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The Oyster River Culvert Analysis Project

L. Stack
Synthetic International

M. H, Simpson
Antioch University of New England

T. Crosslin
Climate Techniques

Robert Roseen
University of New Hampshire - Main Campus

D. Sowers
Piscataqua Region Estuaries Partnership

See next page for additional authors

Authors
L. Stack; M. H, Simpson; T. Crosslin; Robert Roseen; D. Sowers; and C. Lawson

2010

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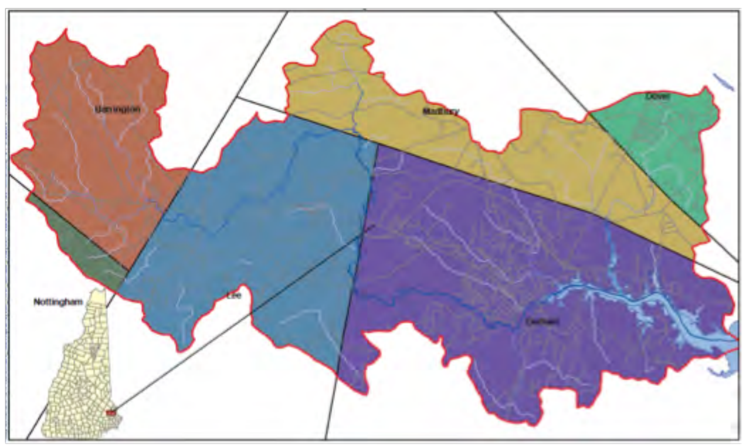
A Joint Project of:
Syntectic International
Antioch University New England
Climate Techniques
University of New Hampshire Stormwater Center
Piscataqua Region Estuaries Partnership

CLIMATE READY ESTUARIES
EPA
Pilot Project

Oyster River Culvert Analysis Project:

Final Technical Report



PISCATAQUA REGION Estuaries Partnership

CLIMATE READY ESTUARIES EPA

March 7, 2010

Oyster River Culvert Analysis Project: Final Technical Report

March 7, 2010

Vulnerability and Required Capacity under Climate Change and Population Growth

Title: The Oyster River culvert analysis project

L. Stack[1], MH Simpson[2], T Crosslin[3], R Roseen[4], D Sowers[5], C Lawson[2]

[1] Syntectic International, 4112 SW Coronado St., Portland, Oregon 97219
[2] Antioch University New England, 40 Avon St., Keene, NH 03431
[3] Climate Techniques, 921 SE 47th AVE, Portland, OR 97215
[4] University of New Hampshire Stormwater Center, Durham, NH 03824
[5] Piscataqua Region Estuaries Partnership, University of New Hampshire, Durham, NH 03824

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Abstract:
Studies have already detected intensification of precipitation events consistent with climate change projections. Communities may have a window of opportunity to prepare, but information sufficiently quantified and localized to support adaptation programs is sparse: published literature is typically characterized by general resilience building or regional vulnerability studies. The Fourth Assessment Report of the IPCC observed that adaptation can no longer be postponed pending the effective elimination of uncertainty. Methods must be developed that manage residual uncertainty, providing community leaders with decision-support information sufficient for implementing infrastructure adaptation programs. This study developed a local-scale and actionable protocol for maintaining historical risk levels for communities facing significant impacts from climate change and population growth.

For a coastal watershed, the study assessed the capacity of the present stormwater infrastructure capacity for conveying expected *peak flow* resulting from climate change and population growth. The project transferred coupled-climate model projections to the culvert system, in a form understandable to planners, resource managers and decision-makers; applied standard civil engineering methods to reverse-engineer culverts to determine existing and required capacities; modeled the potential for LID methods to manage *peak flow* in lieu of, or combination with, drainage system upsizing; and estimated replacement costs using local and national construction cost data.

The mid-21st century, *"most likely"* 25-year, 24-hour precipitation is estimated to be 35% greater than the *TP-40* precipitation for the SRES A1b trajectory, and 64% greater than the *TP-40* value for the SRES A1fi trajectory. 5% of culverts are already undersized for the *TP-40* event to which they should have been designed. Under the *"most likely"* A1b trajectory, an additional 12% of culverts likely will be undersized, while under the *"most likely"* A1fi scenario, an additional 19% likely will be undersized. These conditions place people and property at greater risk than that historically acceptable from the *TP-40*25-year design storm. This risk level may be maintained by a long-term upgrade program, utilizing existing strategies to manage uncertainty and costs. At the upper-95% confidence limit for the A1fi 25-year event, 65% of culverts are adequately sized, and building the remaining 35%, and planned, culverts to thrice the cross-sectional area specified from *TP-40* should provide adequate capacity through this event. Realizable LID methods can mitigate significant impacts from climate change and population growth, however effectiveness is limited for the more pessimistic climate change projections. Results indicate that uncertainty in coupled-climate model projections is not an impediment to adaptation. This study makes a significant contribution toward the generation of reliable and specific estimates of impacts from climate change, in support of programs to adapt civil infrastructures. This study promotes a solution to today's arguably most significant challenge in civil infrastructure adaptation: translating the extensive corpus of adaptation theory and regional-scale impacts analyses into local-scale action.

Executive Summary:

In 2008, the Piscataqua Regional Estuary Partnership (PREP) was award a $50,000 grant from the U.S. Environmental Protection Agency's "Climate Ready Estuaries" initiative. This funded a detailed vulnerability assessment of how climate change is likely to impact the hydrology and drainage system within the watershed of the Oyster River, an important coastal river that empties into the Great Bay estuary in New Hampshire. New England is experiencing an unprecedented and ongoing increase in the frequency of extreme rainfall events, consistent with climate change projections. Additionally, watersheds are being altered by development-associated increases in impervious surfaces such as roads, roofs, and parking lots. Both of these factors exacerbate water running off of the land. Many of the existing drainage systems in New England, including under-road culverts, were not designed to safely pass the amount of water that can be anticipated due to these changes. New systems are being designed using standards that are fifty-years old. As a result, the trend in extreme storms and population growth increases the likelihood of failure of drainage components at road-stream crossings, damaging infrastructure and property, causing loss of life, and degrading both fluvial and down-stream estuarine aquatic ecosystems.

To address these challenges, PREP convened a technical team to conduct a climate adaptation pilot project in the Oyster River watershed in southeastern New Hampshire. The project consisted of various analyses to identify specific road/stream crossing culverts threatened with failure as a result of impacts from increasingly extreme storm events and watershed development. The purpose of the project was to provide leaders with decision-support information sufficient for implementing a practical and pro-active adaptation strategy that maintains historical risk levels for road infrastructure and stream habitat.

The study approach utilized a geographic information system (GIS) based watershed model to examine the hydrological impact, on existing culvert infrastructure, of several climate change and land use scenarios. Fieldwork performed by staff from PREP and Antioch New England University, supplemented with staff from the Town of Durham, the NH Fish and Game Department, and the Strafford Regional Planning Commission, applied a standardized protocol to inventory and map all major culverts in the watershed. This protocol collected data on culvert capacity, vegetation cover, slope, soils, permeability, roads, and land use. The project applied standard hydrological methods to estimate runoff and *peak flow* rates from recent precipitation and current land-use. The NRCS *Curve Number and TR-55* methods were used to estimate runoff volumes and *peak flow* under current and projected future precipitation patterns and land-use. Future scenarios included two full build-out analyses based on current zoning ordinances: one that assumes development consistent with existing construction practices that minimally limit runoff and impervious surfaces; and one that incorporates realizable Low Impact Development (LID) techniques. Output from the Geophysical Fluid Dynamics Laboratory 2.1 coupled-climate model was downscaled for two greenhouse gas emission scenarios

developed by the Special Report on Emissions Scenarios (SRES) published by the Intergovernmental Panel on Climate Change. Using standard engineering methods, culverts were reverse-engineered to determine their present capacity and required capacity for accommodating *peak flow* from climate change and population growth. Standard engineering methods were used to design simple culverts with adequate capacity for a given scenario. Replacement and marginal costs were developed using standard construction cost estimating procedures and unit cost rates. Individual culverts were ranked according to vulnerability and potential hazard to the community, to provide leaders with a prioritized schedule to guide planning for LID ordinances and culvert upgrades.

Together these analyses provided a practical, quantified, and transferable protocol for identifying stormwater drainage system vulnerability; demonstrated that uncertainty between greenhouse gas emissions scenarios is not a significant barrier to climate change adaptation; measured the capacity of achievable LID methods for mitigating increased *peak flow* from climate-changed precipitation; and generated a budgeted schedule that stakeholders can incorporate into town master plans to effectively and economically protect the community. This study found that, for the stormwater management system in the study site, adaptation to climate change has a beneficial cost/benefit ratio, due to both a low risk resulting from uncertainty in climate change projections, and a low overall cost to adapt. As a result, towns in the watershed should plan, budget, and implement a program of adapting to the projected impacts from mid-21st century climate change. Methods and certain results are transferrable to many communities nationally and internationally. This study makes a significant contribution to preparing coastal watersheds for the impacts of climate change and population growth.

Summary of Findings and Conclusions

Research Site:

- The majority of culvert catchments are under 500 acres (Figure III.a.1);
- For most modeled catchments, over 60% of land area is buildable (Figure III.a.1);
- The average catchment elevation is 144 feet (Figure III.a.3);
- The average catchment slope is 4.4% (Figure III.a.3);
- Hydrological Group "C" soils predominate (Figure III.a.4);
- The average width of catchments is 4,700 feet (Figure III.a.5);
- The average length of the main drainage channel for catchments is 9,100 feet (Figure III.a.5);
- For most catchments, the *time of concentration* (t_C) is between 19 and 25 hours (Figure III.a.5, Figure III.a.6);
- Most catchments have a *curve number* (*CN*) between 66 & 69 (Figure III.a.7).

Precipitation:

- The *"most likely"* recent (1971-2000) precipitation event was 5% greater than the *TP-40* event, for the 25-year, 24-hour precipitation (Table III.b.1);
- The *"most likely"* moderate (A1b) and pessimistic (A1fi) precipitation events are projected to be 35% and 64% greater than the *TP-40* event, respectively, for the 25-year, 24-hour precipitation (Table III.b.1);
- The upper-95% confidence limit of the pessimistic (A1fi) precipitation event is projected to be 140% greater than the *TP-40* event, for the 25-year, 24-hour precipitation (Table III.b.1);
- Under the *"most likely"* A1fi climate change scenario, by the mid-21st century the amount of rainfall from what historically was the 25-year storm is projected to become a 7.5-year storm. That is, this amount of rainfall jumps from a 4% to a 13.3% probability of occurring any one year (Figure III.b.1);
- Under the *"most likely"* A1fi scenario, by the mid-21st century the amount of rainfall from what historically was the 150-year storm is projected to become a 25-year storm. That is, this amount of rainfall jumps from a 0.67 % to a 4% probability of occurring any one year (Figure III.b.1);
- For the upper-95% confidence interval of the A1fi scenario, by the mid-21st century the historically 4% probability event increases to a 20% annual probability. And the event that historically had a 0.4% annual probability is projected to occur ten-times more frequently (Figure III.b.1).

Culvert Data:

- The majority of culverts are concrete, followed by metal. Only 5% are HDPE plastic (Table III.c.1);
- For the culverts included in the study, the rate of undersized culverts for Durham and Lee was approximately 28%, and for Barrington and Madbury was approximately 15%, for the A1fi scenario with build-out (Table III.c.1);
- The majority of undersized culverts were conveying runoff from low-order streams, higher in the watershed;
- The majority of undersized culverts were sited under less-traveled, higher-class roads;
- The majority of undersized culverts ranged between 12 and 24 inches in diameter;
- Modeled culverts have inconsistent return-period capacities (Table IV.2);
- The maximum number of culverts that were undersized due to build-out under the *"most likely"* A1fi precipitation and *AMC Type III "wet"* antecedent soil conditions, was twenty-five (25), which is approximately 30% of the culverts in the study. This includes 4 culverts already undersized for the *TP-40* 25-year storm (Table III.e.2);
- The maximum number of culverts that are undersized due to build-out under the *"most likely"* A1fi precipitation and *AMC Type II "average"* antecedent soil conditions, was nineteen (19), which is approximately 23% of the culverts in the study. This includes 4 culverts already undersized for the *TP-40* 25-year storm (Table III.e.2);

- Culverts with large cross-sectional areas (> 60 ft^2) were not undersized for any of the scenarios of the study (Table III.c.2);
- For any of the modeled land-use and *"most likely"* precipitation scenarios, culverts with a current-to-modeled cross-sectional area ratio greater than 2.1 are never undersized (Tables III.c.2 and IV.3, Figure III.c.2);
- Culverts that are three-times the cross-sectional area specified by *TP-40* will be adequately sized for the upper-95% confidence limit of the pessimistic A1fi climate change scenario with build-out (Table IV.3, Figure III.c.2).

Low Impact Development Methods:

- Across all modeled catchments, the mean *CN* increases from 67 to 72 due to build-out, but decreases from 72 to 70 with the incorporation of achievable LID methods (Figure III.e.1);
- For moderate precipitation increases and *"average"* antecedent moisture conditions, achievable LID methods reduce the number of culverts undersized due to build-out from 25-100% (Table III.e.2);
- For more extreme precipitation increases, or *"wet"* antecedent conditions, achievable LID methods reduce the number of culverts undersized due to build-out by 5-8% (Table III.e.2).

Watershed-wide Adaptation Costs, and Marginal Upgrade Costs:

- For the town of Durham, for the *"most likely"* pessimistic A1fi with build-out scenario, the cost of a risk-averse adaptation strategy, which upgrades culverts before the expiration of service life, is 1.6% of the 2010 operating budget;
- For the town of Durham, for the *"most likely"* pessimistic A1fi with build-out scenario, an adaptation strategy that is more tolerant of risk upgrades, over time, culverts projected to be undersized. The adaptation cost for this strategy is the marginal upgrade cost. Budgeted over a thirty-year period, this strategy adds 0.016% to each year's operating budget, based on Durham's 2010 budget;
- For the watershed as a whole, the cost of adapting to the *"most likely"* pessimistic A1fi-with-build-out scenario is 8.5% greater than the cost of replacing culverts with ones that are the same size as is currently in place. This is the watershed-wide marginal adaptation cost;
- For the late-Spring season, the average (per culvert) marginal upgrade cost from build-out is greater than the average marginal cost from climate change (Tables III.g.4 and III.g.5);
- For the Fall season, the average (per culvert) marginal upgrade cost from build-out is between the average marginal costs for the moderate and pessimistic climate change scenarios (Tables III.g.4 and III.g.5);
- For the *"most likely"* pessimistic A1fi scenario with build-out, the marginal upgrade cost per culvert was 49% (Table III.g.1);
- On a per-culvert basis, across all precipitation and build-out scenarios, the average marginal upgrade cost is approximately $3,317 (Table III.g.2);
- Build-out increases the average marginal upgrade cost by 22% (Table III.g.3);

- Build-out with LID methods increases the average marginal upgrade costs by 14%, a reduction of 8%, or 1/3, from build-out without a LID strategy (Table III.g.3).

Uncertainty in Climate Change Projections:

- Both the rate of undersized culverts, and marginal upgrade costs, are insensitive to climate change scenario. The *"most likely"* A1fi storm is 22% greater than the *"most likely"* A1fi storm, however the watershed-wide adaptation cost for the A1fi scenario is only 4.7% greater than that for the A1b storm (Table III.b.1, Figure IV.1);
- Due to the standard sizes available for pre-manufactured culverts, for any of the *"most likely"* precipitation scenarios, once a culvert upgrade is required, the upgraded capacity is adequate for all higher-precipitation scenarios (Table IV.1);

Other findings:

- For culverts projected to be undersized, adaptation can be prioritized based on risk, to better protect the community and increase the affordability of the upgrade program (Table III.g.6);
- Conditions that impair effective capacity were found at 32% of culverts in the watershed;
- The upgrading of culverts, to accommodate impacts from climate change and build-out, also will promote safe passage of aquatic species.

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I. <u>Introduction</u>

In 2008, the Piscataqua Regional Estuary Partnership (PREP) was award a $50,000 grant from the U.S. Environmental Protection Agency's "Climate Ready Estuaries" initiative. This funded a detailed vulnerability assessment of how climate change is likely to impact existing road and stream networks within the watershed of the Oyster River, an important coastal river that empties into the Great Bay estuary in New Hampshire. New England is experiencing an unprecedented and ongoing increase in the frequency of extreme rainfall events, consistent with climate change projections. Additionally, watersheds are being altered by development-associated increases in impervious surfaces such as roads, roofs, and parking lots. Both of these factors exacerbate water running off of the land. Many of the existing drainage systems in New England, including under-road culverts, were not designed to safely pass the amount of water that can be anticipated due to these changes. New systems are being designed using standards that are fifty-years old. As a result, the trend in extreme storms increases the likelihood of failure of drainage components at road-stream crossings, damaging infrastructure and property, causing loss of life, degrading both fluvial and down-stream estuarine aquatic ecosystems.

To address these challenges, PREP convened a technical team to conduct a climate adaptation pilot project in the Oyster River watershed in southeastern New Hampshire. The project consisted of various analyses to identify specific road/stream crossing culverts threatened with failure as a result of impacts from increasingly extreme storm events and watershed development. Results were provided to leaders as decision-support sufficient for implementing a practical and pro-active adaptation strategy maintaining historical risk levels for road infrastructure and stream habitat.

The purpose of this EPA Climate Ready Estuaries pilot project was to provide scientifically-defensible insights into how anticipated impacts of development, and climate change-mediated extreme storm events, will affect watersheds in the Piscataqua Region of New Hampshire and Southern Maine.

The pilot project had two core goals:

1. <u>Local benefit</u>: Identify specific road-stream infrastructure vulnerabilities in the Oyster River Watershed highly likely to fail from storm impacts associated with climate change and forecasted development. Data will also be used to evaluate fish passage barriers throughout the watershed;
2. <u>Regional benefit</u>: Engage stakeholder interest throughout coastal NH/Southern ME in a longer-term climate adaptation planning effort by utilizing the Oyster River case study results to demonstrate direct expected impacts of climate change on local community infrastructure, safety, and environmental quality.

Intended Use of Study Results:
The Piscataqua Region Estuaries Partnership is utilizing study results to develop climate change adaptation decision-support in the:

- Implementation of a specific risk-based prioritization of culvert replacements in the Oyster River watershed, within existing asset management programs;

- Promotion of culvert design standards (for at least the local and state level) that account for climate change impacts on increased watershed runoff volumes, shorter predicted storm return intervals, and fish passage criteria. This action has been added to PREP's Comprehensive Conservation and Management Plan for the Piscataqua Region;
- Raising of awareness among town decision-makers, planning staff, and Public Works staff, about: the need to integrate climate change impacts into aquatic resource and community infrastructure planning; and the opportunity for implementing adaptation programs via zoning, development regulations, and internal policies;
- Demonstration of the mitigating potential of Low Impact Development techniques.

II. Methodology

To provide leaders with best-available information on the long-term hydrological functioning of the existing drainage system, this study estimated future rates of *peak flow* that can be expected under mid-21st century climate-changed conditions. *Peak flow*, the quantity to which drainage systems are designed, is a function of precipitation intensity and runoff rates. Design storm precipitation intensity was modeled for both recent and climate-changed scenarios using historical records for the study site and CCM output, fit to a *point process* model of *peaks over threshold* (*partial duration)*.

The study approach utilized a geographic information system (GIS) based watershed model to examine the hydrological impact on existing culvert infrastructure of several climate change and land use scenarios. Fieldwork performed by staff from PREP and Antioch New England University, supplemented with staff from the Town of Durham, the NH Fish and Game Department, and the Strafford Regional Planning Commission, applied a standardized protocol to inventory and map all major culverts and site conditions in the watershed. This protocol collected data on culvert capacity, vegetation cover, slope, soils, permeability, roads, and land use. The project applied standard hydrological methods, including the NRCS *Curve Number*, *TR-55, and TR-55* methods, to estimate runoff volumes and *Peak Flows* under current and projected future precipitation and land-use patterns. Future scenarios included two full build-out analyses based on current zoning ordinances, the first of which assumed future development consistent with existing construction practices that minimally limit runoff and impervious surfaces. Because up-sizing of drainage systems has been shown as the most costly method for managing increased runoff from climate change (Blanksby et al., 2003), a second build-out scenario applied a set of realizable Low Impact Development (LID) techniques to determine the capacity of runoff management methods for reducing adaptation costs. Coupled-climate model (CCM) output was downscaled for two global greenhouse gas emission scenarios developed by the Special Report on Emissions Scenarios (SRES) published by the Intergovernmental Panel on Climate Change (Nakicenovic et al., 2000). Using standard engineering methods, culverts were reverse-engineered to determine their present capacity and required capacity for accommodating *peak flow* from climate change and population growth. Standard engineering methods were used to design simple culverts with adequate capacity for a given scenario. Replacement and marginal costs were developed using standard construction cost estimating procedures and unit cost rates. Individual culverts were ranked according to vulnerability and potential hazard to the community, to provide leaders with a prioritized schedule to guide planning for LID ordinances and culvert upgrades. A schedule of required upgrades, prioritized by loss exposure and percent undersized, was prepared to assist City leaders in planning and budgeting an upgrade program, and in managing residual climate model uncertainty.

The project consisted of five analyses: runoff/*peak-flow*; recent and climate-changed design storm; culvert reverse-engineering and required future capacity; 100% build-out under current and LID influenced zoning standards; and replacement costs (Figure II.1).

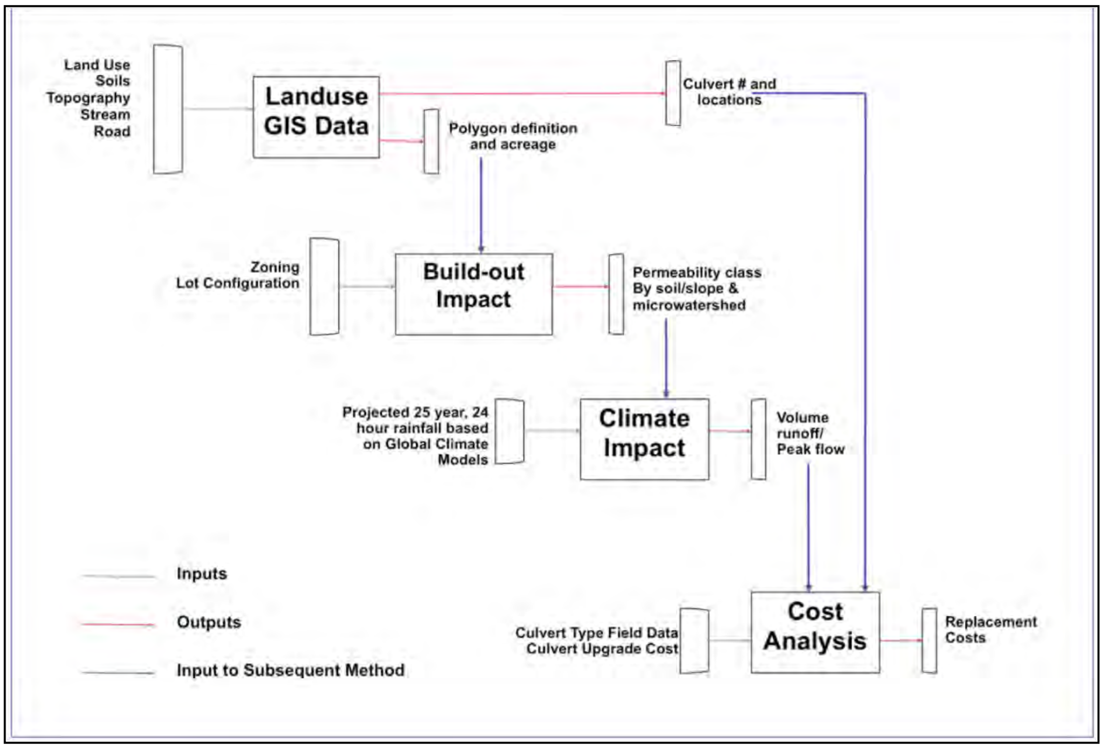

Figure II.1 *Flowchart of project methodology*

II.a **Study Site**

The Oyster River Watershed, a 19,857 acre watershed draining into the Oyster River, is a key source of freshwater for the Great Bay estuary on the New Hampshire coast.

