large or small metropolitan area.
 Rural: non-urban core counties adjacent to a large or small metropolitan area (with or without town).
 Wilderness: non-core counties that are adjacent to micropolitan counties (with or without town).

$$RT = 0.65 + 1.70D \tag{15}$$

Hence, the response time after the EMS provider shutdown (RT$_{After}$) will be estimated to be (in minutes):

$$RT_{After} = 7 + (0.65 + 1.70D) \text{ for urban} \tag{16}$$

$$RT_{After} = 8 + (0.65 + 1.70D) \text{ for suburban} \tag{17}$$

$$RT_{After} = 8 + (0.65 + 1.70D) \text{ for rural} \tag{18}$$

$$RT_{After} = 9 + (0.65 + 1.70D) \text{ for wilderness} \tag{19}$$

Determine the probability of survival before and after the shutdown. This is done using the survival function given in equation (6). It is assumed that a call is placed to EMS as soon as the patient experiences cardiac arrest, and that all EMS units are equipped with defibrillators and staff who are trained to use them. Following Valenzuela et al. (1997), it is also assumed that the time interval to EMS-initiated CPR (I$_{CPR}$) is equal to the EMS response interval plus 1 minute, and the time interval to defibrillation (I$_{Defib}$) is equal to the EMS response time plus 2 minutes. The survival probabilities before and after the shutdown are given by the following formulas:

Before shutdown:

$$Survival\ probability_{Before} = \left(1 + e^{-0.260+0.106\times(7+1)+0.139\times(7+2)}\right)^{-1} \text{ for urban} \tag{20}$$

$$Survival\ probability_{Before} = \left(1 + e^{-0.260+0.106\times(8+1)+0.139\times(8+2)}\right)^{-1} \text{ for suburban} \tag{21}$$

$$Survival\ probability_{Before} = \left(1 + e^{-0.260+0.106\times(8+1)+0.139\times(8+2)}\right)^{-1} \text{ for rural} \tag{22}$$

$$Survival\ probability_{Before} = \left(1 + e^{-0.260+0.106\times(9+1)+0.139\times(9+2)}\right)^{-1} \text{ for wilderness} \tag{23}$$

After shutdown:

$$Survival\ probability_{After} = \left(1 + e^{-0.260+0.106\times(RT_{After}+1)+0.139\times(RT_{After}+2)}\right)^{-1} \text{ for urban, suburban, rural, and}$$
wilderness (24)

Calculate the increase in the number of deaths from cardiac arrests due to the increased EMS response time. The survival probabilities obtained in Step iii, and the number of cardiac arrests estimated in Step i, will be used to approximate the potential increase in the number of deaths:

$$\textit{Number of deaths per year due to cardiac arrest}_{Before} =$$
$$\textit{Number of cardiac arrests per year treated by EMS} \times \left(1 - \textit{survival probability}_{Before}\right) \qquad (25)$$

$$\textit{Number of deaths per year due to cardiac arrest}_{After} =$$
$$\textit{Number of cardiac arrests per year treated by EMS} \times \left(1 - \textit{survival probability}_{After}\right) \qquad (26)$$

$$\textit{Increase in the number of deaths per year due to cardiac arrest} =$$
$$\textit{Number of deaths per year due to cardiac arrest}_{After} \qquad (27)$$
$$- \textit{Number of deaths per year due to cardiac arrest}_{Before}$$

Assign a dollar value to the potential cost in lives due to the increased EMS response time. This methodology uses the Value of Statistical Life from the Life Safety section above. The December 2011estimate for the value of a life is $6,600,000. Hence, the potential cost in lives can be estimated using the following formula:

$$\textit{Cost in lives per day due to the increased EMS response time} =$$
$$\frac{\left(\textit{Increase in the number of deaths per year due to cardiac arrest}\right)}{365} \times \$6{,}600{,}000 \qquad (28)$$

Hospital Services

The steps to estimate the impacts of losing hospital services are the following:

Determine which alternate hospital (Hospital B) will temporarily replace the hospital that is out of service (Hospital A)

Establish the distance between the hospitals

Estimate the population served by each hospital

Determine the dollar loss due to the shutdown in terms of:

The cost of traveling the extra distance to Hospital B

The cost of extra waiting time at Hospital B

The potential cost in lives due to the increased distance to Hospital B for Hospital A's patients

To estimate the dollar loss (Step 4), a series of calculations need to be performed:

Cost of traveling the extra distance to the hospital:

Estimate the extra travel time due to the hospital shutdown: It is assumed that, on average, the additional travel distance for the non-operating hospital (Hospital A) patients will be equal to the distance between the non-operating hospital and the second nearest hospital (Hospital B). Hence the extra travel distance will be approximated through the distance between both hospitals established in Step 2. It is assumed that the trip to the hospital implies a round trip (a trip to the hospital and a trip from the hospital), so the travel time is multiplied by 2 (based on Capps et al. 2006). The extra travel time can be approximated using the formula developed by the New York City Rand Institute in the 1970s (Chaiken et al. 1975) to estimate the relationship between time (T) in minutes and distance (D) in miles:

$$T(minutes) = 0.65 + 1.70\, D(miles) \quad (35)$$

Then the formula to estimate the extra distance will be:

$$Extra\,travel\,time\,(hours) = \frac{0.65 + 1.70 \times Distance\ between\ hospitals\,(miles)}{60} \times 2 \quad (36)$$

Estimate the number of daily ED visits to the non-operating hospital: The population served determined in Step 3 will be used to obtain this number. Since obtaining specific data for a hospital may be difficult, a national average will be used instead. According to the National Center for Health Statistics of the U.S. Department of Health and Human Services (2009), the number of visits to EDs in 2005 was 115.3 million, or 39.6 visits per 100 persons. Additionally, during an emergency (such as a hurricane or tornado) the number of ED visits may increase. There are different studies analyzing the effect of natural disasters on the use of EDs. The results vary depending on the event magnitude. For this analysis, the results obtained by Smith and Graffeo (2005) on the impacts of Hurricane Isabel (a Category 2 hurricane that hit the mid-Atlantic region in 2003) were used. The purpose of this study was to investigate the impact of the hurricane on the number and type of ED patient visits. The results showed that during the subsequent 4 days post-landfall, there was an increase in average daily aggregate ED visits of 25 percent. This number will be used to increase the number of visits per day for both hospitals.

Therefore, the number visits to the non-operating hospital can be approximated as:

$$Number\ of\ visits\ per\ day_{HospitalA} = \frac{0.396 \times population\ served_{HospitalA}}{365} \times 1.25 \quad (37)$$

Determine the cost of the extra distance to get to the hospital: It is assumed that the trip to the hospital will involve two people per patient (patient and companion). Additionally, the cost of

time is estimated using the average employer cost for employee compensation per hour from the U.S. Department of Labor. The employer cost in March 2011 was $30.07 per hour. Finally, the cost of the extra mileage is estimated using the Federal government 2008 mileage reimbursement rate, which is equal to $0.505 per mile for passenger vehicles.[20] The cost of traveling the extra distance to the hospital is given by the following formula:

$$
\begin{aligned}
Cost\ of\ extra\ distance = Extra\ travel\ time \times \$30.07 \times \left(number\ of\ visits\ per\ day \times 2\right) \\
+ \$0.505 \times \left(distantace\ between\ hospitals \times 2\right) \times number\ of\ visits\ per\ day
\end{aligned}
\tag{38}
$$

Cost of extra waiting time at the hospital:

Estimate the number of ED visits per year for both hospitals. These numbers can be estimated using the population served as determined in Step 3, the average number of ED visits per year (39.6 per 100 people in 2005, as discussed in Step I.b.), and the increase in the number of visits during the disaster:

$$
Number\ of\ ED\ visits\ per\ year_{HospitalA} = Population\ served_{HospitalA} \times 0.396 \times 1.25
\tag{39}
$$

$$
Number\ of\ ED\ visits\ per\ year_{HospitalB} = Population\ served_{HospitalB} \times 0.396 \times 1.25
\tag{40}
$$