Figure II.a.1 *Watersheds of the New Hampshire coast*

The watershed is within Strafford County, and includes portions of six townships, although only four have significant land area within the watershed (Figure II.a.2). In 2000 the population density was 304 persons per square mile (United States Census Bureau, 2010). Population growth has been vigorous, at 8.6% for the eight years ending 2008, equaling 10.8% per decade. This exceeds the growth rate through the 1990s of 8.0% per decade. At this rate the population will be 40% greater by 2046, the beginning of the thirty-year climate-changed period modeled in this study, and 70% greater by 2075, the end of the thirty-year climate-changed period. Durham has the largest population among towns in the watershed. The Durham 2000 Master Plan projects that full build-out will occur by 2028 (Town of Durham, NH, 2000). The deleterious impact of recent growth on hydrology is indicated by the change in percentage of impervious surface from 1990 to 2005 (Figure II.a.3). This increase portends significant impacts for the installed drainage system, elevating the importance of quantifying these impacts and investigating the potential for techniques such as Low Impact Development to mitigate increased runoff.

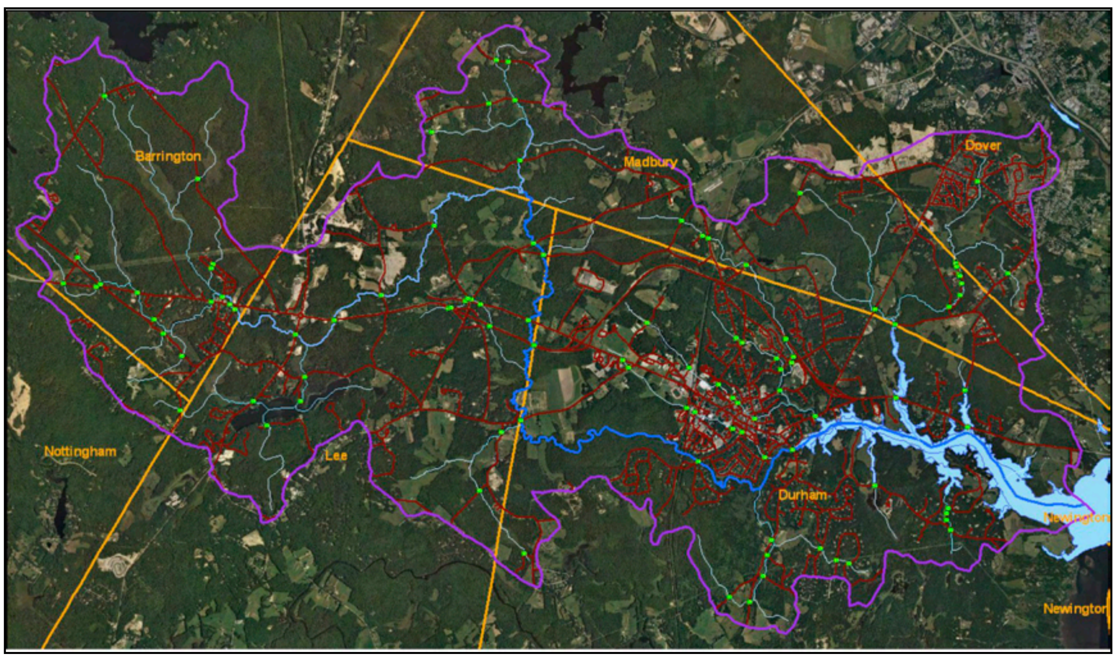

Figure II.a.2 *The Oyster River Watershed. The watershed is circumscribed in purple, streams are colored blue, roads red, green dots indicate culvert locations, and political boundaries between the four towns are in yellow. The body of water at lower-right is the estuary of the Oyster River, at its entrance to Great Bay.*

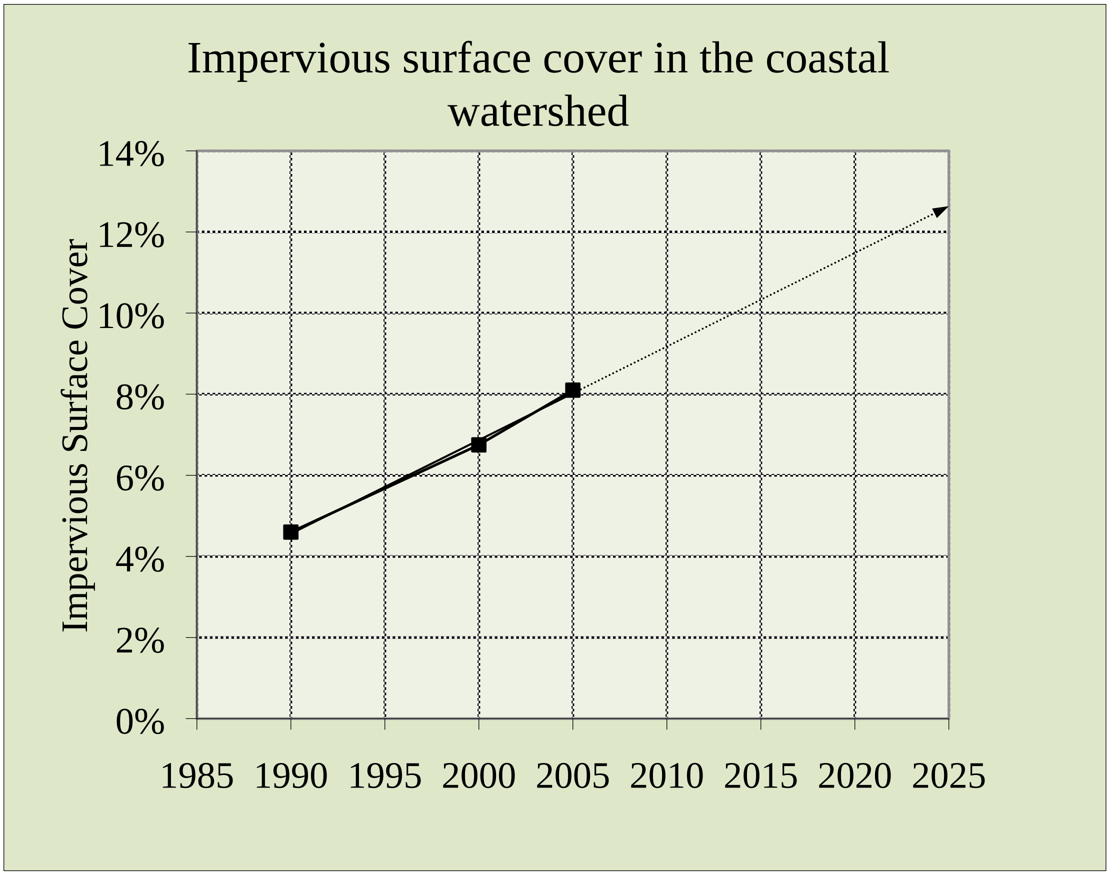

Figure II.a.3 *Change in impervious surface area*

The largest township in the watershed is Durham, in terms of land area, population, and economic activity. Durham was incorporated in 1732, and is home to the main campus of the University of New Hampshire (Town of Durham, 2010). The non-student population of Durham was 12,664 at the 2000 census. 2008 enrollment in the University was approximately 14,968.

The watershed is a fluvial-estuarine system, the central feature of which is its draining into the Great Bay. The health and proper functioning of the Watershed's natural and man-made hydrological features are therefore important to the ecological health of the estuary, as well as the flora and fauna dependent thereon. Drainage of the watershed is channeled through the Oyster River. Two "run-of-the-river" dams on the Oyster River have insignificant storage capacity and little impact on river hydrology. However, the lower dam creates a boundary between freshwater and tidal portions of the river.

Elevation for the watershed ranges from 4 to 383 feet. For the 85 catchments modeled, mean within-catchment elevation was 144 feet above sea level. Mean within-catchment slope was 4.4%, Mean within-catchment maximum slope was 29.4%. The average catchment consists of 67% "C" soils, which are sandy-clay-loam, with a medium-low infiltration rate of 0.05-0.15 inches per hour.

II.b Runoff/Peak-Flow

The runoff calculation methods used were a modification of the Natural Resource Conservation Service (NRCS) *TR-55 Curve Number(CN)* method (NRCS, 1986). The *CN* method was selected for runoff computation because it commonly-used and well-validated. To estimate *peak flow*, the factor to which culverts are designed, we used the NRCS *TR-55* method and a *Time of Concentration* (t_C) calculation that incorporates an NRCS *lag time* (t_L) method (Durrans, 2003). Modeling of build-out, LID, and costs, were generally limited to runoff/*peak flow* occurring in antecedent soil moisture conditions (AMC) that are "average", or *AMC Type II*. However, certain results were extended to "wet" antecedent conditions, *AMC Type III*.

The unit peak runoff rate (q_u) was estimated using a regression procedure from the HEC-22 manual (Brown, et al. 2001). This procedure required calculating the *time of concentration*, t_c, for each catchment. Numerous methods have been proposed for computing t_c and *lag time*, t_L, and little guidance is available for selecting one method over another. Without resources for real time precipitation/flow measurements, we used the NRCS TR-55 method, such that $t_c = 1.67t_L$.

The *lag time* calculation method was selected from a table of methods published in Haestad Methods (Table 5.9, Durrans, 2003). We chose an NRCS method that is a function of basin length, *Curve Number*, and average basin slope. This approach was selected because it includes the *Curve Number* as a variable, so that t_L changes as land cover changes. This was important because the study strategy calculated a baseline runoff volume from the current land use configuration, and modified this as land use changed according to different build-out scenarios. Thus the impact of build-out was incorporated into the model via the impact of land-use on *Curve Number*.

II.c Precipitation Model

The adequacy of the existing drainage system is a function of several hydrological variables, including the precipitation intensity-duration-frequency (IDF) relationship. This relationship is obtained by fitting precipitation data to a statistical distribution, from which estimates can be made of the precipitation amount likely to be received for the design storm specified by New Hampshire Department of Public Works and Highways regulations (NHDPWH, 1996). For common culverts, this design storm is the 4% probability (once-in-25-year) rainfall received within twenty-four hours.

Precipitation data has been fit to a variety of statistical distributions over the last century (Bobee and Ashkar, 1991). Recent studies have applied *point process* theory to modeling extreme precipitation events (see for example, Coles and Pericchi, 2003), and the present study fit data to a *point process* model of *peaks-over-threshold (POT)*, following the methods of Zwiers and Kharin (1998), and Katz et al. (2002). Semenov and Bengtsson (2002), and Watterson and Dix (2003) proposed that extreme value methods were potentially reliable means for downscaling coupled-climate model output, and this method may be considered state-of-the art in statistical downscaling.

To estimate the impact of climate change on the 25-year (4% probability) design storm, we established, for the study site, the IDF relationship for the thirty-year baseline period 1971-2000, using the Summary of the Day dataset (NCDC, 2008). For this same thirty-year baseline period, the IDF relationship was derived for *coupled-climate model* (CCM) output, for six gridpoints surrounding the study site. These IDF relationships were used to estimate the baseline period 25-year event, for the NCDC station and the CCM gridpoints.

The IDF relationship, and the 25-year event derived therefrom, were also calculated for CCM output for the climate-changed thirty-year period 2046-2075. This period was chosen because it is centered on 2060. This corresponds to the end of a 50-year typical service life for culverts installed under rural roads, for a culvert installed today. 2060 thus demarks the period of worst impacts that such a culvert would be subject to. For each CCM gridpoint, we calculated the percentage change in the 25-year event from the baseline period to the mid-21st century period, and derived a linear regression equation to estimate this percentage change. This equation was used to project the climate-changed 25-year rainfall for the study site.

The IDF relationship was modeled for two three-month seasons during which recent extreme precipitation events have occurred, late-Spring (April, May, June), and Fall (September, October, November). However, Fall 25-year events were consistently greater than those for late-Spring, and because culverts would be designed for the greater precipitation, culvert and cost modeling focused on the Fall season.

In order to study a range of possible climate change outcomes, output from two SRES greenhouse gas emission scenarios were studied (Nakicenovic et al., 2000). The moderate A1b scenario posits a global energy mix that is a **b**alance (hence the "*b*" in A1b) of fossil fuel and less-greenhouse-gas-intensive sources. The more pessimistic A1fi scenario posits a world for which the primary source of energy continues to be **f**ossil **i**ntensive (hence the "*fi*" in A1Fi). Output from a single CCM was selected for study, the Geophysical Fluid Dynamics Laboratory’s (GFDL) 2.1 model (Delworth et al., 2006). A single coupled-climate model was used, rather than the more typical ensemble data because, from a real-world perspective, the United States can be expected to follow the practice of countries that have national adaptation programs. For these countries, the common practice has been to utilize output from the IPCC-recognized model that each country funds and operates. Three research institutions in the United States operate an IPCC-recognized CCM, one of which is the GFDL.

II.d Culvert Model

Field data collection, management, and dissemination

Information used to model culvert capacity was obtained from an inventory of culverts and proximate site conditions in the Oyster River watershed. The inventory process was managed by the Piscataqua Region Estuaries Partnership (PREP), with substantial assistance from Antioch New England University, and support from the Town of Durham, the Strafford Regional Planning Commission (SRPC), and the New Hampshire Department of Fish & Game. All field staff were trained in the use of a standardized culvert assessment protocol based on previous assessments conducted in Massachusetts, New Hampshire, and Vermont, and tailored to this project (Appendix 2).

Potential culvert locations were preliminarily identified by intersecting road and stream layers in the GIS. Field teams used printed maps to field-verify the presence or absence of potential culvert locations. The field data collection protocol gathered information required for modeling culvert capacity, as well as information necessary to determine the geomorphic compatibility of the culvert with the stream system and the likelihood that it would act as a barrier or partial obstruction to the movement of aquatic organisms throughout the stream system. The field protocol provided documentation of each culvert's:

- Physical attributes (e.g. type, dimensions, slope, condition, *etc*.);
- Upstream/downstream geomorphic setting and the potential impacts of the crossing on stream morphology (e.g. bankfull widths, scour, erosion, armoring, pool dimensions, deposition, perching, sediment character, alignment, *etc*.);
- Site characteristics (e.g. aerial sketch, GPS location, street name, road configuration, *etc*.);
- Pipe and site condition (inlet/outlet and upstream/downstream photographs).

Calculation of culvert capacity

Culverts are designed to convey flows of water through (usually) manmade obstructions to natural flow, such as roadways or railway embankments. Typically, a culvert is designed to convey the maximum, or *peak flow* (Q_P) from a specified design storm, established by New Hampshire standards as the once-in-twenty-five-year (4% annual probability), 24-hour precipitation amount (NHDPWH, 1996). For each catchment in the watershed and each precipitation and land-use scenario, the culvert model estimated the minimum required cross-sectional area needed by a culvert to safely pass estimated *peak flow*. The required cross-section was compared with the actual cross-section of the culvert currently in place, to determine the adequacy of the current culvert. The culvert sizing methods selected in this study comply with New Hampshire design guidelines (NHDPWH, 1996).

Determining flow regime and pipe size

The "trial sizing" outlined in the NHDPW manual, and used for the present study, is a simple method appropriate for planning purposes. This approach does not consider design considerations such as ponding and greater headwater-to-depth ratios, engineering design nuances that might be considered during detailed design of an individual culvert. However, for watershed-wide planning purposes a simplified design method, uniformly applied to all culverts in the study site, is appropriate. This simplified design approach results in a capacity determination such that, if a pipe has less than the calculated capacity based on *peak flow*, flooding may occur and therefore the pipe size is considered undersized. The approach adheres to the NHDPW manual requirement that culverts be designed as open flow channels. This method estimates replacement sizes based solely on hydrologic capacity and does not include site-specific design considerations that may optimize culverts for passage of fish and other aquatic organisms, ensure geomorphic compatibility with the stream reach, or simulate a more natural stream channel bottom.

In accordance with the NHDPW manual, we assumed *inlet control* as a primary design assumption, meaning that sizing decisions would be based on the point of water inflow to the culvert. Culvert sizing was calculated using a method promoted by the Federal Highway manual (Normann, Houghtalen, and Johnston, 2001), and published as equation 9.4 in Hastaed Methods (Durrans, 2003). Estimation of costs and capacity for accommodating a range of *peak flow* scenarios was based on culvert replacement size. Replacement size is the smallest stock culvert, readily available in the marketplace, that is equal to, or larger than, the required size.

II.e Build-out Model

Population growth is manifested on the landscape as development of commercial and residential real estate. Future real estate development is guided by zoning plans and regulations enacted at the municipal level. Therefore the impact of population growth on the hydrology of the study site was modeled by performing a complete build-out of the watershed to current zoning standards. This had two objectives. Firstly, to estimate the adequacy of the existing culvert regime for accommodating projected impacts from population growth. Secondly, to establish a baseline standard development, to which Low Impact Development (LID) methods for new development would be applied. We followed standard build-out conventions and assumed that all undeveloped portions of the watershed would be built-out at the density established by zoning regulations for the six towns within the study site. Land areas that are not buildable, such as conserved lands and wetlands, were excluded from parcels to be developed. The rate of build-out depends on population growth, and the validity of our analysis depended on full build-out occurring no later than the time period of the study, the mid-21st century. The town of Durham expects full build-out to occur in 2028 (Town of Durham, NH, 2000).

Within zoning-specified lot-size limits, percentages of forested, lawn, and impervious surfaces determine runoff rates, and are subject to local building conventions. Current building practices were initially determined by combining GIS analysis of the landscape with aerial photo-interpretation of typical development conventions within the various zoning density districts. These photos have enough resolution to identify key features associated with each land-cover attribute, including the foot-print of the primary and secondary structures on the site, impervious surfaces (e.g. patios, driveway, etc), semi-impervious surfaces (e.g. unpaved driveways), lawns, and forests. Each specific feature can be easily identified and measured with online spatial tools. This initial assessment of aerial photos was validated by field visits to a representative sample of sites for each zoning class. For each zoning district, a site visit was made to four development parcels representative of district-wide development patterns. Lots were selected from developments constructed after 1980, to correspond to practices most likely to be used in future development. Sampled lots were identified on tax parcel maps and cross-referenced with satellite images to determine if they fit a particular zoning district's "average" building lot. Fieldwork was performed to establish the typical building lot configuration for that zoning type. Landscape and building features identified by these analyses were mapped to the standard land cover categories used as inputs in the *curve number* calculation.

II.f **Low Impact Development (LID) Model**

Low Impact Development (LID) increases infiltration and storage of water from development, decreasing runoff to more closely approximate the natural, pre-development hydrology of a site (Dietzl, 2007). LID methods benefit communities by dispersing stormwater runoff on-site, rather than concentrating and transferring it downstream. At both the parcel and watershed scale, these methods reduce both the volume of run-off and contamination to receiving waters from non-point source pollution. LID methods promote the recharge of groundwater supplies and, in certain instances, can obviate the need for conventional stormwater systems. These methods can lower the one-time costs incurred during construction, as well as the costs of on-going operation and maintenance.

In order to study the capacity of runoff reduction methods for mitigating impacts of climate change and population growth, results from the standard build-out were modified by applying LID principles. Run-off and *peak flow* were compared for scenarios of build-out with, and without, the application of LID techniques. The difference between the number of undersized culverts with and without LID was used as an indicator of the efficacy of LID methods. LID is not a monolithic proscription, but rather a combination of techniques deployed according to site conditions and the judgment of the designer. Generally, these techniques fall within two groups. The first applies LID methods during construction, and may include:

- Minimizing disturbed areas;
- Maintaining natural buffers;
- Minimizing impervious cover;
- Disconnecting impervious cover from the stormwater drainage system;
- Minimizing soil compaction;
- Using alternative pavement;

The second LID approach utilizes what are called structural LID techniques. These are landscape features or devices constructed to allow water to infiltrate soil, be filtered by soil and plants, and be stored and treated on-site. Examples include:

- Rain gardens (bioretention);
- Gravel wetlands;
- Porous pavements;
- Tree filters;
- Vegetated swales (for curbless roads);

LID construction and structural methods increase effective water infiltration, also known as site recharge volume. The impact of LID methods can be estimated from the following formula:

$$Re_v = [(S)(R_v)(A)]/12$$

where:
Re_v = Site recharge volume
$Rv = 0.05 + 0.009(I)$, where I is percentage of impervious cover
A = site area in acres
S = soil-specific recharge factor

With unlimited financial resources, the application of LID methods can theoretically make a building lot effectively run-off free. However, the set of LID regulations likely to be enacted by towns in the study site will be constrained by resource limitations and political realities. The goal for the present study was to assume a set of LID techniques with a realistic expectation of adoption within the economic and political constraints of the community (Dietzl, 2007). Based on the study team's knowledge of the community, it was decided that reasonably adoptable regulations would implement structural LID methods that maintained, on-site, one inch of precipitation. For the different sized parcels specified by zoning districts, a set of LID practices was created that achieved this standard. The impact of these practices on the *CN* value for each catchment was computed and served as an input to the precipitation-runoff model.

II.g Cost Model

For culverts under-sized for the various climate change and build-out scenarios, the goal of this analysis was to determine the cost of removing the existing culvert and replacing it with one that is adequately-sized. Quantities of materials required for each upgrade were calculated based on field data that established existing culvert type, cross-sectional area, length, elevation below the road, and road and shoulder dimensions.

Costs for culvert removal and replacement were calculated based on guidelines for culvert replacement from the Durham, NH Department of Public Works (Cedarholm, 2009), as well as New Hampshire standards (NHDPWH, 1996). Cost categories included labor, equipment, and materials. Labor included both the hourly base rate and overhead. Costs were calculated for excavation and removal of the existing culvert, as well as replacement of the culvert, fill, and road surface.

Costing results are intended to be indicative, and for planning purposes only. More accurate estimates sufficient to support capital budgeting would require a formal engineering design process for each culvert, beyond the scope of this study. To maximize the accuracy of results, costs were estimated only for tasks and components with a high degree of predictability. Therefore estimated replacement costs likely understate actual replacement costs. Excluded were costs for engineering design, excavation of the stream course, bank stabilization that may be incurred from culvert enlargement, and headwall demolition and replacement.

The primary source for construction material and labor costs was the 2009 National Construction Estimator - 57th edition program (Ogershok and Pray, 2009). These data were modified as appropriate using 2008 average bid costs provided by the New Hampshire Department of Transportation (NHDPWH, 1996). A list of culvert material costs was also developed from regional manufacturers.

III. Results

III.a Runoff/Peak-flow Model

Available data for downtown Durham topography and hydrology was insufficient for reliable modeling of runoff and *peak flow*. As a result, culverts in this area were excluded from this study. A initial GIS-based assessment identified 85 road-stream crossings as potential culvert locations, for which runoff and *peak flow* were modeled. Fieldwork verified the presence of culverts at 81 of the initially identified locations.

By catchment, Figure III.a.1 summarizes the distribution of catchment size and the percentage of buildable area. Buildable area is land that is not subject to conservation easements, wetlands buffers, or similar restrictions. Two-thirds of catchments are under 500 acres, 85% percent are under 1,500 acres. On average, 67% of land area of individual catchments is buildable, however 52 (61%) catchments have over 67% of land area buildable, and 9 (11%) catchments had less than 33% of land area buildable. These latter are predominantly on Pettee Brook.

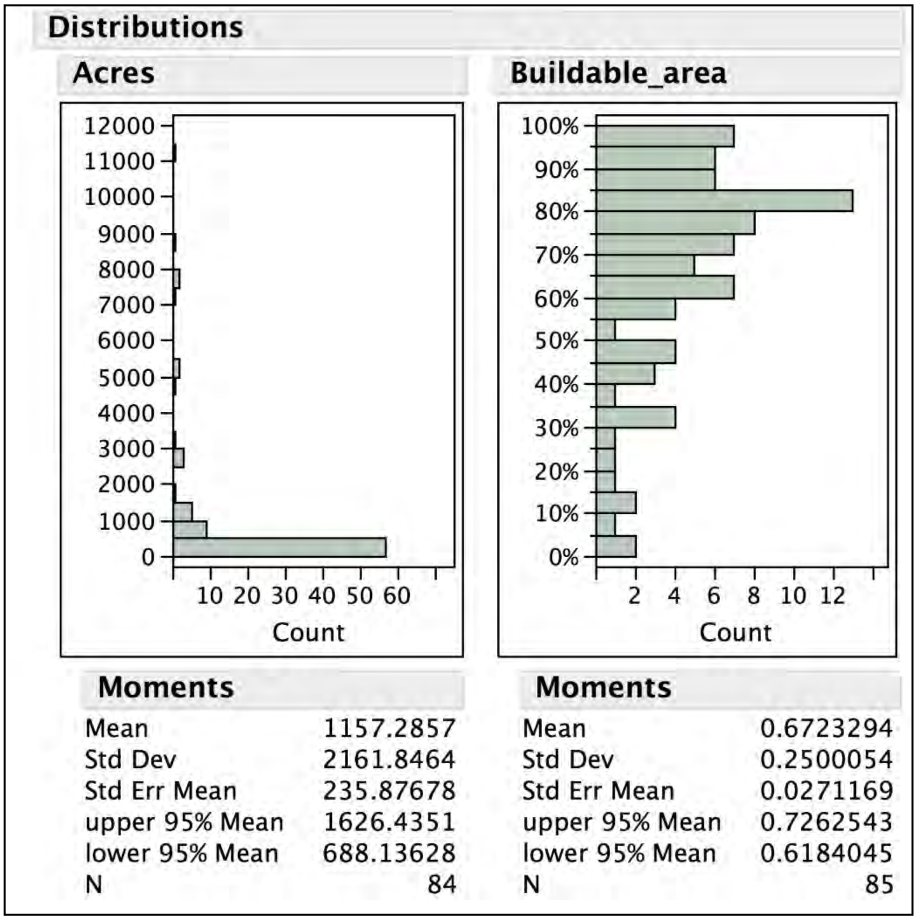

Figure III.a.1 *Histograms of catchment size and percentage buildable area for each catchment*

Most culverts in the study site do not drain directly to the Great Bay Estuary. Rather, they drain into the catchment that is immediately below. This creates a nested hierarchy of catchments and associated culverts, grouped in Figure III.a.2 by color. For each nested group, culverts lower on the drainage convey the sum of runoff from all catchments above, so that a given culvert would be larger than culverts higher in the drainage topography.

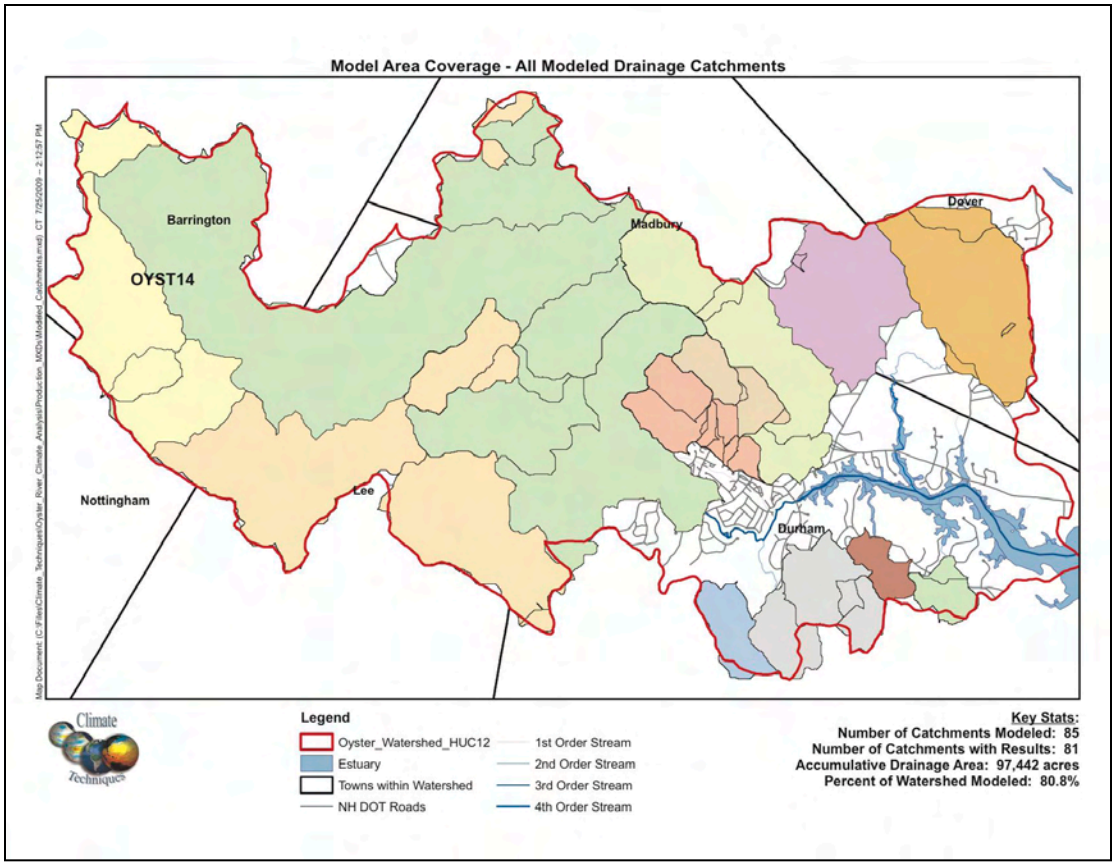

Figure III.a.2 *The hierarchy of nested catchments*

Figure III.a.3 summarizes catchment elevation and slope from Digital Elevation Model(DEM) data. Average catchment elevation was 144 feet. The maximum within-catchment elevation averaged 234 feet. Average catchment slope was 4.4%, and the average maximum slope was 29.4%.

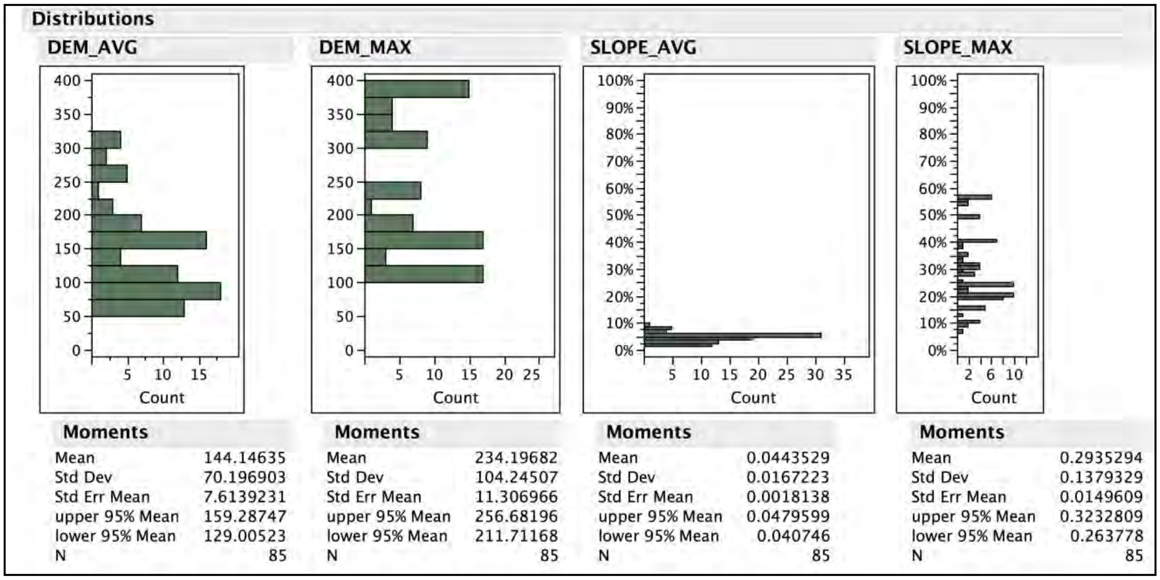

Figure III.a.3 *Summary of elevation and slope for modeled catchments.*

Among the four soil categories used in the *Curve Number* computation, Hydrological Soil Group "C" predominates in Oyster River catchments (Figure III.a.4). Group "C" soils are sandy clay loam, with infiltration rates of 0.05-0.15 inches per hour. Some catchments also have significant Group "A" or "B" soils, with higher hourly infiltration rates of >0.30, and 0.15-0.30 inches, respectively.

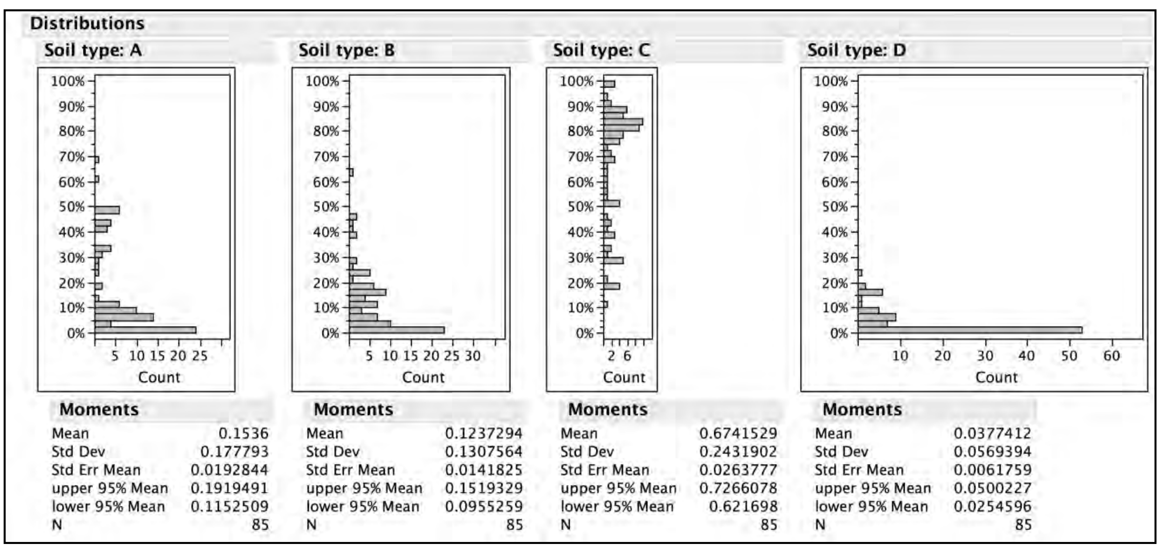

Figure III.a.4 *Distribution of the four NRCS Hydrological Soil Groups*

Additional physical characteristics pertinent to the catchment *peak flow* computation are summarized in Figure III.a.5. Most catchments are between ~3,700 and ~5,700 feet wide (mean = ~4,700 ft), have main drainage channels between ~7,400 and ~10,800 feet long (mean = ~9,100 ft), and have computed t_c values between ~18 and ~25 hours (mean = ~21 hours).

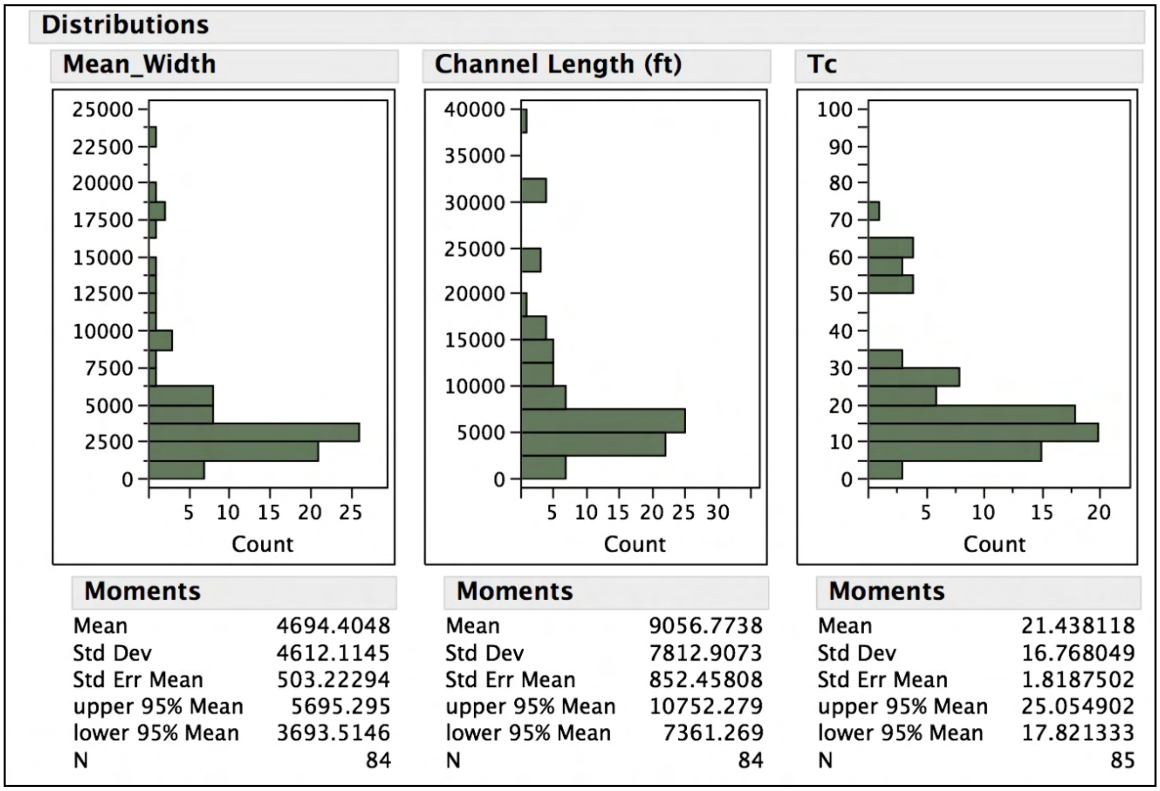

Figure III.a.5 *Distribution, across catchments, of three physical features important to runoff and peak flow estimation*

The relationship between catchment size and *time of concentration* is not linear (Figure III.a.6). As the size of catchments increases, the rate of increase in t_c slows. *Times of concentration* for catchments under 2,000 acres are predominantly under 30 hours.

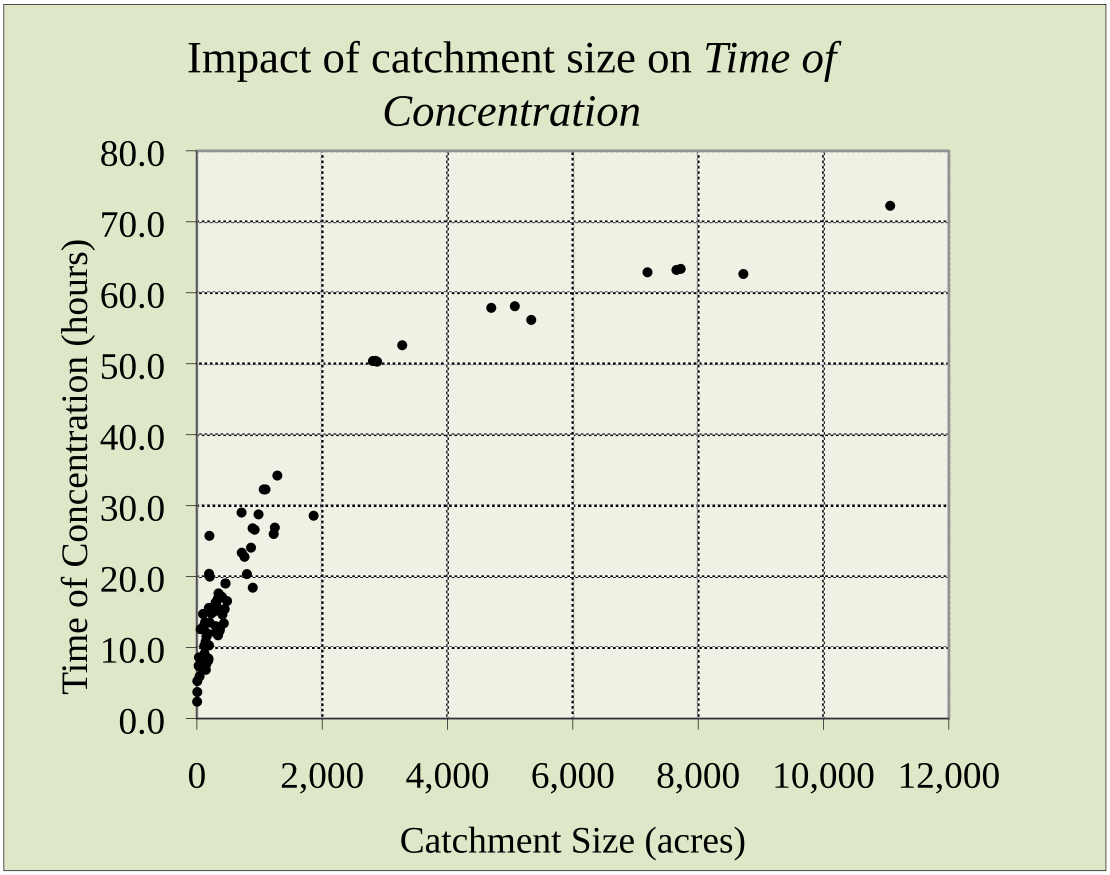

Figure III.a.6 *Relationship between catchment acreage and time of concentration*

The distribution of *Curve Numbers* for all modeled catchments is presented in Figure III.a.7 for the current land-use scenario, i.e. no build-out or LID. Most catchments (95% confidence interval) have a mean *CN* value between 65.8 and 68.9, although individual polygons within catchments may have *CN* values as low as 30, or as high as 95.

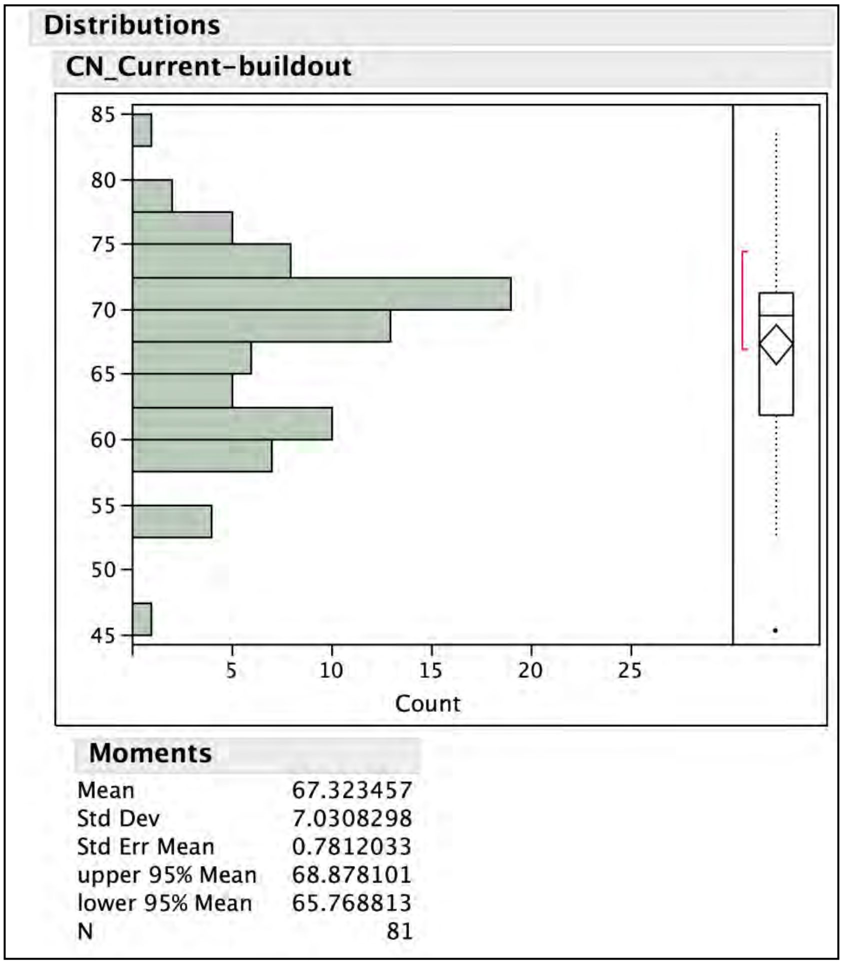

Figure III.a.7 *The distribution of catchment-average Curve Numbers*

III.b **Precipitation Model**

Results of precipitation modeling for the study site, for the baseline (1971-2000) and climate-changed (2046-2075) periods are presented in table III.b.1.

Table III.b.1 *For the study site, estimated 4% probability (25-year return period), 24-hour precipitation for recent and climate-changed scenarios, at mid-21st century, and elation to the TP-40 25-year, 24-hour precipitation*

	25-year, 24-hour precipitation (in.)				Percentage increase over TP-40		
	TP-40	1971-2000 (Baseline)	2046-2075 A1b	2046-2075 A1fi	1971-2000 (Baseline)	2046-2075 A1b	2046-2075 A1fi
+95% c.i.		7.46	9.53	12.22	46%	87%	140%
"most likely"	5.1	5.37	6.86	8.35	5%	35%	64%
-95% c.i.		3.85	4.92	5.66	-25%	-4%	11%

Figure III.b.1 shows the change in the intensity/return-period, modeled for the recent-past (1971-2000), and the two mid-21st century climate change scenarios, for return periods from one to one-thousand years. Slope increases for the climate change scenarios, consistent with previous research (Hennessy et al., 1997; Groisman et al., 1999). The extent to which an extreme storm will occur more frequently due to climate change can be determined as follows: For the return period of interest, move vertically from the *x* axis to the intersection with the black "recent historical" line. Note the precipitation amount. Move horizontally to the left to intersect with the line for the climate change scenario of interest. Move vertically downward to determine the estimated mid-21st century return period. Following this procedure, this graph shows that what recently had been the 25-year event is projected to be a new 5-year event at the upper-95% confidence limit for the A1fi scenario, and what had been the 250-year event is projected to be the new 25-year event.

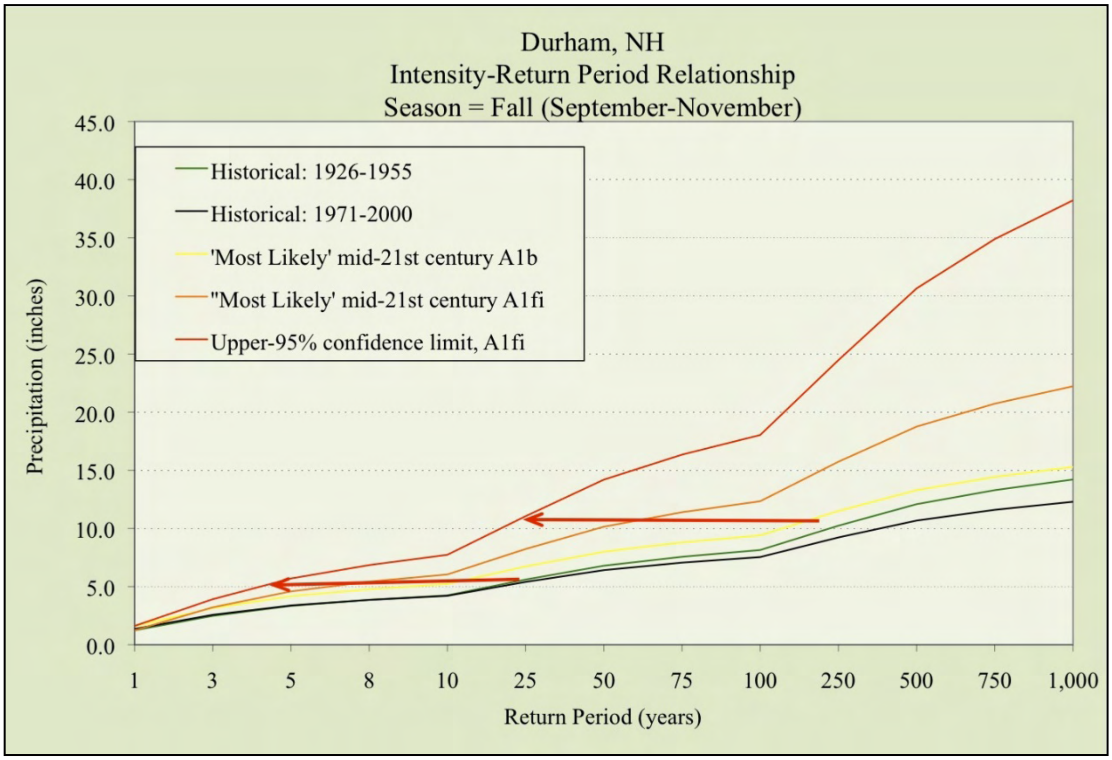

Figure III.b.1 *Estimated change in the intensity/return-period relationship due to climate change*

III.c **<u>Culvert Model</u>**

To establish the capacity of existing culverts, specifications obtained from fieldwork and standard civil engineering culvert modeling methods were used to reverse-engineer each culvert. These methods were also used to estimate the required capacity for the climate change and build-out scenarios. Of the 85 catchments with sufficient data for modeling runoff, we were able to model 81 culverts. Culverts in downtown Durham were not modeled due to the lack of elevation data with sufficient resolution for reliably routing runoff to an individual culvert. The drainage area represented by the 81 modeled culverts was approximately 16,000 acres, corresponding to 81% of the watershed.

Figure III.c.1 shows the location of culverts undersized for the mid-21st century climate-changed scenarios, with current land-use. Land use is current development, that is with no build-out. Circle quadrants indicate under-sized conditions for each season, for each emissions scenario, per the legend.