Estimate the waiting time increase at the replacing hospital for both groups of patients: This can be obtained using a relationship between the number of ED users and waiting time. Such a relationship was estimated using data from the survey *Emergency Department Pulse Report* (Press Ganey Associates 2007). This survey analyzes the experiences of more than 1.5 million patients treated at more than 1,500 hospitals in the United States. The survey shows that the average waiting time at the ED increases as the number of patients increases. Using that information, a regression analysis was conducted to obtain the relationship between waiting time and the number of patients, measured as the number of annual visits to EDs:[21]

$$
Waiting\ time\ per\ patient\ \left(in\ hours\right) = 2.49 + 0.000042 \times number\ of\ visits\ per\ year
\tag{41}
$$

The extra waiting time for both groups of patients (Hospital A users that will have to use Hospital B due to the shutdown, and Hospital B users) can be estimated using the following formulas:

$$
Waiting\ time\ per\ patient_{HospitalA} = 2.49 + 0.000042 \times number\ of\ visits\ per\ year_{HospitalA}
\tag{42}
$$

---

[20] The extra mileage cost is included because only 4.2 percent of the patients visiting EDs use emergency medical transport (Institute of Medicine of the National Academies 2006).
[21] The regression R^2 is equal to 0.9910.

$$Waiting\ time\ per\ patient_{HospitalB} = 2.49 + 0.000042 \times number\ of\ visits\ per\ year_{HospitalB} \qquad (43)$$

$$Waiting\ time\ per\ patient_{HospitalB\ with\ HospitalA\ shutdown} = 2.49 + 0.000042$$

$$\times \begin{pmatrix} number\ of\ visits\ per\ year_{HospitalA} \\ + number\ of\ visits\ per\ year_{HospitalB} \end{pmatrix} \qquad (44)$$

The waiting time increases per patient are then calculated:

$$Waiting\ time\ increase\ per\ patient_{HospitalA\ patients} =$$
$$Waiting\ time\ per\ patient_{HospitalB\ with\ HospitalA\ shutdown} \qquad (45)$$
$$- Waiting\ time\ per\ patient_{HospitalA}$$

$$Waiting\ time\ increase\ per\ patient_{HospitalB\ patients} =$$
$$Waiting\ time\ per\ patient_{HospitalB\ with\ HospitalA\ shutdown} \qquad (46)$$
$$- Waiting\ time\ per\ patient_{HospitalB}$$

Calculate the cost of the extra waiting time: As in Step I.c., it is assumed that the trip to the hospital involves two people per patient, and that the cost of time is estimated using the average employer cost for employee compensation per hour from the U.S. Department of Labor ($30.07 per hour in March 2011). The cost per day of the extra waiting time at the hospital would be:

$$Cost\ of\ waiting\ time\ increase = waiting\ time\ increase\ per\ patient_{HospitalA\ patients}$$

$$\times \left(\frac{number\ of\ visits\ per\ year_{HospitalA}}{365} \right) \times 2 \times \$30.07$$

$$+ waiting\ time\ increase\ per\ patient_{HospitalB\ patients} \qquad (47)$$

$$\times \left(\frac{number\ of\ visits\ per\ year_{HospitalB}}{365} \right) \times 2 \times \$30.07$$

Potential cost in lives due to the increased distance to hospital:

After conducting an extensive literature search, only one study could be found that analyzed the link between mortality and distance to a hospital (Buchmueller et al. 2005). The study uses data from the Los Angeles County Health Surveys for 8,000 cases between 1997 and 2003 to test the effect of distance on mortality from emergency (Acute Myocardial Infarction [AMI] and

unintentional injuries)[22,23] and non-emergency conditions (such as cancer or chronic heart disease). The results show that increased distance to the nearest hospital is associated with an increase in deaths from AMI and unintentional injuries, but not from the other causes for which timely emergency care is less important. The results are the presented in Table 10:

Table 1: Percentage Change in Number of Deaths Due to a Mile Increase in Distance to the Hospital

	AMI	Unintentional Injuries
Increase in the number of deaths due to a 1-mile increase in distance	6.04 percent	6.14 percent

Source: Buchmueller et al. (2005).