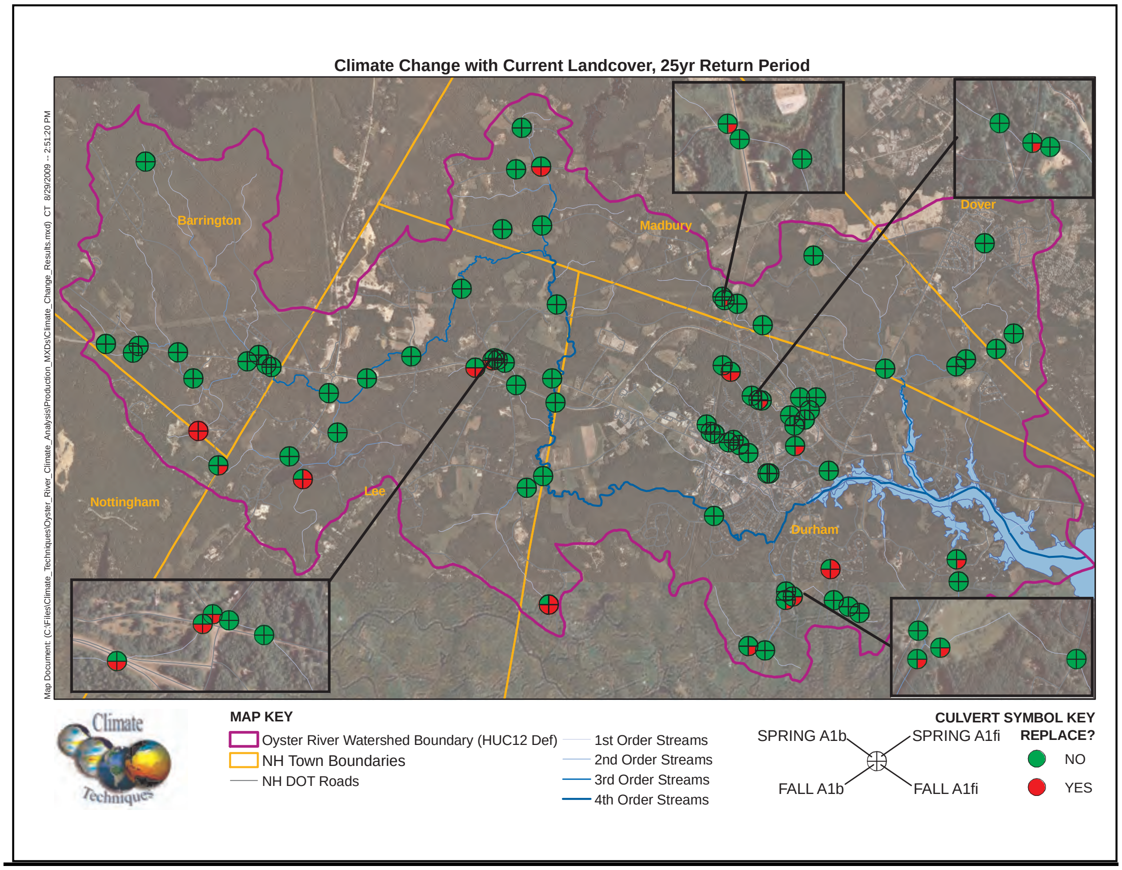

Figure III.c.1 *The location of culverts projected to be undersized due to climate, with no impact from population growth*

Table III.c.1 summarizes several characteristics of culverts in the study site. 56% of culverts are concrete, 35% are steel or aluminum, and 5% are plastic. The high rate of concrete culverts will complicate efforts to adapt to climate change and population growth during routine culvert replacement, because the relatively longer service life for concrete pipe (typical service life of 65 years versus 50 years for medium-gauge galvanized pipe) means that adaptation of these pipes will need to occur prior to expiration of service life.

Culverts modeled as undersized are located almost exclusively under either rural roads or trails, rather than major thoroughfares. These locations likely lower the risk for the community, as washouts would likely cause less damage and less disruption, than washouts of more important arteries for the operation and commerce of the community.

The rate of undersized culverts varies by town. For modeled culverts, Durham and Lee were projected to have rates of undersized culverts of 28% and 29%, respectively, while Barrington and Madbury have undersized rates of only 13% and 17%, respectively.

Table III.c.1 *Selected culvert characteristics*

Material	Count	% of total	undersized	%_undersized
Alum_Corr	2	3%	2	100%
Concrete	44	56%	7	16%
Plastic	4	5%	1	25%
Steel_Corr	25	32%	6	24%
Stone	3	4%	2	67%
Total	78	100%	18	
Road_Type	**Count**	**% of total**	**undersized**	**%_undersized**
City	2	3%	0	0%
Hwy	18	25%	1	6%
Railroad	3	4%	0	0%
Rural	43	60%	13	30%
Trail	6	8%	3	50%
Total	72	100%	17	
Town	**Count**	**% of total**	**undersized**	**%_undersized**
Barrington	8	10%	1	13%
Dover	4	5%	0	0%
Durham	36	46%	10	28%
Lee	17	22%	5	29%
Madbury	12	15%	2	17%
Nottingham	1	1%	1	100%
Total	78	100%	19	

Culverts are undersized if the actual cross-sectional area of the culvert currently in place is less than the cross-sectional area modeled for a given scenario. This relationship can be concisely summarized by the ratio of these two values, designated in this study as the current-to-model (C/M) ratio. The size of this ratio indicates a culvert's adequacy for conveying *peak flow* for a given scenario: if the C/M ratio is less than one, the current cross-section is less than the required cross-section, and the culvert is considered undersized. The extent to which a ratio is less than, or greater than, one provides information on the extent of vulnerability.

Table III.c.2 shows the C/M ratio for the eight precipitation/build-out scenarios (in coulmns), for two subsets of culverts in the study site. The upper subset are culverts with the smallest ratios of current-to-*TP-40* cross-sectional area (C/$M_{TP\text{-}40}$, column 1), i.e. those either already undersized or most likely to become undersized. The lower subset are culverts with the largest C/$M_{TP\text{-}40}$ ratios, i.e. those least likely to become undersized. Pink shading highlights C/M ratios less than one, indicating an undersized condition.

Table III.c.2 *Ratios of current-to-model cross sectional area for the most, and least, vulnerable culverts in the watershed*

	Column:	1	2	3	4	5	6	7	8	9
Precipitation Scenario:		*TP-40*	Fall_Baseline	Fall_A1b	Fall_A1b	Fall_A1b	Fall_A1fi	Fall_A1fi	Fall_A1fi	Fall_A1fi
Land-use scenario:		Current	Current	Current	LID	Build-out	Current	LID	Build-out	Build-out
Culvert ID	Current Cross-sectional area (ft^2)	"Most likely"	"Most likely"	"Most likely"	"Most likely"	"Most likely"	"Most likely"	"Most likely"	"Most likely"	+95% confidence limit
Culverts undersized for any of the climate change or build-out scenarios:										
UNKN10	0.79	0.5	0.5	0.3	0.3	0.2	0.3	0.3	0.2	0.1
UNKN29	1.77	0.6	0.6	0.4	0.4	0.2	0.3	0.3	0.2	0.1
CHES01	0.79	0.7	0.7	0.5	0.3	0.5	0.3	0.3	0.3	0.2
UNKN42	1.77	0.8	0.8	0.6	0.6	0.4	0.4	0.4	0.4	0.2
LITT104	1.77	1.0	1.0	0.6	0.6	0.4	0.4	0.4	0.4	0.3
OYST01	1.77	1.0	1.0	0.7	0.6	0.6	0.6	0.6	0.4	0.3
UNKN32	3.14	1.0	1.0	0.7	0.7	0.6	0.6	0.6	0.5	0.4
UNKN34	3.14	1.0	1.0	0.7	0.7	0.7	0.6	0.5	0.6	0.4
BEAR100	3.14	1.3	1.3	0.7	1.0	0.7	0.6	0.7	0.6	0.4
BEAU100	2.84	1.7	1.7	1.0	0.9	0.9	0.7	0.6	0.6	0.4
LITT101	2.20	1.8	1.8	1.1	0.9	0.7	0.9	0.7	0.5	0.3
UNKN41	3.14	1.8	1.8	1.3	0.4	0.3	0.9	0.3	0.2	0.2
LITT100	3.14	1.8	1.8	1.2	1.0	0.7	0.9	0.7	0.6	0.4
BEAR08	6.28	2.1	2.0	1.4	1.3	0.9	0.9	0.9	0.7	0.5
UNKN26	6.61	1.4	1.4	1.0	1.0	1.0	0.7	0.9	0.9	0.6
LONG02	8.00	1.7	1.6	1.0	1.1	1.1	0.7	0.9	0.9	0.6
OYST102	3.14	1.8	1.3	1.0	1.0	1.0	0.9	0.7	0.7	0.5
HAME04	6.48	2.1	2.1	1.4	1.4	1.0	1.0	1.0	0.9	0.7
UNKN21	8.80	2.8	1.9	1.3	1.8	1.2	1.0	1.2	0.9	0.6
HAME03	3.14	1.8	1.8	1.0	1.0	1.0	1.0	1.0	1.0	0.6
OYST101	3.14	1.8	1.8	1.0	1.0	1.0	1.0	1.0	1.0	0.6
HAME100	9.05	2.0	2.0	1.4	1.4	1.4	1.3	1.3	1.3	0.8
OYST103	0.79	2.2	2.2	1.4	1.4	1.4	1.0	1.0	1.0	0.7
UNKN22	7.07	2.3	2.3	1.5	1.5	1.1	1.1	1.1	1.0	0.6
UNKN27	9.08	3.0	3.0	2.0	2.0	2.0	1.4	1.4	1.4	0.9
LITT102	7.07	3.0	3.0	2.2	2.2	1.1	1.5	1.5	1.0	0.6
UNKN39	1.77	3.2	3.2	2.2	1.5	1.0	1.5	1.0	1.0	0.7
BEAR02	9.42	4.0	4.0	2.7	2.1	1.9	1.9	2.1	1.4	0.9
The ten largest culverts:										
OYST07	96.0	31.4	30.6	18.0	14.5	14.5	12.0	10.9	10.9	7.6
OYST03	96.1	31.4	31.4	21.0	14.5	14.5	14.5	13.6	10.9	6.4
OYST14	60.8	35.4	35.4	23.1	8.6	9.2	17.8	6.3	8.6	4.8
JOHN09	64.8	37.7	36.7	25.8	21.2	6.7	19.4	14.1	5.2	6.7
OYST10	106.7	45.3	45.3	34.0	16.1	34.0	23.3	12.1	23.3	12.1
OYST08	254.5	55.5	51.8	36.0	36.0	21.5	26.4	26.4	17.0	10.7
OYST05	126.0	53.5	53.5	40.1	27.5	25.7	27.5	19.0	19.0	10.7
OYST06	150.0	84.9	63.7	49.1	32.7	30.6	32.7	30.6	22.6	15.6
OYST11	125.7	104.3	73.1	53.3	27.4	27.4	41.1	25.6	18.9	13.1
OYST16	176.0	102.4	102.4	74.7	26.5	18.3	56.0	24.9	14.9	9.6
LITT106	200.0	116.4	116.4	84.9	65.5	84.9	65.5	43.7	65.5	40.7

Table III.c.2 facilitates comparing results across scenarios on a culvert-by-culvert basis, and highlights information that otherwise may not be readily apparent. For example:

- Culverts that share a C/$M_{TP\text{-}40}$ ratio may not share a ratio under a climate-change or build-out scenario. For example, consider the six culverts with a C/$M_{TP\text{-}40}$ ratio of 1.8

(column 1): under any of the climate-change or build-out scenarios (columns 3 through 9), the C/M ratio varies from culvert to culvert. It is apparent that differences under a build-out scenario would likely result from variation in development between catchments, for example as might result from variations in zoning or buildable land. Variations under the climate-change scenarios have perhaps less obvious causes, though these would be expected to result from hydrological characteristics causing different runoff rates.

That existing culverts which share the same capacity under *TP-40* may not share the same capacity under increased *peak flows* from climate change or build-out, has implications for adaptation planning. Current capacity may not be a reliable predictor of future performance, so that future upgrade sizes are best determined on a culvert-by-culvert basis;

- For the largest culverts in the study site, listed under the second group of culverts, $C/M_{TP\text{-}40}$ ratios are very large (column 1). For example, OYST07 has a current cross-section that is 31.4 times larger than required under *TP-40*, and the current cross-section for LITT106 is 116.4 times larger than required under *TP-40*. Culverts in this group do not become undersized even at the upper-95% confidence limit of the A1fi-plus-build-out scenario (column 9). That these culverts are currently sized so much larger than the *TP-40* specification to which one would expect them to have been designed, indicates that other factors likely influenced culvert design. An example of a design being driven by other factors than *peak flow* is culvert OYST16. This box culvert is located in a wetland complex, with about 1/3rd of its cross-section submerged even under low-flow conditions;

- For culverts that are undersized when the study site is built-out (columns 5 and 8), the C/M ratio generally varies by a factor of only 0.1 to 0.2 between the A1b and A1fi scenarios. This is one of several results in this study indicating that uncertainty in climate model output is not a significant impediment to climate change adaptation;

- To determine the $C/M_{TP\text{-}40}$ ratio above which no culverts become undersized under any of the climate change and build-out scenarios, even the extreme A1fi upper-95% confidence limit, a linear regression was performed of the $C/M_{TP\text{-}40}$ ratio on the percentage increase in the design storm. Results are shown in Figure III.c.2, with individual culverts plotted as black points. Percentages of increase in the 25-year *TP-40* event are plotted on the *x* axis, and the $C/M_{TP\text{-}40}$ ratio is plotted on the *y* axis. As one moves to the right along the *x* axis, the percentage increase in design storm required to make the culvert undersized rises. Points at 0% on the *x* axis are culverts that are undersized even for the *TP-40* event. Points to the furthest right of the *x* axis, at the "∞" vertice, are culverts that never fail up to a design storm increase of 200%.

  The upward-sloping linear best-fit line intersects the vertical A1fi upper-95% confidence limit at a $C/M_{TP\text{-}40}$ ratio of approximately 3.2. This finding is significant, in that culverts that currently are at least triple the cross-sectional area called for under *TP-40*, i.e. culverts that have a $C/M_{TP\text{-}40}$ ratio greater than or equal to 3.2, should be adequately sized for all 25-year (4%) events modeled, even that from the upper-95% confidence limit of the pessimistic A1fi scenario, and even in a watershed 100% built-out to current zoning regulations.

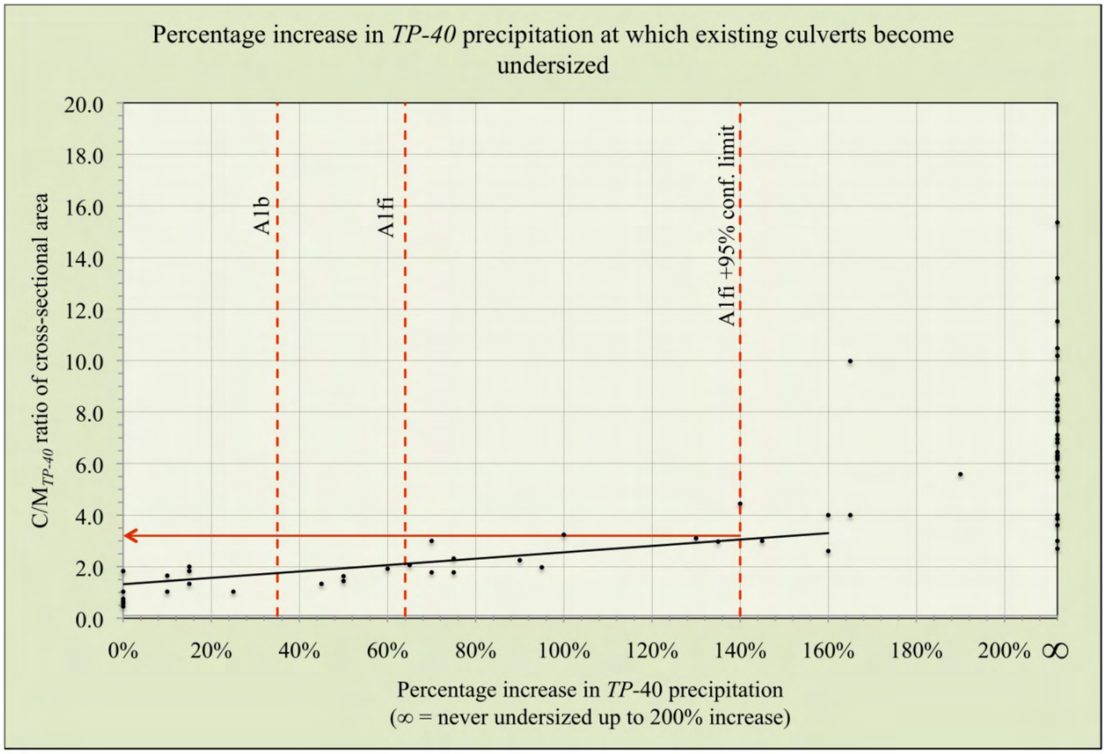

Figure III.c.2 *The percentage increase in precipitation that causes a culvert with a given* $C/M_{TP\text{-}40}$ *ratio to become undersized*

Figure III.c.3 shows the relationship between the number of undersized culverts, and arbitrary increases in the design storm. This is an engineering and hydrological relationship, independent of climate change and build-out. The design storm was increased by arbitrary 0.2" increments.

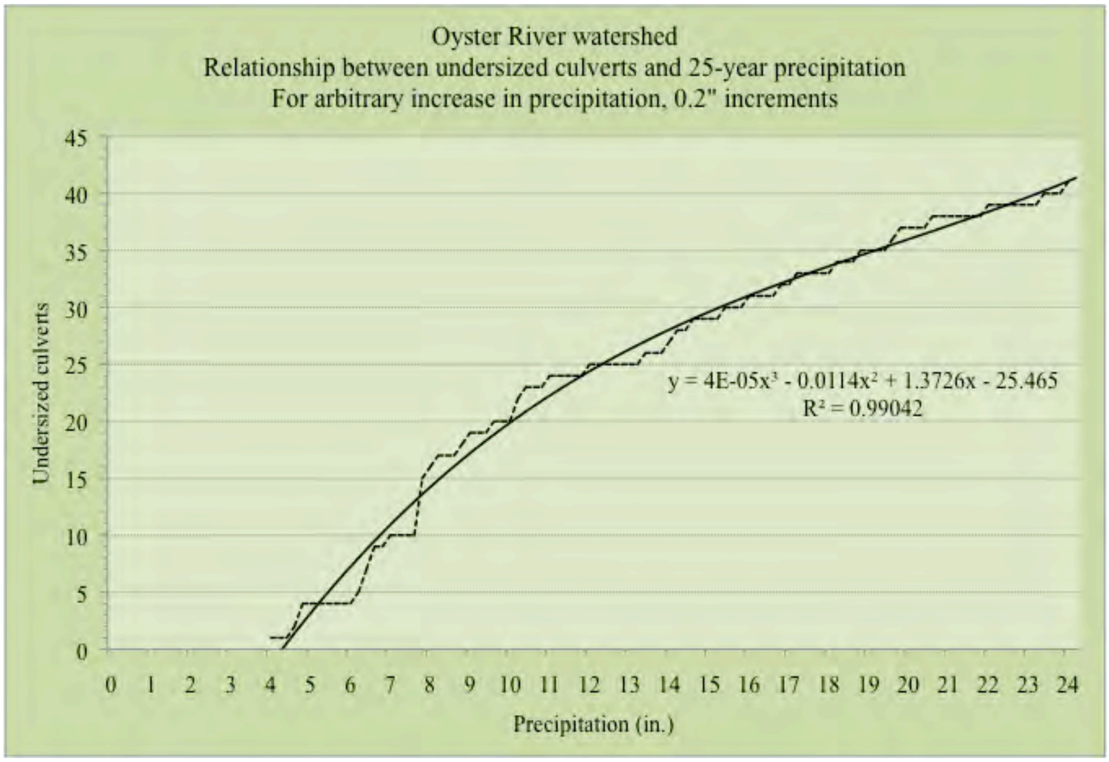

Figure III.c.3 *The relationship between arbitrary increases in the design storm, and the number of undersized culverts*

Figure III.c.4 exhibits the relationship between the percentage of undersized culverts and the percentage increase in the design storm. The design storm is increased by arbitrary 5% increments over the estimated baseline computed for the 1971-2000 period. As with Figure III.c.3, this is an engineering and hydrologic relationship, independent of climate change and build-out.

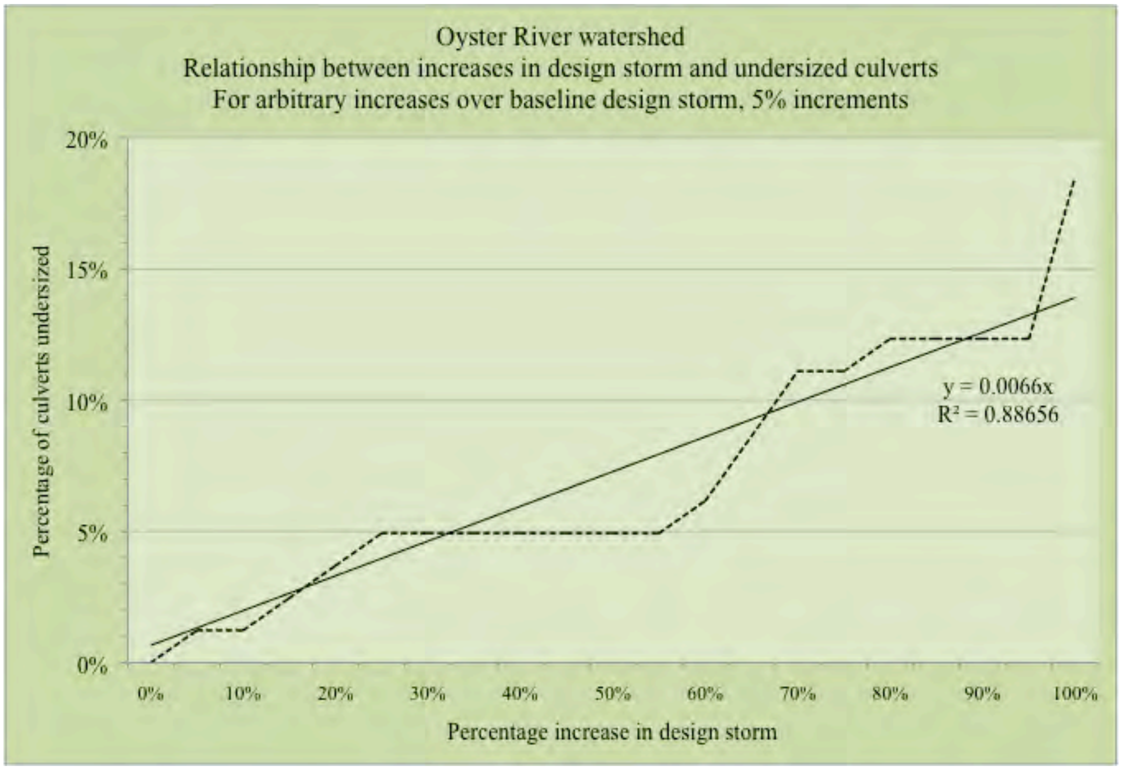

Figure III.c.4 *The relationship between arbitrary percentage increases in the design storm, and the percentage of undersized culverts*

III.d **Build-out Model**

Figure III.d.1 identifies land area in the study site that is buildable. Buildable land area, in conjunction with current zoning regulations (Figure III.d.2), and existing building practices (Figure III.d.3), formed the basis for the build-out analysis of the watershed.

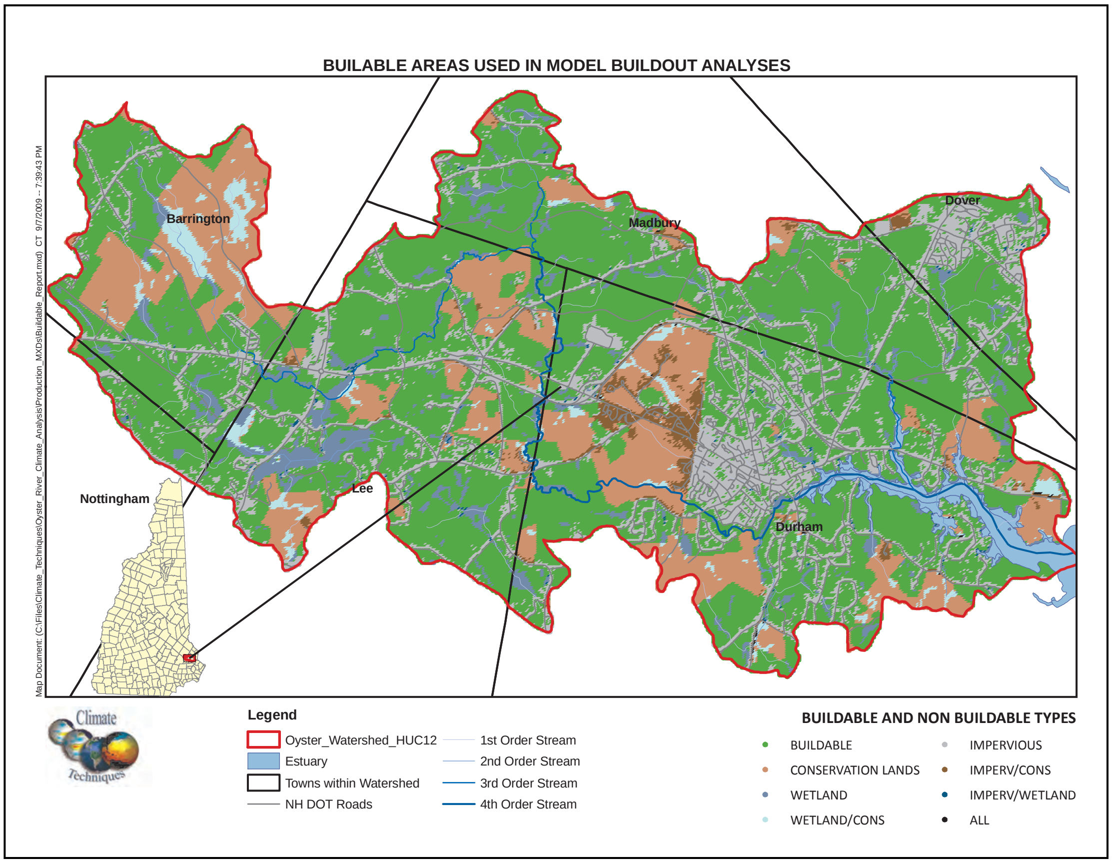

Figure III.d.1 *Buildable, not-buildable, and built land area in the Oyster River watershed*

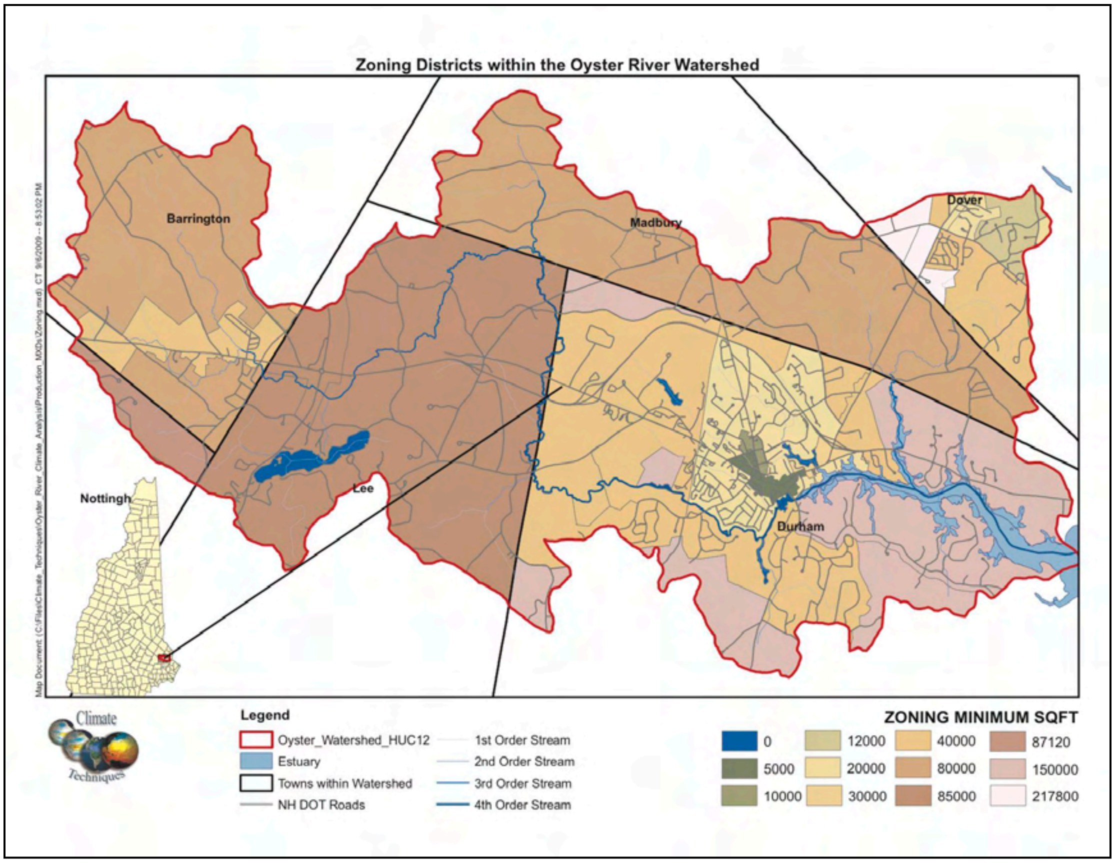

Figure III.d.2 *Zoning Density Districts*

Figure III.d.3 shows a typical breakdown of built-lot land cover rates, for One-Acre Residential "B", and Central Business zoning districts in Durham. Together with similar information for other zoning districts, these rates formed the basis for the build-out model, and for the type and extent of construction changes incorporating LID principles.

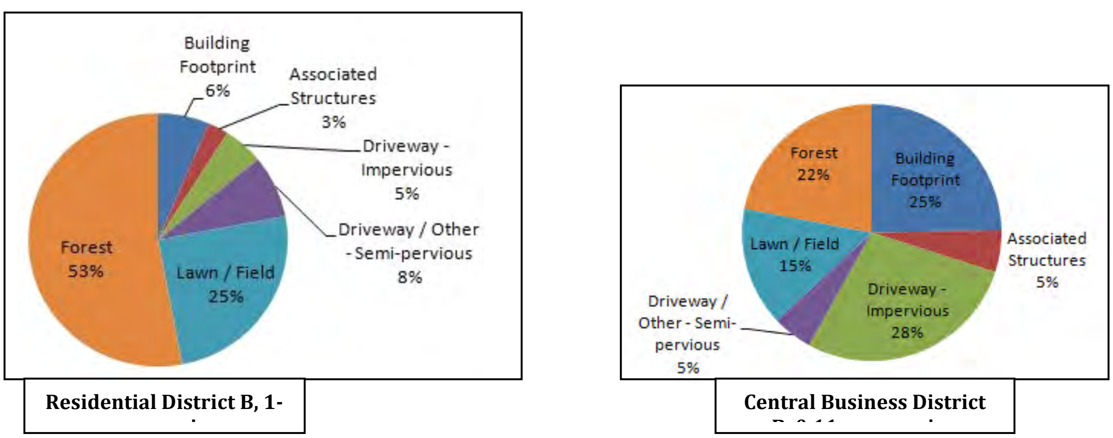

Figure III.d.3 *Typical lot configuration, Durham, NH*

Table III.d.1 shows the rates of residential cover-types for all residential zoning districts in the watershed. These typical lot configurations informed the development conventions for both standard build-out and build-out under LID principles.

Table III.d.1 *Residential structure and cover types, by lot size*

Lot Size		%				
acres	sq. ft. x 000	Structures Footprint	% Field/Grass	% Forest	% Other	Total
0.0	12	27%	60%	5%	8%	100%
0.0	20	17%	34%	40%	10%	100%
0.0	30	15%	31%	47%	8%	100%
0.0	40	9%	25%	53%	13%	100%
0.0	80	10%	29%	50%	12%	100%
0.0	85	10%	20%	60%	10%	100%
0.0	87	11%	18%	56%	15%	100%
0.0	120	8%	14%	66%	12%	100%
0.0	150	5%	22%	68%	5%	100%

III.e **Low Impact Development Model**

Table III.e.1 shows *CN* values modeled under LID assumptions for different lot sizes and soil types.

Table III.e.1 *Estimated Run-off Coefficients With LID*

	Lot size	Curve Numbers by soil group			
Zoning district	(sq. ft, 000)	A	B	C	D
Commercial/business		62	74	83	88
Industrial		62	74	83	87
Residential (acres):					
1/8	5.4	61	74	82	85
1/4	10.9	50	68	78	82
1/3	14.5	48	66	77	82
1/2	21.8	44	63	75	80
1	43.6	43	62	74	80
2	87.1	42	61	74	80
5	212.8	42	61	74	80

The capacity of LID methods to mitigate the impacts of build-out is shown in Figures III.e.1 through III.e.3. Figure III.e.1 shows how the distribution of *curve number* values changes from current land-use, through 100% build-out to current zoning standards, to 100% build-out with the application of achievable LID methods. The mean *CN* value increases from 67.3 to 72.2 with build-out, then declines to 70.0 with the application of LID methods. Note that the standard deviation is smaller under both build-out and build-out-with-LID, as compared with current land use. The variability in building practices across the study site is artificially reduced for the build-out scenarios, due to the imposition of watershed-wide standard build-out and LID assumptions for building, lawn, and driveway footprints. Figures III.e.2 and III.e.3 show how the the spatial distribution of *curve numbers* changes due to the implementation of LID methods.

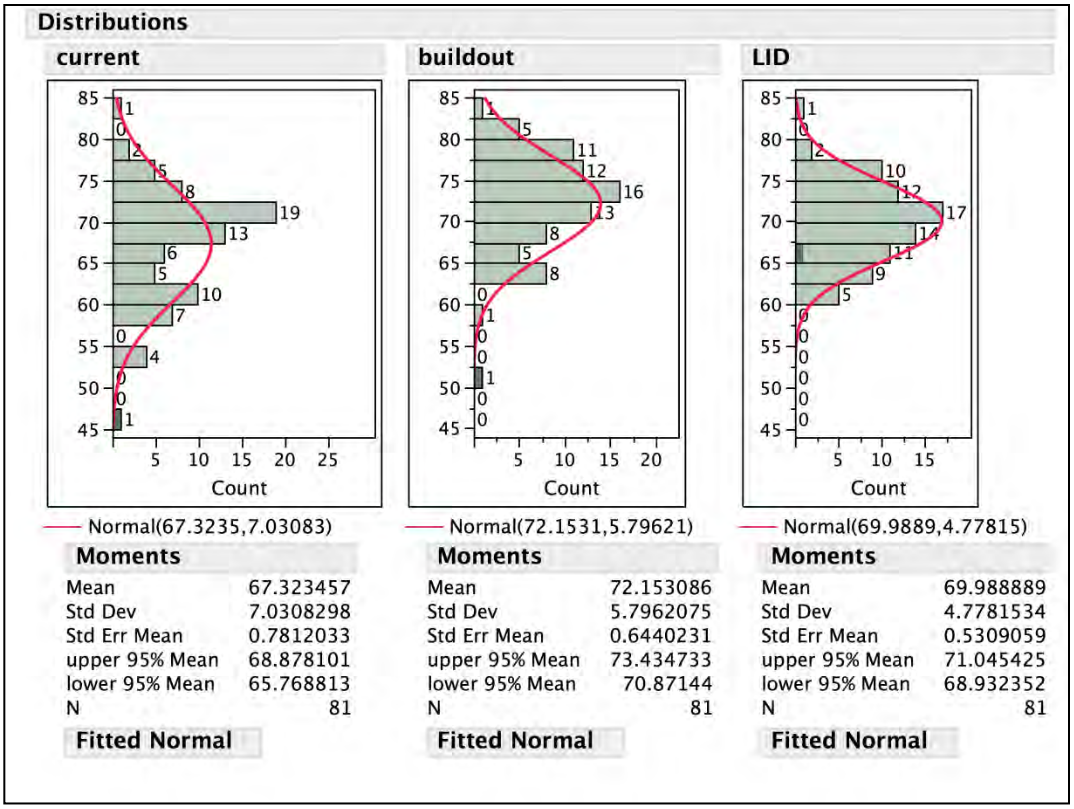

Figure III.e.1 *Impact of build-out and LID on the distribution of curve numbers*

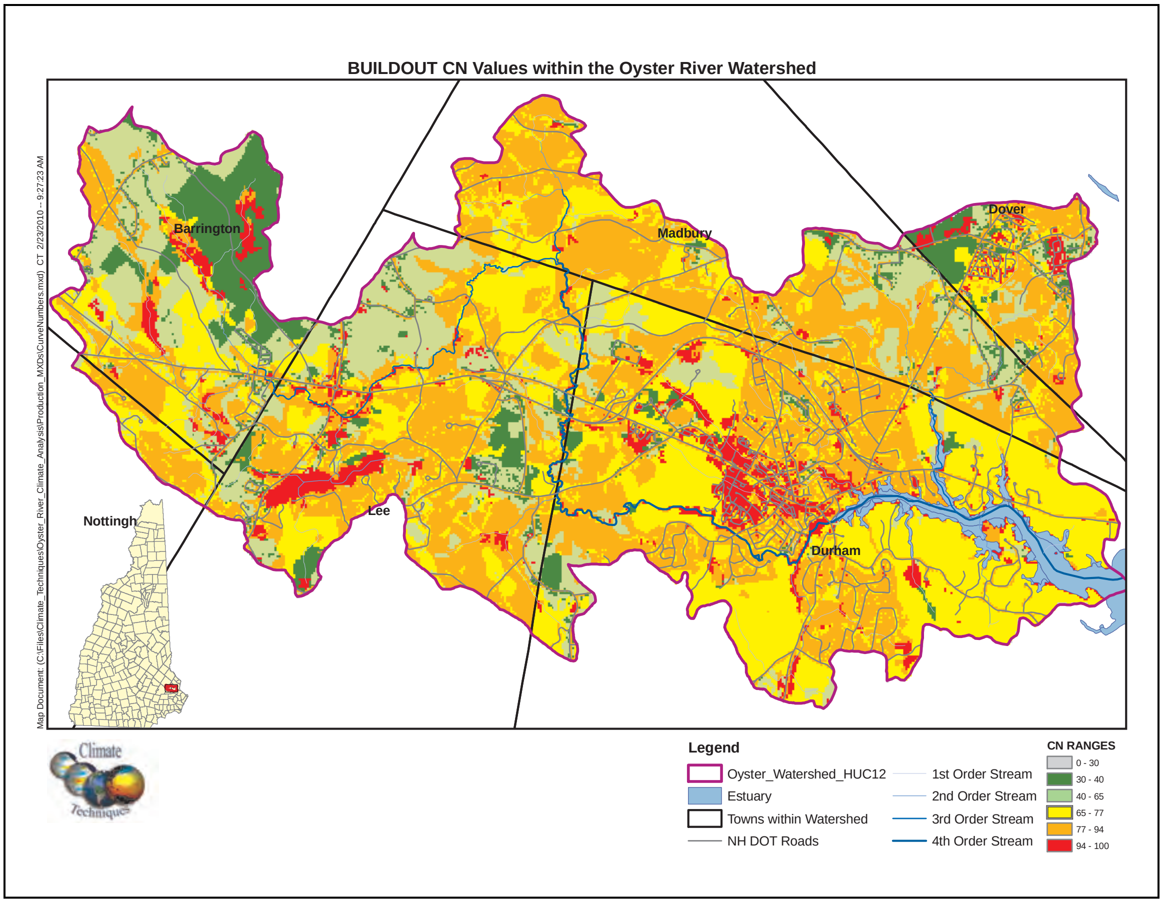

Figure III.f.2 *Spatial distribution of curve numbers at 100% build-out to current zoning standards*

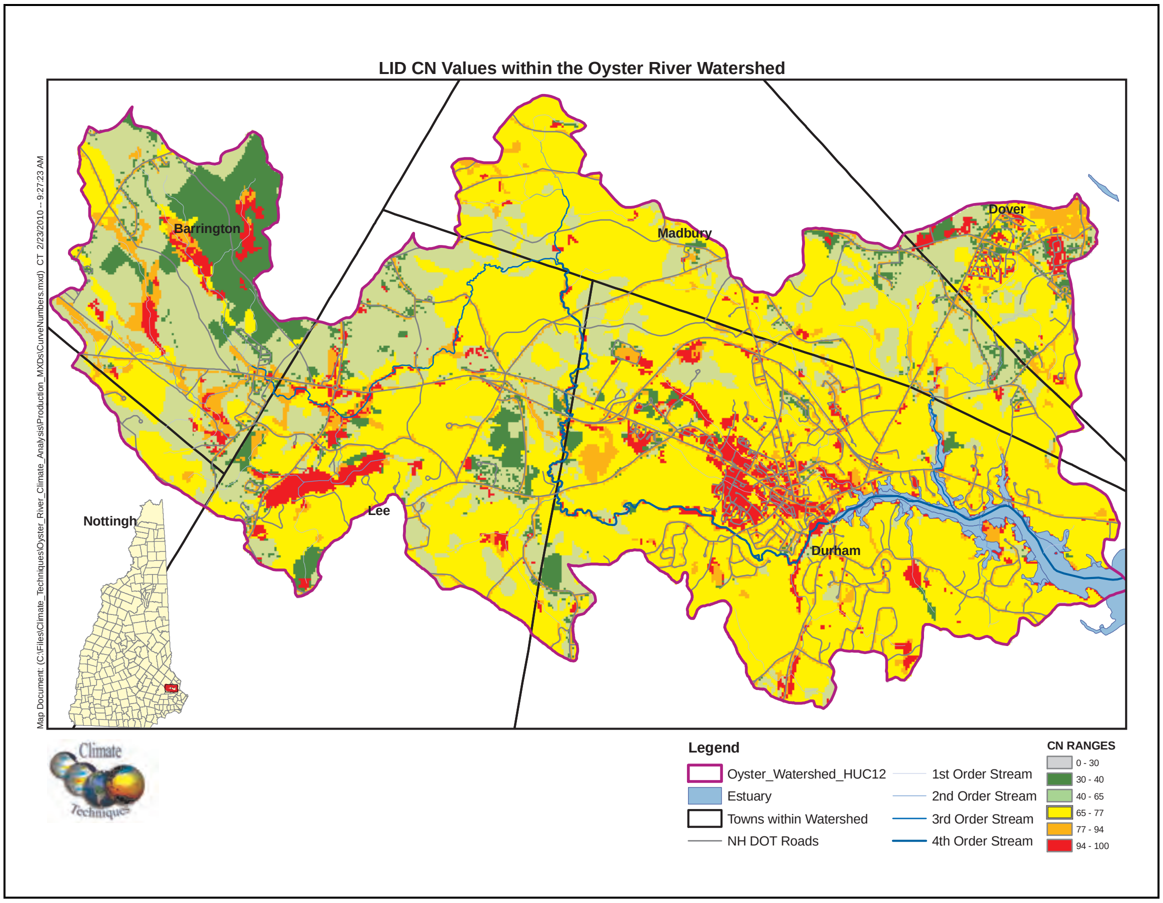

Figure III.e.3 *Spatial distribution of curve numbers under 100% build-out using LID methods*

Table III.e.2 summarizes the impact of realizable LID methods on the rates of undersized culverts, for the various climate change precipitation scenarios, and for normal and wet antecedent moisture conditions. As would be expected, when soils are saturated (or frozen), as given by Type III *antecedent moisture conditions* (AMC III), the efficacy of LID is reduced. However, even for the most pessimistic precipitation projections, the Fall A1fi/AMC-II, A1b/AMC-III, and A1fi/AMCIII conditions, there is still a five to eight percent (5-8%) reduction in projected undersized culverts as a result of LID practices. With the more moderate precipitation increases, the potential benefit of LID methods is greater, ranging from twenty-five to one-hundred percent (25-100%).

Table III.e.2 *Impact of LID scenario on rate of undersized culverts*

		Undersized culverts			
		Buildout scenario			
Scenario		Standard	w/ LID	Difference	% Difference
late-Spring					
	Baseline, AMC II	4	0	4	100%
	A1b, AMC II	4	2	2	50%
	A1fi, AMC II	7	5	2	29%
	A1b, AMC III	10	7	3	30%
	A1fi, AMC III	15	12	3	20%
Fall					
	Baseline, AMC II	8	6	2	25%
	A1b, AMC II	16	12	4	25%
	A1fi, AMC II	19	18	1	5%
	A1b, AMC III	20	19	1	5%
	A1fi, AMC III	25	23	2	8%

III.f <u>Summary Maps of Culvert Capacity Results</u>

This section of the report synthesizes results of the various analyses. Figures III.f.1 through III.f.3 locate adequate and undersized culverts within the watershed. Each figure represents a single land-use scenario. Each culvert is represented by a circle, with quadrants colored according to adequacy for a given season and emissions scenario. Green indicates an adequately-sized condition, red indicates an undersized condition. Results for Spring were modeled and are shown here. However the downscaled 25-year, 24-hour precipitation for Spring was lower than Fall for all climate change scenarios. Because culverts would be designed for the more extreme conditions, generally only Fall results were used for cost modeling.

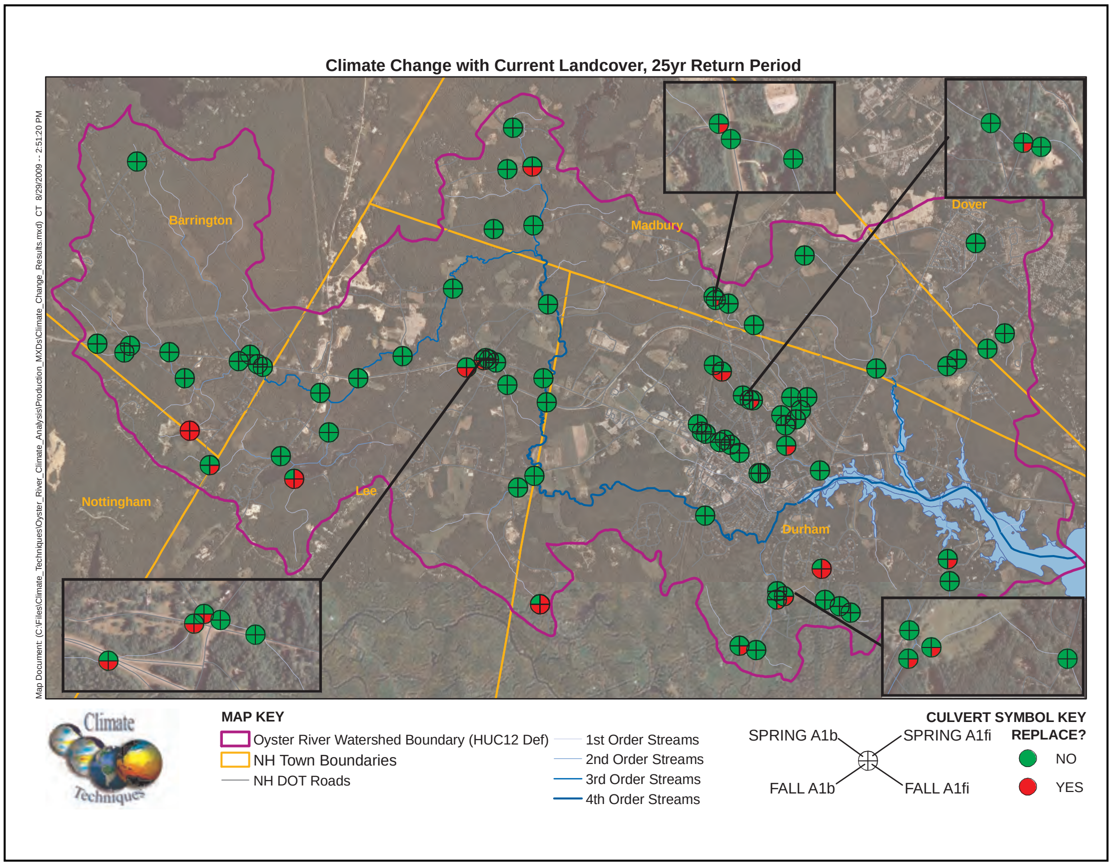

Figure III.f.1 *Spatial display of undersized culverts for current land-use and all climate change scenarios*