The steps to determine the potential cost in lives are the following:

Estimate the number of deaths from AMI and unintentional injuries in the affected area: These numbers were obtained using the population served as determined in Step 3.[24] Since obtaining specific data for an area may be difficult, a national average was used. The National Center for Health Statistics of the U.S. Department of Health and Human Services publishes the *National Vital Statistics Report* (NVSR), which contains data on death rates and causes of death. The last report available contains data for 2005 (National Center for Health Statistics 2008). The death rate in 2005 was 825.9 per 100,000 population, while the death rates for AMI and unintentional injuries were 50.9 and 39.7 per 100,000 population, respectively. Therefore, the number of deaths in the affected area (i.e., the area served by Hospital A) can be approximated as:

$$Number\ of\ deaths\ per\ year\ due\ to\ AMI = \frac{population\ served_{HospitalA} \times 50.9}{100,000} \quad (48)$$

$$Number\ of\ deaths\ per\ year\ due\ to\ unintentional\ injuries = \\ \frac{population\ served_{HospitalA} \times 39.7}{100,000} \quad (49)$$

---

[22] AMI are covered by the *International Classification of Diseases*, Tenth Revision (ICD-10) codes I21-I22, and unintentional injuries are covered by codes V01-X59 and Y85-Y86.
[23] Unintentional injuries are: 1) transport accidents and their consequences, and 2) other external causes of accidental injury and their consequences.
[24] No studies were found regarding how a natural disaster will increase the mortality rate from AMI and unintentional injuries. Even if that data were available, it would need to be established how an increased distance to a hospital would affect the increase in the mortality rate.

Calculate the increase in the number of deaths from AMI and unintentional injuries due to the increased distance to the hospital: The percentages provided in Table 10, the estimates obtained in the previous step, and the distance between Hospital A and Hospital B will be used to approximate the potential increase in the number of deaths:

$$
\begin{aligned}
&\textit{Increase in the number of deaths per year due to AMI} = \\
&\textit{number of deaths per year due to AMI} \qquad\qquad (50) \\
&\times 0.0604 \times \textit{distance between Hospital A and Hospital B}
\end{aligned}
$$

$$
\begin{aligned}
&\textit{Increase in the number of deaths per year due to unintentional injuries} = \\
&\textit{number of deaths per year due to unintentional injuries} \times 0.0614 \qquad (51) \\
&\times \textit{distance between Hospital A and Hospital B}
\end{aligned}
$$

Assign a dollar value to the potential cost in lives due to the increased distance to the hospital: This methodology uses the Statistical Value of Life developed in the Life Safety section above. The December 2011 estimate for the value of a life is $6,600,000. Hence, the potential cost in lives can be estimated using the following formula:

$$
\begin{aligned}
&\textit{Cost in lives per day due to the increased distance to hospital} = \\
&\frac{\left(\textit{Increase in the number of deaths per year due to AMI}\right)}{365} \times \$6,600,000 \qquad (52) \\
&+ \frac{\left(\textit{Increase in the number of deaths per year due to unintentional injuries}\right)}{365} \times \$6,600,000
\end{aligned}
$$

The total dollar loss due to the hospital shutdown then is obtained as the sum of items I, II, and III:

$$
\begin{aligned}
&\textit{Total dollar loss} = \textit{Cost of extra distance} + \textit{Cost of waiting time increase} \\
&+ \textit{Cost in lives due to the increased distance to hospital}
\end{aligned}
\qquad (53)
$$