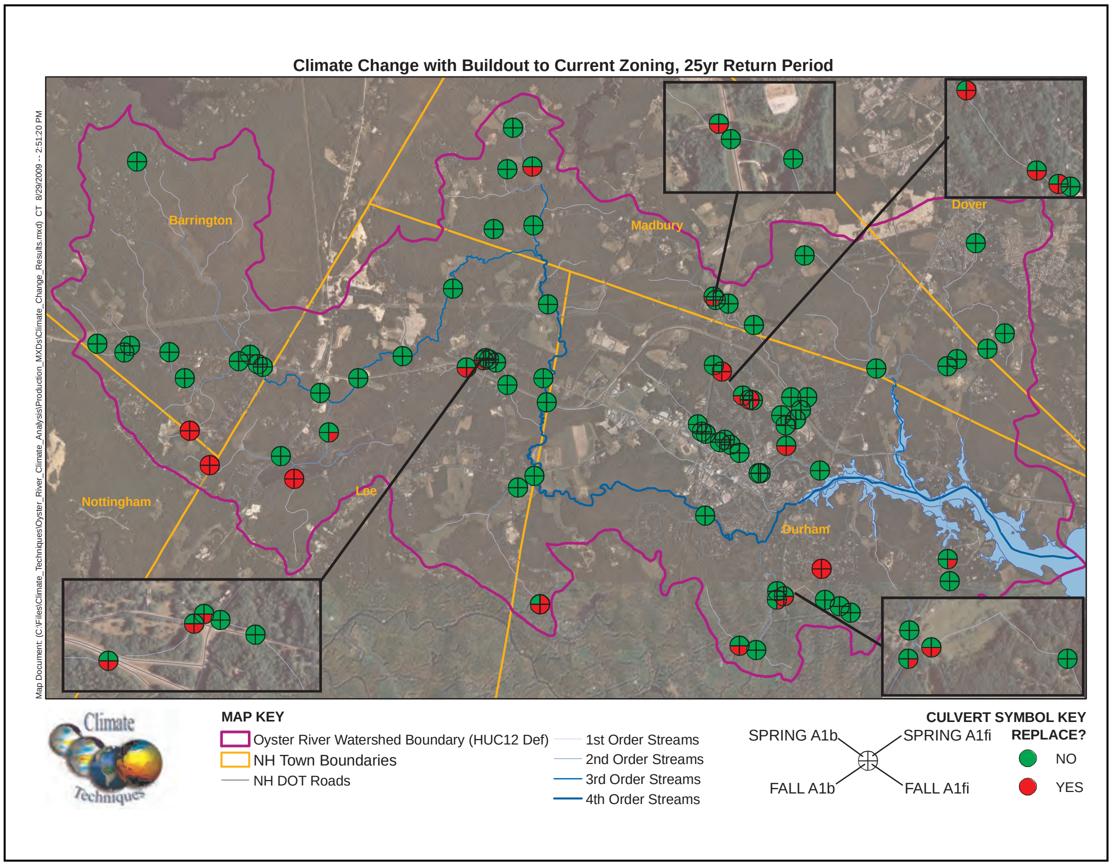

Figure III.f.2 *Spatial display of undersized culverts for build-out, and all climate change scenarios*

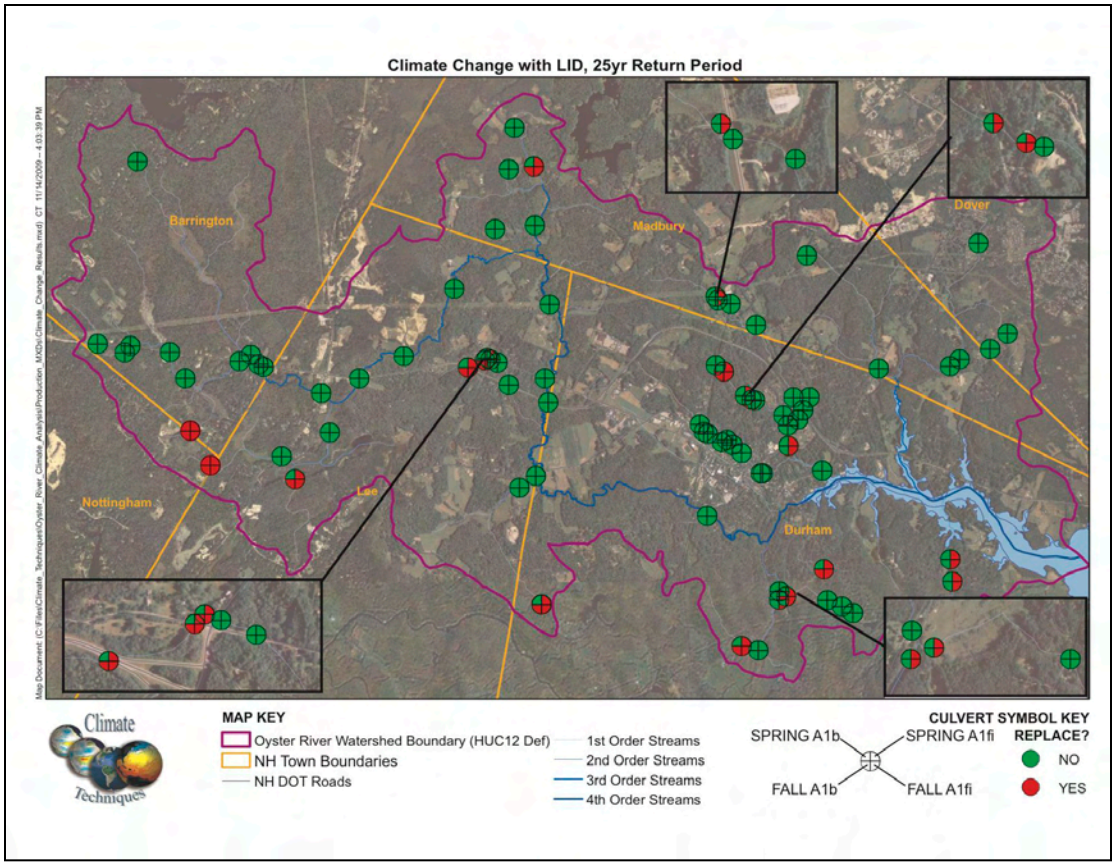

Figure III.f.3 *Spatial display of undersized culverts for build-out-with-LID land-use, and all climate change scenarios*

Figures III.f.4 through III.f.6 show the spatial impact of land use on culvert capacity. Each map is for the Fall season only. These images facilitate understanding the impact of land-use on culvert capacity, by showing all land-use scenarios on a single map, with separate maps for the recent (1971-2000) climate, and the future A1b and A1fi climates.

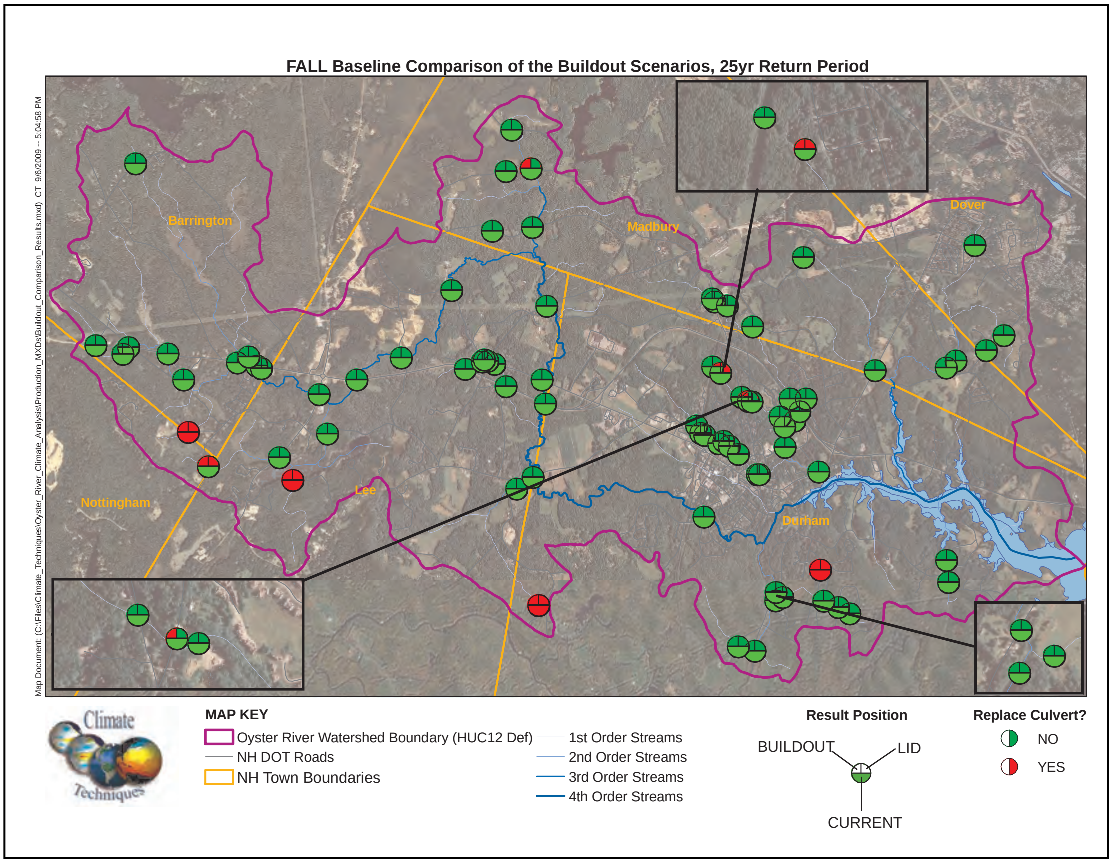

Figure III.f.4 *Spatial display of undersized culverts for all land-use scenarios, for the recent (1971-2000) 25-year precipitation*

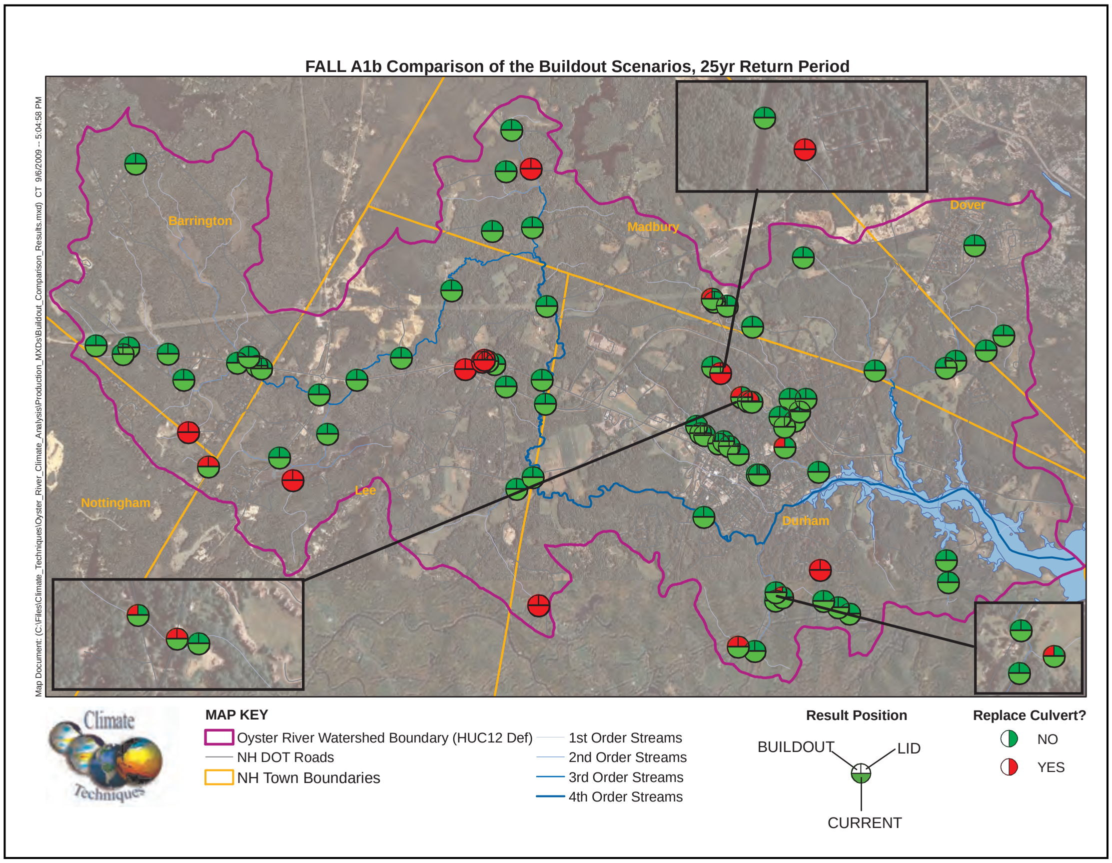

Figure III.f.5 *Spatial display of undersized culverts for all land-use scenarios, for the SRES A1b climate-changed 25-year precipitation*

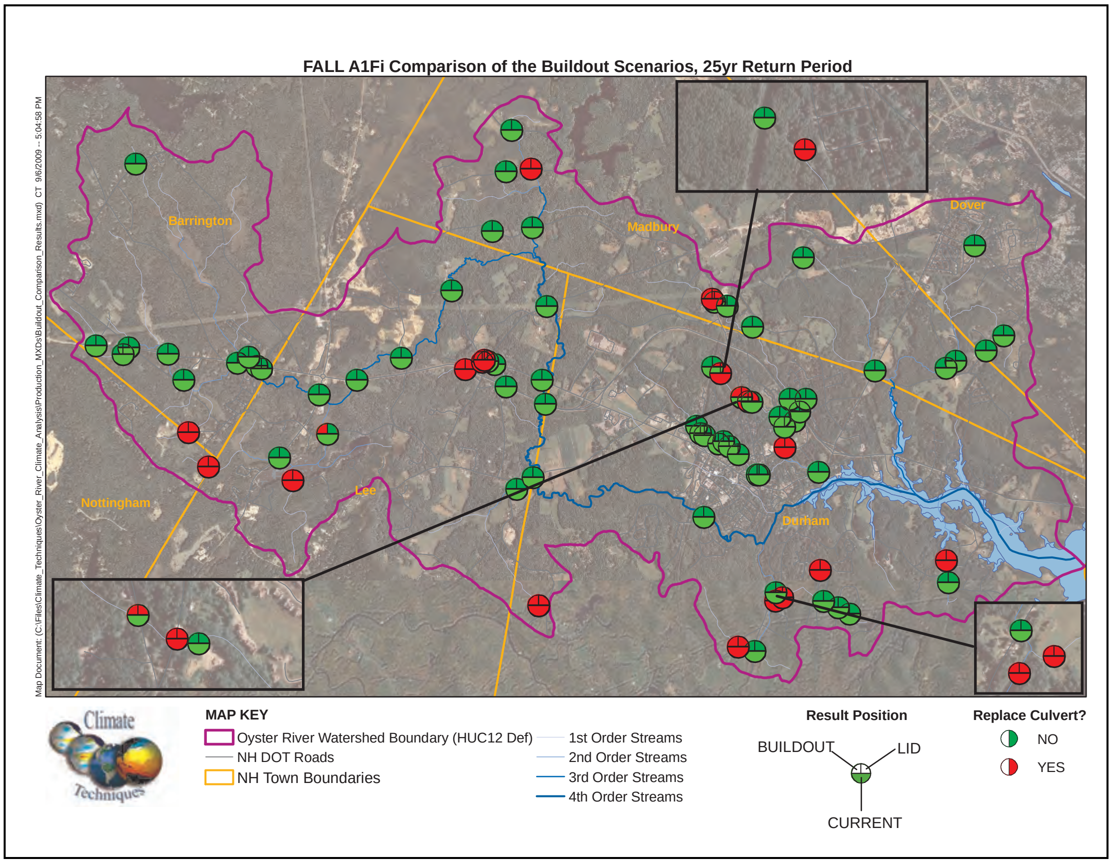

Figure III.f.6 *Spatial display of undersized culverts for all land-use scenarios, for the SRES A1fi climate-changed 25-year precipitation*

III.g **Cost Model**

Marginal cost is the additional cost resulting from upgrading a culvert to a larger size, rather than replacing it with one of equal size. For individual culverts, the factors that most influence marginal cost are the extent of increase in culvert cross-section, the height-to-road-surface, and the culvert length. For the pessimistic A1fi scenario with build-out, marginal costs averaged 49% per culvert, with a 95% confidence interval of 27%-71% (Table III.g.1).

Table III.g.1 *Per-culvert marginal costs, A1fi emissions scenario, with build-out*

	Marginal cost per culvert
+95% c.i.	71%
mean	49%
-95% c.i.	27%

Tables III.g.2 summarizes the results of the cost analysis by antecedent moisture condition, and precipitation and land-use scenarios. This information is shown graphically in Figure III.g.1. Total replacement and total upgrade costs are well-fit by linear regression. Marginal cost is the vertical distance between these two lines.

Table III.g.2 *Undersized culverts: Fall marginal costs scenario analysis*

Antecedent Moisture Condition	Precipitation Scenario	Land-use Scenario	Precip. (in.)	Number of under-sized Culverts	Replacement cost	Upgrade cost	Marginal cost	% difference	Marginal cost per culvert
AMC II	Baseline	Current	5.4	4	16,824	24,582	7,758	46%	1,940
		Build-out	5.4	8	56,542	88,264	31,722	56%	3,965
		LID	5.4	6	28,894	50,446	21,553	75%	3,592
	A1b	Current	6.9	9	75,621	101,184	25,562	34%	2,840
		Build-out	6.9	16	145,786	204,293	58,507	40%	3,657
		LID	6.9	12	110,832	152,590	41,757	38%	3,480
	A1fi	Current	8.3	17	147,118	203,726	56,608	38%	3,330
		Build-out	8.3	19	171,521	234,356	62,835	37%	3,307
		LID	8.3	18	160,695	222,267	61,572	38%	3,421
AMC III	A1b	Current	6.9	18	151,344	208,859	57,516	38%	3,195
		Build-out	6.9	20	175,746	239,488	63,742	36%	3,187
		LID	6.9	19	164,921	227,400	62,479	38%	3,288
	A1fi	Current	8.3	22	191,817	273,192	81,375	42%	3,699
		Build-out	8.3	25	224,761	321,339	96,578	43%	3,863
		LID	8.3	23	200,912	269,803	68,891	34%	2,995
							+95% c.i.:	48%	3,565
							Mean:	42%	3,317
							-95% c.i.:	37%	3,070

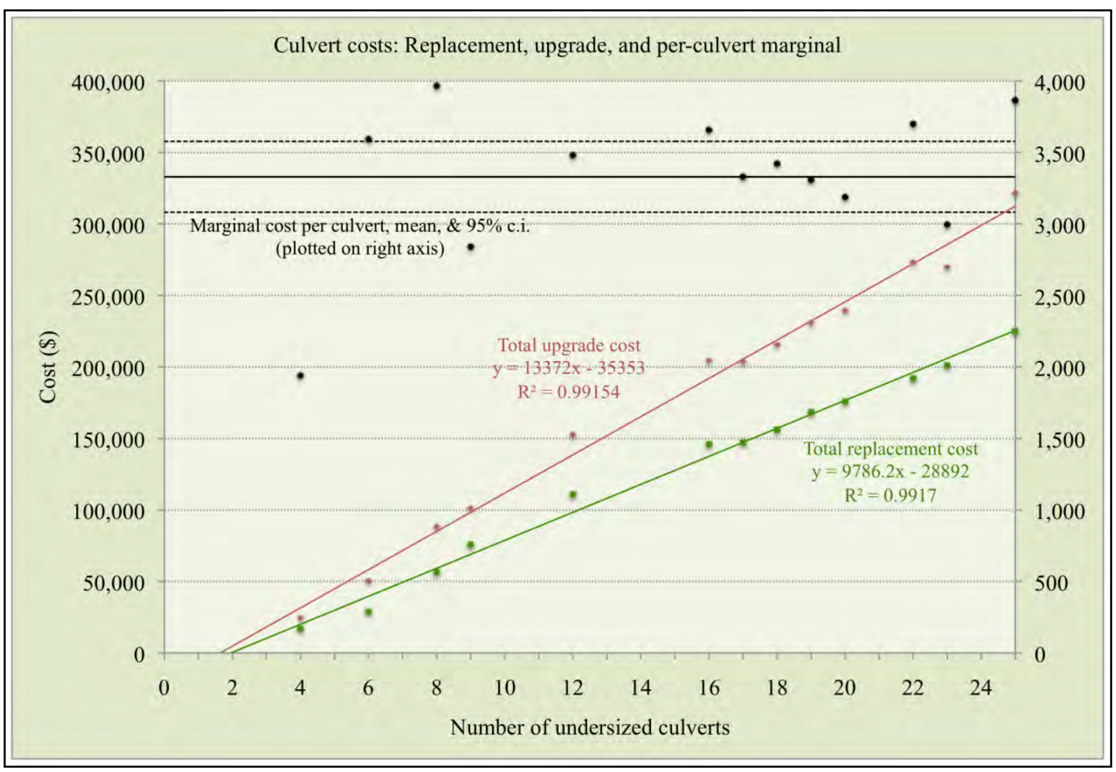

Figure III.g.1 *Undersized culverts: replacement, upgrade, and marginal costs*

When the data in Table III.g.2 are aggregated by land-use scenario, the cost differential between build-out, and build-out with LID, is apparent (Table III.g.3). The additional runoff from build-out increases the per-culvert marginal cost by 22%. The additional runoff from build-out with LID also increases the per-culvert marginal cost, but by only 14%. LID methods reduce the marginal cost per culvert by 8%, or 1/3.

Table III.g.3 *Per-culvert marginal costs by land-use scenario, recent precipitation*

Land-use	Marginal cost per culvert	% increase over "Current" land-use
Current	2,952	
Build-out	3,596	22%
LID	3,372	14%

Tables III.g.4 and III.g.5 compare the average marginal cost of build-out to the marginal cost of climate change. For the Spring season, the average marginal cost of build-out is greater than the cost of climate change. However, for the Fall season, the average marginal cost of build-out is greater than that for the A1b scenario, but less than the cost for the A1fi scenario.

Table III.g.4 *Marginal cost impact: Build-out but recent climate (1971-2000)*

Season	Average marginal cost
late-Spring	$16,949
Fall	$31,722

Table III.g.5 *Marginal Cost Impact: Current land-use but climate change*

Season	Climate Scenario	Average marginal cost
late-Spring	A1b	$608
	A1fi	$7,758
Fall	A1b	$25,562
	A1fi	$56,608

Table III.g.6 prioritizes culvert upgrade by risk, and aggregates culverts by town. These are culverts undersized for the 100% build-out and pessimistic A1fi climate change scenario. Town managers and public works officials can use this list to schedule culvert upgrades. For economy, information on this schedule should be incorporated into existing asset management programs. That is, an upgrade should ideally occur at the expiration of service life, so that a new culvert is installed only once: to both replace an aging culvert and adapt to climate change. The adoption of LID techniques by towns would remove from this list culverts BEAR100, LITT100, UNKN21, and HAME04, that are undersized for build-out but adequately sized for build-out under LID.

Table III.g.6 *Undersized culverts, by Town and Upgrade Priority*

Culvert ID	C:M ratio	Upgrade Priority	Town	SRES A1fi, Buildout, AMC II	Running Total by Town	Total by Town
UNKN10	0.5	1.5	Barrington	$ 4,645	$ 4,645	$ 4,645
CHES01	0.7	1.0	Durham	$ 5,164	$ 5,164	
UNKN42	0.7	1.0	Durham	10,893	16,057	
LITT101	1.8	1.0	Durham	28,192	44,249	
BEAU100	1.7	2.0	Durham	6,616	50,865	
BEAR100	1.3	2.5	Durham	12,758	63,623	
LITT100	1.8	3.0	Durham	18,541	82,164	
OYST102	1.3	3.5	Durham	9,477	91,640	
LITT104	1.0	4.5	Durham	9,267	100,907	
OYST101	1.8	4.5	Durham	10,584	111,491	
LITT102	3.0	4.5	Durham	18,959	130,450	
HAME03	1.8	5.0	Durham	18,690	149,140	
HAME04	2.1	5.0	Durham	2,910	152,051	
LONG02	1.6	6.0	Durham	8,498	160,548	
HAME100	2.0	6.0	Durham	8,115	168,663	$ 168,663
UNKN32	1.0	2.0	Lee	$ 8,595	$ 8,595	
UNKN26	1.4	2.0	Lee	34,662	43,257	
UNKN29	0.6	3.0	Lee	3,880	47,137	
UNKN34	1.0	3.0	Lee	14,452	61,590	
UNKN21	1.9	4.5	Lee	12,089	73,678	
UNKN22	2.3	5.0	Lee	17,546	91,225	
UNKN27	3.0	5.0	Lee	19,543	110,768	$ 110,768
OYST01	1.0	1.0	Madbury	$ 9,625	$ 9,625	
BEAR08	2.0	2.0	Madbury	17,494	27,120	
BEAR02	4.0	3.0	Madbury	19,399	46,518	
OYST103	2.2	6.0	Madbury	6,234	52,753	
UNKN39	3.2	6.0	Madbury	8,358	61,111	$ 61,111
UNKN41	1.8	1.5	Nottingham	$ 16,598	$ 16,598	$ 16,598

IV. Discussion and Conclusion

This study makes a significant contribution to preparing coastal watersheds for the impacts of climate change and population growth, by developing a reliable protocol for identifying vulnerable drainage system components, and by demonstrating that uncertainty in climate change projections is not a significant impediment to adaptation of stormwater management systems. For the study site, adaptation to climate change has a beneficial cost/benefit ratio, due to both low risk resulting from uncertainty in climate change projections, and a low overall cost to adapt. As a result, the towns in the watershed should plan, budget, and implement a program of adapting to the projected impacts from mid-21st century climate change. This finding likely is transferrable to many communities nationally and internationally.

The project developed a practical, quantified, and transferable protocol for identifying stormwater drainage system vulnerability; demonstrated that uncertainty between greenhouse gas emissions scenarios is not a significant barrier to climate change adaptation; measured the capacity of achievable LID methods for mitigating increased *peak flows* from climate-changed precipitation; and generated a budgeted schedule that stakeholders can incorporate into town master plans to effectively and economically protect the community.

Significance of climate change impacts

For the study site, climate change is estimated to have a profound impact on the precipitation intensity-duration-frequency relationship, resulting in undersized culverts, increased flooding, and increased hazard to life and property. The present study estimates that the *"most likely"* 25-year event for the mid-21st century A1b scenario will be 35% greater than the 25-year *TP-40* event; the *"most likely"* 25-year A1fi scenario will be 64% greater than the 25-year *TP-40* event; and the upper-95% confidence limit for the mid-21st century A1fi scenario will be 140% greater than the 25-year *TP-40* event (Table III.b.1). For comparison, the *TP-40* 100-year precipitation event for a 24-hour duration was only 24% greater than the 25-year event.

Inconsistent return-period capacities among existing culverts in the study site

Under textbook conditions, drainage system components are sized according to catchment hydrology, to accommodate uniformly applied design storm regulations. In this idealized scenario, variations in culvert size do not translate to variations in capacity for accommodating a given return-period storm. For example, in a text-book world, all culverts in the study site would be adequate for *peak flow* from the *TP-40* 25-year, 24-hour event specified by the New Hampshire design manual (NHDPWH, 1996), and would become undersized more-or-less simultaneously as the design storm precipitation was exceeded. For isolated culverts, risk factors at individual sites may result in higher design storm values (e.g. building to the 50-year event), but these would be exceptions.

However, this study found that existing culverts in the study site vary widely in their adequacy for a given precipitation event (Figure III.c.2, Table III.c.2), a significant implication for adapting to climate change and population growth. 5% of culverts (4/81) are currently undersized based on the *TP-40* design storm to which they presumably should have been constructed (Table III.c.2). When build-out is considered, an additional 7% (6/81) are already undersized for the *"most likely"* 25-year, 24-hour event experienced during the 1971-2000 interval (at the upper-95% confidence interval for the 1971-2000 period, 17% of culverts are undersized). At the other extreme, only 35% of culverts are undersized under full-build-out with no LID methods, for the precipitation estimated at the upper-95% confidence limit of the pessimistic A1fi climate change scenario. That 65% of culverts watershed-wide are adequate for accommodating the most extreme climate change and land-use scenario is a significant finding with favorable implications for climate change adaptation programs.

The study found that the culverts most likely to be under capacity are those in the upper reaches of the watershed, on smaller town or private roads (Table III.d.1, Figures III.g.1 through III.g.6). This may result from rural catchments experiencing relatively higher percentage increases in *peak flow*, compared with urban catchments, from a given change in precipitation (Jobin, 2001). In the study site, 60% of culverts are under rural roads (Table III.c.1). Because most of the vulnerable components are distant from more-densely populated areas and are under less-important roads, the risk to communities is lower than would be the case if vulnerable culverts were large, and located in more populated regions or under major transportation arteries.

Mitigation of risk from uncertainty in climate change predictions resulting from standard sizing for pre-fabricated culverts

Because pre-fabricated culverts come in standard, discrete sizes, once a culvert is upgraded the new size will accommodate a range of precipitation/*peak-flow* values before again becoming undersized. In fact, as shown in Table IV.1, the cost to upgrade a culvert does not change across scenarios: upgrade cost will be the same for all *"most likely"* scenarios with greater *peak-flow*. That is, once a culvert requires upgrading, it does not cost more to upgrade for even the *"most likely"* A1fi emissions scenario. For example, a culvert that is currently adequate for *TP-40* may be inadequate for A1b or A1fi flows (e.g. culvert LITT104 in Table IV.1). But if a culvert is currently inadequate for the *TP-40*, an upgrade sufficient for *TP-40* will cost the same as one sufficient for the recent past, the A1b scenario, and the *"most likely"* A1fi scenario (e.g. culvert CHES01 in Table IV.1). Note that the study did not estimate upgrade costs for the A1fi upper-95% confidence limit. The impact of this finding is significant for adaptation programs: there is little cost penalty for being overly-pessimistic in adaptation standards: for the study site, adapting to a more extreme climate appears to cost little more than adapting to a less-extreme climate.

Table IV.1 *Climate change cost to upgrade undersized culverts, current land-use. Green-shading indicates adequate current size, yellow-shading indicates upgrade required even for TP-40 compliance, and orange-shading indicates upgrade required for climate change. Blue arrows indicate that numbers from a previous scenario are carried forward to the next.*

Existing Land-use									
	Replace		Size for:						
	Current size		TP-40		1971-2000		A1b		A1fi
CHES01	3,474		5,164	→	5,164	→	5,164	→	5,164
UNKN10	4,037		4,645	→	4,645	→	4,645	→	4,645
UNKN29	2,862		3,880	→	3,880	→	3,880	→	3,880
UNKN42	6,451		10,893	→	10,893	→	10,893	→	10,893
LITT104	6,353	→	6,353	→	6,353		9,267	→	9,267
OYST01	4,284	→	4,284	→	4,284		9,625	→	9,625
UNKN26	32,705	→	32,705	→	32,705		34,662	→	34,662
UNKN32	6,772	→	6,772	→	6,772		8,595	→	8,595
UNKN34	8,684	→	8,684	→	8,684		14,452	→	14,452
BEAR08	7,801	→	7,801	→	7,801	→	7,801		17,494
BEAR100	11,565	→	11,565	→	11,565	→	11,565		12,758
BEAU100	6,129	→	6,129	→	6,129	→	6,129		6,616
HAME04	2,010	→	2,010	→	2,010	→	2,010		2,910
LITT101	23,365	→	23,365	→	23,365	→	23,365		28,192
LONG02	7,801	→	7,801	→	7,801	→	7,801		8,498
OYST102	7,108	→	7,108	→	7,108	→	7,108		9,477
UNKN41	5,717	→	5,717	→	5,717	→	5,717		16,598

Risk aversion determines cost, timing of adaptation

The timing and cost of adaption will, to a certain extent, depend on a community's comfort with risk. For Durham, a more risk-averse strategy might upgrade all undersized culverts soon, before mid-21st century climate change impacts manifest. The cost to upgrade all culverts projected to be undersized is $168,663 (from Table III.g.6), for the *"most likely"* A1fi and build-out scenario. Such a strategy is the most costly, as it upgrades culverts before the expiration of service life, so that the adaptation cost to the town is not the marginal cost but the more expensive full-upgrade cost. Yet even this most-expensive strategy is only 1.6% of Durham's fiscal year 2010 operating budget $10,324,489 (Town of Durham, 2009).

If Durham were more tolerant of risk it might utilize a more economical adaptation strategy, waiting to upgrade culverts until the expiration of their service life. In this case the adaptation cost becomes the marginal cost which, for Durham is $50,334, or 0.49% of Durham's fiscal year 2010 operating budget (Town of Durham, NH, 2009). However, because service lives do not all expire at once, upgrades would occur over a number of years. Over a thirty-year period, the impact on any single year is only 0.016% of the fiscal year 2010 annual operating budget. The downside to this strategy is that road-stream crossings with newer, or longer-lasting culverts (e.g. reinforced concrete), will likely not be upgraded before more extreme storms manifest.

The actual adaptation strategy implemented by towns in the watershed would likely be a combination of the above approaches. Higher-risk culverts might be upgraded prior to expiration of their service life, while the upgrade of low-risk culverts might coincide with routine asset management.

Low cost of adaptation, in the context of watershed-wide asset management

For the watershed as a whole, over the asset management life-cycle for the watershed all 81 modeled culverts must be replaced as service lives are exceeded. We estimate watershed-wide replacement costs at $645,000. However, only a fraction of culverts need upgrading for climate change, so that the cost of adaptation is relatively low in the context of watershed-wide adaptation. For example, from Table III.g.2, 4 culverts are undersized for *TP-40*, at a marginal cost of $7,758. Subtracting these from the marginal cost for the A1fi with build-out scenario yields a net cost of $55,077. The percentage cost of watershed-wide adaptation is the marginal cost for A1fi-plus-build-out ($55,077), divided by the total cost to replace all 81 culverts (estimated at $645,000). Thus, the cost to adapt the whole watershed for the pessimistic A1fi scenario and population growth is only 8.5% more than the replacement cost that will be incurred without consideration of adaptation and population growth.

It is cost-effective for communities to adapt to a more pessimistic climate change projection

Climatologists are currently unable to reliably identify the most likely future emissions trajectory. In addition, uncertainty persists in current generation coupled-climate models. Leaders have responded to these sources of uncertainty either by not adapting, or by limiting adaptation to general resilience/capacity building programs. These better enable communities to respond to extreme events, but the lack of specific infrastructure adaptation results in only limited prevention of risks.

The SRES scenarios modeled in the present study, A1b and A1fi, represent moderate and pessimistic expectations about the extent to which the global community will reduce greenhouse gas emissions. Therefore, adapting to the A1fi scenario is risk-averse in that it protects communities from all scenarios up to, and including, the A1fi. One should expect, however, that adapting to the more extreme A1fi scenario would be more costly than adapting to A1b, representing a disincentive to adapting to A1fi. There should thus be consequences to choosing an incorrect scenario on which to base adaptation: an excessively optimistic decision incurs lower adaptation costs but higher damage costs from under-estimating impacts; an excessively pessimistic decision raises adaptation costs but lowers damage costs.

This study found that both marginal upgrade costs, and the percentage of undersized culverts, are relatively insensitive to uncertainty in climate change projections. Table IV.1 showed that, for the *"most likely"* estimates for the recent and climate-changed scenarios, once an individual culvert becomes undersized the required upgrade will be sufficient, and costs unchanged, for all more-extreme scenarios. For the watershed as a whole, Figure IV.1 shows the insensitivity of undersized rates and marginal costs to climate change scenario. In Figure IV.1, the diagonal black line represents a 1:1 relationship, for which a given percentage increase in the design storm results in an equal percentage increase in marginal cost or numbers of undersized components. For both the percentage change in marginal upgrade cost and the percentage change in undersized culverts, the slope of the line from A1b to A1fi is significantly flatter than the 1:1 line. This indicates that the relatively large increase in the 25-year climate-changed storm over that experienced recently (1971-2000) yields a disproportionately small increase in both the rate of undersized culverts and marginal upgrade cost. This leverage can be exploited to implement a risk-averse adaptation strategy with little disincentive caused by the excess cost of over-estimating required capacity. For example, from Table IV.1, upgrading five culverts for the A1b event has a marginal cost of 3.1% across the watershed-wide 81 culvert life-cycle replacement cost. Upgrading the additional eight culverts that are undersized for the A1fi scenario adds another 4.7% to the marginal cost across the watershed-wide total life-cycle expenditure. This 4.7% increment is the cost of being risk-averse by adapting to the more pessimistic scenario, the "no regrets" strategy.

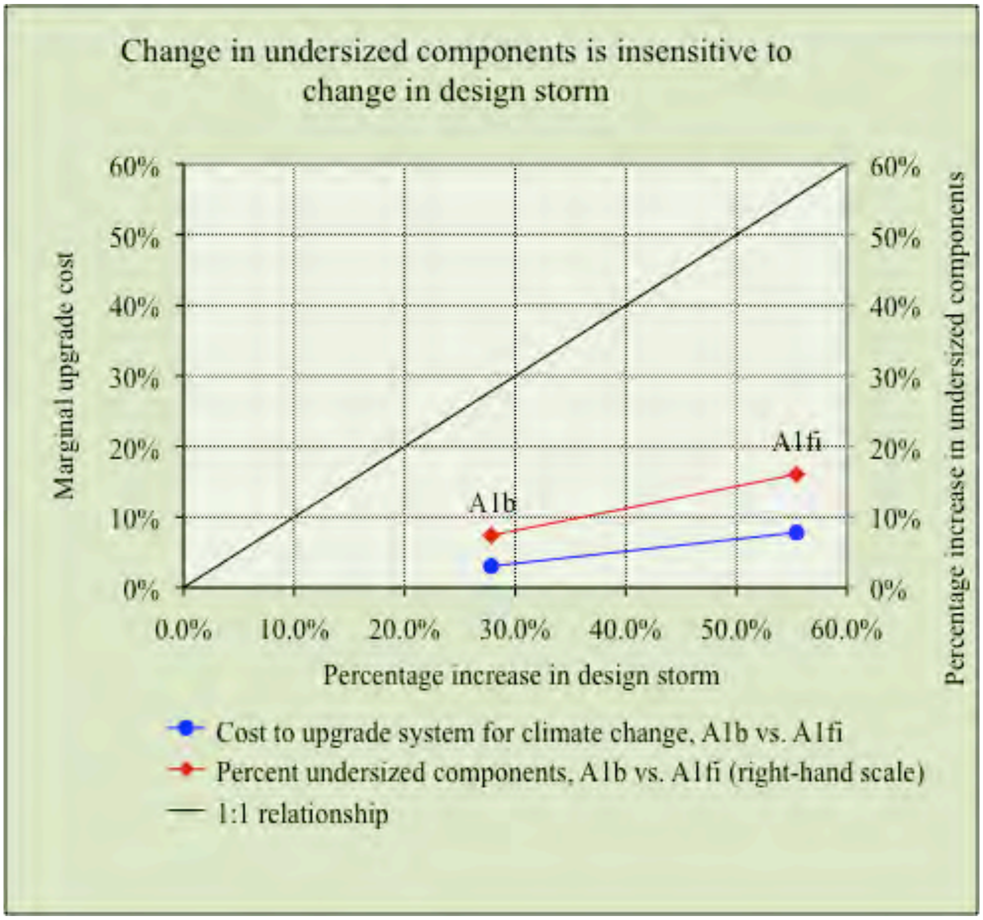

Figure IV.1 *Marginal costs, and the number of undersized culverts, are insensitive to uncertainty in climate change projections.*

Threshold analysis

In order for adaptation studies to most readily provide adaptation decision-support to leaders and stakeholders, raw results must be presented in forms that are understandable to lay-persons. These must communicate the extent of impacts across a range of climate change scenarios, and show, for each scenario, the effectiveness of various adaptation tactics. One such tool is the threshold analysis, which portrays infrastructure capacity across a range of climate change impacts, and overlays specific adaptation strategies at specific points along the impacts continuum. In this way decision-makers are given a long-range view of a range of impacts, the specific mitigating capacity of specific adaptations, and the order of preference for implementing the various adaptation tactics.

A rudimentary threshold analysis is presented in Table IV.2, which depicts the capacity of individual culverts to convey *peak flows*, in a fully-built-out watershed, and across a range of increases in the design storm. This table shows increases over the *TP-40* value in 5% increments, to 140%, i.e. to 2.4 times the *TP-40* value. At the top of this table, the four Precipitation Scenario rows show, for the study site: the 25-year and 100-year events specified by *TP-40*; the 25-year event modeled for the recent past (1971-2000 baseline); and the downscaled mid-21st century A1b and A1fi climate-changed 25-year events. For each scenario, the "most-likely" number is shown as a darker-colored cell, and the 95% confidence band on either side of the *"most likely"* value is shown with lighter-shading. For example, the second row plots the A1b scenario, with the *"most likely"* estimate in darker blue, and the 95% confidence band in teal. For the A1b scenario, the *"most likely"* event is about 35% greater than the *TP-40* number. To facilitate reading this table, the vertical dotted-lines extend the *"most likely"* and upper 95% confidence limit values downward.

Individual culverts are listed in rows on the left, ordered from most to least vulnerable as measured by the $C/M_{TP\text{-}40}$ ratio that was introduced in section III.c of this report. The colored band to the right of each culvert shows the adequacy of the culvert for conveying *peak flow* from the amount of precipitation listed in row one. The green-shaded region indicates that a culvert is adequately-sized for a given scenario or percentage increase in the design storm. For each culvert, the right-most edge of the green band is the limit to that culvert's being adequately-sized. For most culverts, LID implementation, shown as orange shading, provides some mitigating effect. Because the implementation of LID methods is expected to be less-costly than, and therefore preferable to, culvert upgrade, LID implementation is shown adjacent to the green band. The width of the orange bar indicates the range over which LID methods can mitigate effects of build-out: the left edge of an orange bar is the point of undersizing without LID, and the right edge is the limit of Lid's mitigating capacity. Red shading indicates the range of precipitation over which, given the adaptation options considered for this study, culvert upgrade is required. Note that this simplified threshold analysis did not consider other adaptation options, such as increasing the community's resilience to flooding by relocating at-risk populations and infrastructure, or applying Best Management Practices that channel rainfall offsite to retention ponds prior to encountering a culvert.

Table IV.2 presents the same information as Table III.c.2 and Figure III.c.2, but organized to show adaptation tactics and to highlight the vulnerability of the watershed across a range of design storm increases. On Table IV.2, following the curve of the red-green boundary downward and to the right, to its intersection with the upper-95% confidence limit of the A1fi estimate, i.e. the right-most edge of the table, indicates the point after which culverts do not become undersized even for the upper 95% confidence limit of the A1fi 25-year storm. 65% of culverts are below this point.

Table IV.2 *Threshold analysis of culvert adequacy in the fully-built-out watershed, showing impacts from climate change and LID methods.*

Percentage increase in 4% (25-year) precipitation, over baseline (1971-2000): 0% | 5% | 10% | 15% | 20% | 25% | 30% | 35% | 40% | 45% | 50% | 55% | 60% | 65% | 70% | 75% | 80% | 85% | 90% | 95% | 100% | 105% | 110% | 115% | 120% | 125% | 130% | 135% | 140%

TP-40 | *TP-40* 100-year

Precipitation Scenarios:

- Baseline (1971-2000): "Most likely" & ±95% confidence interval
- Climate Change, A1b (2046-2075): "Most likely" & ±95% confidence interval
- Climate Change, A1fi (2046-2075): "Most likely" & ±95% confidence interval

Culvert Name	C/M_{TP-40} Ratio
UNKN10	0.5
UNKN29	0.6
CHES01	0.7
UNKN42	0.7
LITT104	1.0
UNKN41	1.8
LITT101	1.8
OYST01	1.0
UNKN32	1.0
BEAU100	1.7
BEAR100	1.3
LITT100	1.8
BEAR08	2.0
UNKN34	1.0
UNKN26	1.4
HAME04	2.1
OYST102	1.3
LONG02	1.6
UNKN21	1.9
LITT102	3.0
OYST101	1.8
HAME03	1.8
UNKN22	2.3
OYST103	2.2
HAME100	2.0
UNKN39	3.2
BEAR02	4.0
UNKN27	3.0
LITT105A	4.4
BEAR106	3.0
UNKN14	2.6
OYST02	2.7
PETT06	3.0
JOHN02	3.6
PETT09	3.9
BEAR104	4.0
CALD102	4.0
HAME01	4.0
UNKN23	4.0
PETT07A	5.5
LITT103	5.6
GERR01	5.8
CALD103	5.9
UNKN40	6.2
PETT05	6.3
BEAR103	6.4
CALD02	6.4
CALD03	6.5
GERR02	6.8
CALD01	7.0
PETT02	7.1
HAME101	7.7
BEAR102	7.8
BEAR0A	8.0
BEAU02	8.3
BEAR101	8.5
BEAR105	8.7
PETT04	9.3
JOHN01	9.3
UNKN25	10.0
CALD104	10.2
PETT03	10.5
CALD101	11.5
JOHN08	13.2
CHES02	15.4
OYST07	30.6
OYST12	31.1
OYST03	31.4
OYST13	31.7
OYST14	35.4
OYST15	44.6
OYST10	45.3
OYST08	51.8
OYST05	53.5
OYST06	63.7
OYST11	73.1
OYST16	102.4
LITT106	116.4

Section III.c of this report introduced the concept of the current-to-model ratio of cross-sectional area, as an indicator of a culvert's adequacy. The C/M_{TP-40} ratio was used to assess the adequacy of the existing culvert system across the range of climate-change and build-out scenarios, and it was determined from linear regression that culverts with a C/M_{TP-40} ratio of 3.2, i.e. an approximate tripling of the current capacity over that specified using *TP-40*, would have sufficient capacity for even extreme climate change and build-out.

The usefulness of the C/M_{TP-40} ratio as a rule-of-thumb for preliminary sizing of culverts is limited, by the numerator, to existing culverts. For new drainage components, engineers and public works officials need a similar rule-of-thumb to suffice until the state or federal government publishes *TP-40* equivalent maps that account for climate change. For the design of new culverts, such a rule-of-thumb is provided by substituting the *TP-40* cross-sectional area for the current cross-sectional area in the numerator of the ratio. The denominator remains the modeled cross-sectional area, for the various combinations of build-out and climate change. The ratio is interpreted as the multiple of the *TP-40* cross-sectional area that provides adequate capacity for a given scenario, denoted here as the M_{TP-40}/M_x ratio, where *x* refers to a build-out and climate change scenario. Table IV.3 provides descriptive statistics for this ratio, across all 81 culverts modeled, under full build-out without LID methods. The mean M_{TP-40}/M_x ratio was 1.47 for the *"most likely"* A1b-plus-build-out scenario; was 1.89 for the *"most likely"* A1fi-plus-build-out scenario; and was 2.85 for the upper-95% confidence limit of the A1fi-plus-build-out scenario. Rounding up the ratio for the latter scenario gives a rule-of-thumb, such that building a culvert to a cross-sectional area 3 times larger than specified by *TP-40* should be adequately sized for extreme mid-21st century climate change and build-out.

Table IV.3 M_{TP-40}/M_x ratios for full build-out, and three climate change scenarios

	A1b	A1fi	
	"Most Likely"	"Most Likely"	+95% c.i.
Maximum	1.78	2.59	3.87
+95% c..i.	1.51	1.96	2.94
Mean	1.47	1.89	2.85
-95% c.i.	1.44	1.83	2.75
Minimum	1.00	1.43	1.93

Prioritizing the adaptation of individual culverts

Undersized conditions at culverts do not have equal significance to the communities in the watershed. Certain culverts are associated with higher risk due to potential for down-stream damage, the importance to the community's transportation system of the road that a culvert crosses, and the degree to which a culvert is vulnerable to becoming undersized. Based on these factors a simple schedule, ordered by adaptation priority, has been prepared as Table III.g.6.

Benefits of LID methods

Upgrading existing drainage systems is considered to be the most expensive means of accommodating increased *peak flow* resulting from climate change (Blanksby et al., 2003). More economical adaptation strategies reduce *peak flow* through application of Low Impact Development (Coffman, 2005), Best Management Practices (Urbonas and Stahre, 1993), Sustainable Urban Drainage methods (Butler, 2000), or Smart Growth lot design (Daniels, 2001). To study the effectiveness of non-upgrade accommodation to *peak flo*w, the project modified a 100% build-out of the watershed using a set of achievable LID standards. Although LID methods can potentially maintain pre-development runoff rates, the set of methods that are likely to be achievable in the near future in the study site can be expected to be limited. Based on current development patterns, a set of achievable LID methods was derived and the impact of this set on post build-out rates of *peak flow* was measured.

Study findings indicate that a set of LID methods that is modest but achievable can significantly mitigate the impacts of climate change and population growth. The set of LID methods developed for this study reduced the increase in *Curve Number* resulting from build-out by almost half, from 7.3% to 4.0% (Figure III.e.1). Under recent climate (1971-2000) conditions, LID methods reduced the marginal upgrade cost per culvert by 1/3 from the cost of build-out without LID (Table III.g.3). However, the set of LID methods selected for this study had a declining ability to mitigate *peak flows* as climate change impacts become more severe. For the Fall *"most likely"* A1b scenario, LID reduced the number of undersized culverts by 50%, but under the Fall *"most likely"* A1fi scenario LID methods reduced the number of undersized by only 5% (Table III.e.2, Figures III.f.5 and III.f.6). The declining effectiveness of LID methods also can be seen in Table IV.2, where the number of culverts with tan-colored LID bands declines as one progresses from top-left to bottom-right along the red-green boundary between adequate- and under-capacity. The effect of LID methods can also be seen in the cost of adaptation. From Table III.g.2, the marginal upgrade cost for the A1b scenario with LID ($41,757), is 29% less than the marginal cost for the A1b scenario without LID methods ($58,507. However, for the *"most likely"* A1fi scenario, the marginal cost with LID ($61,572), is only 2% less than the marginal cost without LID methods ($62,835).

Catchments do not respond equally to LID methods. On Table IV.2 note that the horizontal tan bands indicating *peak flow* mitigation from LID are of varying width. This indicates that LID is more effective for certain catchments than for others, based on the extent of currently undeveloped land, zoning regulations, and catchment hydrology. For two culverts, LITT102 and BEAR02, LID methods even can mitigate impacts from the upper-95% confidence limit A1fi event.

Combining the results of the LID analysis with the risk-prioritized upgrade schedule presented in Table III.g.6, certain culverts benefit more from the application of LID methods, either due to the extent of mitigation provided by LID, or due to the relatively higher risk assigned to a culvert in relation to other culverts. The catchments draining to these culverts should be given priority as LID methods are implemented. These culverts include Beau100, UNKN21, UNKN32, BEAR100, LITT100, HAME04, BEAR08, OYST102, and INKN21.

Impaired conditions reduce the effective capacity of the existing drainage system

32% of culverts (26/81) in the study site had impaired effective capacity, due either to partial or complete collapse of the culvert, significant sedimentation in the culvert, or obstruction of either the culvert inlet or outlet from vegetation or debris. In conjunction with the 5% of culverts (4/81) that are already undersized for the 25-year *TP-40* design storm, these may lead to significantly greater flooding than expected. This problem may be common, as previous work by the study team found impaired conditions for approximately 25% of culverts at a study site in southwestern New Hampshire (Stack et al., in review).

Conclusion

Scheraga (2003) noted that climate change adaptation need not wait for “perfect” science. Community leaders are adept at decision-making under conditions of uncertainty, indeed this is a defining characteristic of leadership. The present study showed several ways in which uncertainty does not appear to be a significant obstacle to infrastructure adaptation. The study also presented several methods for managing residual uncertainty in climate change projections. For watersheds similar to the study site, this study estimates that the incremental cost for upgrading to the more pessimistic A1fi, rather than the moderate A1b scenario is 4.7% of the total life-cycle expenditure. This range is comparable to the uncertainty of future interest rate projections that a community must consider in a long-term bond-funded capital improvement program.

The results of this study echo, in a tangible way, the findings of previous research: climate change will result in communities experiencing a fundamental change in the coefficients of the [risk = (size of exposure) x (probability of occurrence)] equation associated with design storm specification. The design storm specified for common culverts by New Hampshire regulations has been the 1-in-25 year (4% probability) event. For Durham, this study found that, for the upper-95% confidence limit of the A1fi scenario, the historical 1-in-25-year event is likely to become a 1-in-5 year event, and what had been a 1-in-250 year event is likely to become the new 1-in-25 year event. Either communities will be assuming the higher degree of hazard associated with this compression of the risk curve, or drainage systems must be upgraded to maintain the historical risk level. Historical risk levels may be maintained with carefully planned and budgeted adaptation programs.

This study makes a significant contribution to climate change adaptation of estuaries and coastal watersheds, by proposing a simple model capable of generating specific estimates of civil infrastructure vulnerabilities. These results may be of interest to climate scientists, civil engineers, municipal planners, and public works officials, as they consider preparing for predicted increases in rainfall intensity and watershed runoff. The authors hope that this work will increase awareness of the need for, and practicality of, climate change adaptation.

Summary of findings and Conclusions

Research Site:

- The majority of culvert catchments are under 500 acres (Figure III.a.1);
- For most modeled catchments, over 60% of land area is buildable (Figure III.a.1);
- The average catchment elevation is 144 feet (Figure III.a.3);
- The average catchment slope is 4.4% (Figure III.a.3);
- Hydrological Group "C" soils predominate (Figure III.a.4);
- The average width of catchments is 4,700 feet (Figure III.a.5);
- The average length of the main drainage channel for catchments is 9,100 feet (Figure III.a.5);
- For most catchments, the *time of concentration* (t_C) is between 19 and 25 hours (Figure III.a.5, Figure III.a.6);
- Most catchments have a *curve number* (*CN*) between 66 & 69 (Figure III.a.7).

Precipitation:

- The *"most likely"* recent (1971-2000) precipitation event was 5% greater than the *TP-40* event, for the 25-year, 24-hour precipitation (Table III.b.1);
- The *"most likely"* moderate (A1b) and pessimistic (A1fi) precipitation events are projected to be 35% and 64% greater than the *TP-40* event, respectively, for the 25-year, 24-hour precipitation (Table III.b.1);
- The upper-95% confidence limit of the pessimistic (A1fi) precipitation event is projected to be 140% greater than the *TP-40* event, for the 25-year, 24-hour precipitation (Table III.b.1);
- Under the *"most likely"* A1fi climate change scenario, by the mid-21st century the amount of rainfall from what historically was the 25-year storm is projected to become a 7.5-year storm. That is, this amount of rainfall jumps from a 4% to a 13.3% probability of occurring any one year (Figure III.b.1);
- Under the *"most likely"* A1fi scenario, by the mid-21st century the amount of rainfall from what historically was the 150-year storm is projected to become a 25-year storm. That is, this amount of rainfall jumps from a 0.67 % to a 4% probability of occurring any one year (Figure III.b.1);
- For the upper-95% confidence interval of the A1fi scenario, by the mid-21st century the historically 4% probability event increases to a 20% annual probability. And the event that historically had a 0.4% annual probability is projected to occur ten-times more frequently (Figure III.b.1).

Culvert Data:

- The majority of culverts are concrete, followed by metal. Only 5% are HDPE plastic (Table III.c.1);
- For the culverts included in the study, the rate of undersized culverts for Durham and Lee was approximately 28%, and for Barrington and Madbury was approximately 15%, for the A1fi scenario with build-out (Table III.c.1);
- The majority of undersized culverts were conveying runoff from low-order streams, higher in the watershed;

- The majority of undersized culverts were sited under less-traveled, higher-class roads;
- The majority of undersized culverts ranged between 12 and 24 inches in diameter;
- Modeled culverts have inconsistent return-period capacities (Table IV.2);
- The maximum number of culverts that were undersized due to build-out under the *"most likely"* A1fi precipitation and *AMC Type III "wet"* antecedent soil conditions, was twenty-five (25), which is approximately 30% of the culverts in the study. This includes 4 culverts already undersized for the *TP-40* 25-year storm (Table III.e.2);
- The maximum number of culverts that are undersized due to build-out under the *"most likely"* A1fi precipitation and *AMC Type II "average"* antecedent soil conditions, was nineteen (19), which is approximately 23% of the culverts in the study. This includes 4 culverts already undersized for the *TP-40* 25-year storm (Table III.e.2);
- Culverts with large cross-sectional areas (> 60 ft^2) were not undersized for any of the scenarios of the study (Table III.c.2);
- For any of the modeled land-use and *"most likely"* precipitation scenarios, culverts with a current-to-modeled cross-sectional area ratio greater than 2.1 are never undersized (Tables III.c.2 and IV.3, Figure III.c.2);
- Culverts that are three-times the cross-sectional area specified by *TP-40* will be adequately sized for the upper-95% confidence limit of the pessimistic A1fi climate change scenario with build-out (Table IV.3, Figure III.c.2).

Low Impact Development Methods:

- Across all modeled catchments, the mean *CN* increases from 67 to 72 due to build-out, but decreases from 72 to 70 with the incorporation of achievable LID methods (Figure III.e.1);
- For moderate precipitation increases and *"average"* antecedent moisture conditions, achievable LID methods reduce the number of culverts undersized due to build-out from 25-100% (Table III.e.2);
- For more extreme precipitation increases, or *"wet"* antecedent conditions, achievable LID methods reduce the number of culverts undersized due to build-out by 5-8% (Table III.e.2).

Watershed-wide Adaptation Costs, and Marginal Upgrade Costs:

- For the town of Durham, for the *"most likely"* pessimistic A1fi with build-out scenario, the cost of a risk-averse adaptation strategy, which upgrades culverts before the expiration of service life, is 1.6% of the 2010 operating budget;
- For the town of Durham, for the *"most likely"* pessimistic A1fi with build-out scenario, an adaptation strategy that is more tolerant of risk upgrades, over time, culverts projected to be undersized. The adaptation cost for this strategy is the marginal upgrade cost. Budgeted over a thirty-year period, this strategy adds 0.016% to each year's operating budget, based on Durham's 2010 budget;
- For the watershed as a whole, the cost of adapting to the *"most likely"* pessimistic A1fi-with-build-out scenario is 8.5% greater than the cost of replacing culverts

with one that is the same size as is currently in place. This is the watershed-wide marginal adaptation cost;

- For the late-Spring season, the average (per culvert) marginal upgrade cost from build-out is greater than the average marginal cost from climate change (Tables III.g.4 and III.g.5);
- For the Fall season, the average (per culvert) marginal upgrade cost from build-out is between the average marginal costs for the moderate and pessimistic climate change scenarios (Tables III.g.4 and III.g.5);
- For the *"most likely"* pessimistic A1fi scenario with build-out, the marginal upgrade cost per culvert was 49% (Table III.g.1);
- Across all precipitation and build-out scenarios, the mean marginal, per culvert upgrade cost is approximately $3,317 (Table III.g.2);
- Build-out increases the average marginal upgrade cost by 22% (Table III.g.3);
- Build-out with LID methods increases the average marginal upgrade costs by 14%, a reduction of 8%, or 1/3, from build-out without a LID strategy (Table III.g.3).

Uncertainty in Climate Change Projections:

- Both the rate of undersized culverts, and marginal upgrade costs, are insensitive to climate change scenario. The *"most likely"* A1fi storm is 22% greater than the *"most likely"* A1fi storm, however the watershed-wide adaptation cost for the A1fi scenario is only 4.7% greater than that for the A1b storm (Table III.b.1, Figure IV.1);
- Due to the standard sizes available for pre-manufactured culverts, for any of the *"most likely"* precipitation scenarios, a culvert upgrade provides adequate capacity for all higher-precipitation scenarios (Table IV.1);

Other findings:

- For culverts projected to be undersized, adaptation can be prioritized based on risk, to better protect the community (Table III.g.6);
- Conditions that impair effective capacity were found at 32% of culverts in the watershed;
- The upgrading of culverts, to accommodate impacts from climate change and build-out, also will promote safe passage of aquatic species.

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Appendices

Appendix 1 Sample catchment data summary report

Appendix 2 Field data collection form

Appendix 1 Sample catchment data summary report, page 1 of 2

Oyster River Watershed Catchment Results

Culvert ID	BEAU02
Current-Baseline-Fall-TypeII (Replace?)	NO
Buildout-A1fi-Fall-TypeII (Replace?)	NO
LID-A1fi-Fall-TypeII (Replace?)	NO
Road Name	RT 108
Stream	BEAUDETTE CREEK
Sample Date	8/13/2008
Town	DURHAM
Location	108 south of Durham
Culvert Type	Box Culvert
Culvert Material	Concrete
Headwall Material	Concrete
Condition	Old
Culvert Count	1
Dim_A (height (ft))	5.6
Dim_B (width (ft))	4.5
Length (ft)	54
Culvert Depth	Yes
Inlet Vertical Alignment	At_Grade
Outlet Vertical Alignment	At_Grade
Outlet Drop	0
Headwall Orientation	90 degree
Culvert Velocity	Yes
End Condition	flush
Edge Bevel	no
Mitre	no
Wingwalls	no

INLET

OUTLET

Appendix 1 Sample catchment data summary report, page 2 of 2

Appendix 2 Field data collection form, p. 1 of 5

Structure ID	Road Name	
Observers	Stream name	
Date and Time	Number of travel lanes ____	**Structure material**: concrete plastic-corrugated plastic-smooth tank stone steel-corrugated steel-smooth aluminum-corrugated other (describe)____________ **Headwall material**: concrete, metal, stone
Town	Number of shoulder lanes ____	
Location	Road surface __paved ___unpaved	
Lat	Road type trail railroad	
Long	Reference bankfull widths (ft) ____ ____ ____ ____ ____	

Flow conditions are: ___ unusually low ___typical low flow ___higher than average ___flood conditions

# of culverts at crossing_____	Overflow pipe(s) yes no	Structure skewed to roadway yes no

Crossing type __ford ___bridge ___open bottom arch ___single culvert ___multiple culverts (# or culverts___)

Condition of crossing: __New ___Old ___Collapsing ___eroding ___rusted

General

Floodplain filled by roadway approaches: Entirely Partially not significant

Structure located at a significant break in valley slope: yes no unsure

Culvert slope as compared with the channel slope is: higher lower about the same

Water depth in the crossing matches that of the stream? __Yes ___No (significantly deeper ___No (significantly shallower)

Water velocity in crossing matches that of stream? ___Yes ___No (significantly faster) ___No (significantly slower)

Upstream

Structure opening partially obstructed by: wood sediment wood and sediment deformation of culvert none

Steep riffle present immediately upstream of structure: yes no

If channel avulses: stream will: cross road follow road cross and follow road unsure

Estimated distance avulsion would follow road: ______(feet)

Angle of stream flow approaching structure: sharp bend mild bend naturally straight channelized straight

Evidence of streambed erosion or aggradation immediately upstream of culvert: erosion aggradation none

Culvet inlet: at grade cascade free fall

Upstream Bankfull widths ____ ____ ____ _____ _____ (feet)

Downstream

Water depth in culvert (at outlet): _____(0.0 feet)

Culvert outlet at grade cascade free fall backwatered _____ft Stepped footers yes no

Outlet drop (invert to water surface) ______(0.0 feet) Pool present immediately downstream of structure: yes no

Pool depth at point of streamflow entry: _____(0.0 feet) Maximum pool depth: ______(0.0 feet)

Downstream bank heights are substantially higher than upstream bank heigths: yes no

Hydraulic control type: bedrock boulders cobble gravel sand wood other:__________

Distance from downstream end of culvert to hydraulic control: ___________(feet)

Evidence of streambed erosion or aggradation immediately downstream of culvert: erosion aggradation none

Downstream Bankfull widths ____ ____ ____ _____ _____ (feet)

	Upstream	**Downstream**	**In structure**
Dominant bed material at structure	1 2 3 4 5 UNK bedrock present:Y N	1 2 3 4 5 UNK bedrock present:Y N	1 2 3 4 5 UNK sediment throughout:Y N
If substrate is present in the structure, how deep is it? ___< 1 foot ___1-2 feet ___>2feet UNK			
Bedrock present in channel at structure? yes no	Material throughout? yes no		
Sediment deposit types	none delta side point mid-channel	none delta side point mid-channel	none delta side point mid-channel
Elevation of sediment deposits is greater than or equal to 1/2 bankful elevation	yes no	yes no	yes no
Beaver dam near structure Distance from structure to dam	yes no distance: feet	yes no distance: feet	Bed Materials: 0 none
Hard bank armoring	intact failing none unknown	intact failing none unknown	1 - bedrock 2 - boulder
Bank erosion	high low none	high low none	3 - cobble
Streambank scour causing undermining around/under structure	none culvert footer wing walls	none culvert footer wing walls	4 - gravel 5 - sand UK - unknown

Wildlife Data	LEFT	RIGHT	LEFT	RIGHT	
(left/right bank determined facing dowsntream)					Vegetation Type codes:
Dominant vegetation type					C - coniferous forest D - deciduous forest
Does a band or shrub/forest vegetation that is at least 50ft wide start within 25ft of structure and extends 500ft or more up/downstream?	yes no	yes no	yes no	yes no	M - mixed forest S - shrub/sapling H - herbaceous/grass B - bare
Road-killed wildlife w/in 1/4 mile of structure	species:			none	R - road embankment

Wildlife sign and species observed near (up/downstream) and inside structure	Outside structure		Inside structure	
	species	sign	species	sign

Appendix 2 Field data collection form, p. 2 of 5

Page 2

Spatial data collected w/GPS yes no

Photos taken : yes no

Photo filename	Photo view	Description of features in photo

Site sketch

Upstream

Looking upstream into culvert

Flow

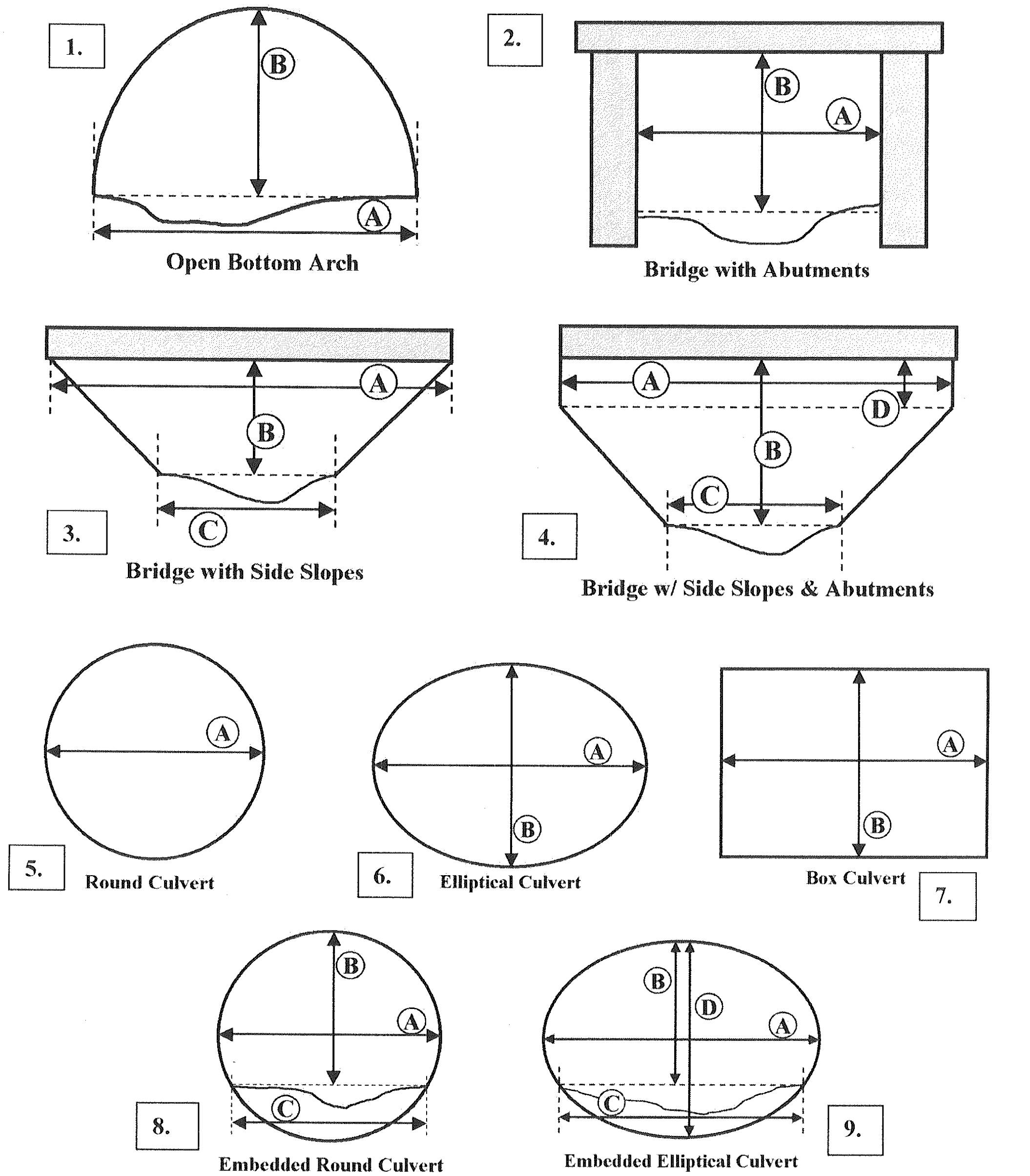
Looking downstream into culvert

Site comments:

Downstream

Appendix 2 Field data collection form, p. 3 of 5

Crossing Dimensions



Crossing Type (from above): ☐ 1. ☐ 2. ☐ 3. ☐ 4. ☐ 5. ☐ 6. ☐ 7. ☐ 8. ☐ 9. ☐ Ford

Upstream Dimensions (ft.): A) ____________ B) ____________ C) ____________ D) ____________

Downstream Dimensions (ft.): A) ____________ B) ____________ C) ____________ D) ____________

Length of stream through crossing (ft.): ______________________ **Crossing slope (%)** ____________________

Appendix 2 Field data collection form, p. 4 of 5

DIMENSIONS WORKSHEET FOR MULTIPLE CULVERT CROSSINGS

Crossing ID# ________

Note: *When inventorying multiple culverts, label left culvert 1 and go in increasing order from left to right from downstream end (outlet) looking upstream.*

Number of Culverts or Bridge Cells ________

Culvert or Bridge Cell 2 of _______

Crossing Type (from above): ☐ 1. ☐ 2. ☐ 3. ☐ 4. ☐ 5. ☐ 6. ☐ 7. ☐ 8. ☐ 9. ☐ Ford

Upstream Dimensions (ft.): A) ________ B) ________ C) ________ D) ________

Downstream Dimensions (ft.): A) ________ B) ________ C) ________ D) ________

Length of stream through crossing (ft.): ________ **Crossing slope (%)** ________

Culvert or Bridge Cell 3 of _______

Crossing Type (from above): ☐ 1. ☐ 2. ☐ 3. ☐ 4. ☐ 5. ☐ 6. ☐ 7. ☐ 8. ☐ 9. ☐ Ford

Upstream Dimensions (ft.): A) ________ B) ________ C) ________ D) ________

Downstream Dimensions (ft.): A) ________ B) ________ C) ________ D) ________

Length of stream through crossing (ft.): ________ **Crossing slope (%)** ________

Culvert or Bridge Cell 4 of _______

Crossing Type (from above): ☐ 1. ☐ 2. ☐ 3. ☐ 4. ☐ 5. ☐ 6. ☐ 7. ☐ 8. ☐ 9. ☐ Ford

Upstream Dimensions (ft.): A) ________ B) ________ C) ________ D) ________

Downstream Dimensions (ft.): A) ________ B) ________ C) ________ D) ________

Length of stream through crossing (ft.): ________ **Crossing slope (%)** ________

Culvert or Bridge Cell 5 of _______

Crossing Type (from above): ☐ 1. ☐ 2. ☐ 3. ☐ 4. ☐ 5. ☐ 6. ☐ 7. ☐ 8. ☐ 9. ☐ Ford

Upstream Dimensions (ft.): A) ________ B) ________ C) ________ D) ________

Downstream Dimensions (ft.): A) ________ B) ________ C) ________ D) ________

Length of stream through crossing (ft.): ________ **Crossing slope (%)** ________

Culvert or Bridge Cell 6 of _______

Crossing Type (from above): ☐ 1. ☐ 2. ☐ 3. ☐ 4. ☐ 5. ☐ 6. ☐ 7. ☐ 8. ☐ 9. ☐ Ford

Upstream Dimensions (ft.): A) ________ B) ________ C) ________ D) ________

Downstream Dimensions (ft.): A) ________ B) ________ C) ________ D) ________

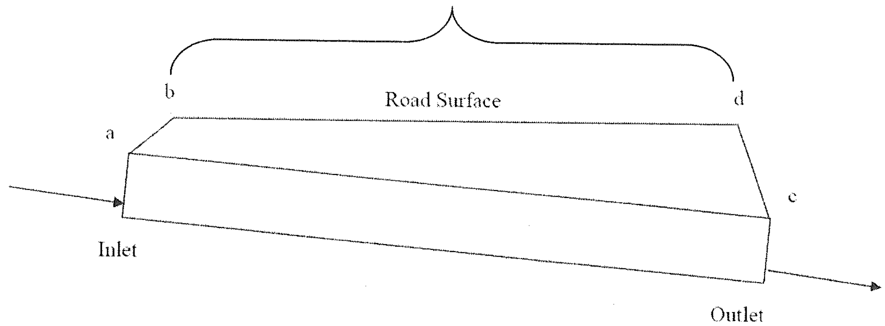
Length of stream through crossing (ft.): ________ **Crossing slope (%)** ________

Appendix 2 Field data collection form, p.5 of 5

Field Data Form: Road-Stream Crossing Inventory

Culvert/Road Elevations (ft.): A) ____________ B) ____________ C) ____________ D) ____________

Road + Shoulder Width (RW) = ______________ feet



Field Data Form: Road-Stream Crossing Inventory

Culvert/Road Elevations (ft.): A) ____________ B) ____________ C) ____________ D) ____________

Road + Shoulder Width (RW) = ______________ feet