Final Project Report
Design and Implementation of a Decision-Support Program for Adapting Civil Infrastructures to Climate Change:

Stormwater drainage system vulnerability, capacity, and cost, under population growth and climate change
Lake Sunapee Watershed, New Hampshire
April 6, 2012

Principal Investigators:

Michael Simpson, Antioch University New England
Latham Stack, Syntectic International

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Program Manager: Nancy Beller-Simms, PhD
Sectoral Applications Research Program
1315 East West Highway, Room 12221
Silver Spring, Maryland 20910-5603
P: 301-734-1205
nancy.beller-simms@noaa.gov

Prime Contractor: Syntectic International, LLC
Suite 212
1037 NW 20th Ave..
Portland, OR 97209
Duns Number: 806805425
Employer I.D. Number: 26-0826323

Co-Principal Investigators:
Name: Latham J. Stack
Position and Affiliation: Principal, Syntectic International, LLC
Address: 4112 SW Coronado St.
Portland, OR 97129
P: 503-901-1939
F: 503-922-4049
lstack@syntectic.com

Name: Michael H. Simpson
Position and Affiliation: Chairman, Department of Environmental Studies
Antioch University New England
Address: 40 Avon St., Keene, NH 03431
P: 603-283-3331
msimpson@antiochne.edu

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Abstract

Numerous studies report that intensified precipitation resulting from anthropogenic climate change will stress civil infrastructures. Communities may have a window of opportunity to prepare, but information to support adaptation programs is sparse. For a moderately-sized watershed, the present stormwater drainage system's capacity for conveying expected *peak flow*, Q_p, resulting from climate change and population growth, was assessed. For a set of climate models and emissions scenarios, a modified delta method was used to downscale the design storm precipitation value to the study site. Runoff rates, current and required culvert sizes, construction costs, and Low Impact Development methods were applied using standard engineering, hydrologic, and costing methods. An outreach, education, and stakeholder participation program was applied to promote the implementation of infrastructure adaptation. 12% of culverts are already undersized for current landuse and the recent climate. 35% of culverts are estimated to be undersized for the *"most likely"* estimator of a mid-21st century pessimistic climate change and population growth scenario. At the +95% confidence limit for the design storm estimated under the A1fi emissions trajectory, with population growth, 70% of culverts are projected to be undersized. The watershed-wide cost of upgrading the culvert system for the *"most likely"* A1fi design storm is estimated to be 12% greater than constructing culverts to the historical TP-40 design storm. Funding adaptation via a 20-year, 2% municipal bond, the average property tax bill is estimated to increase by $0.05 per $1,000 of assessed value, resulting in an average annual property tax increase of $15.00 per household, based on the recent median home price. In the context of an ongoing trend of extreme and record storms regionally proximate to the study site, the Outreach program and robust estimates of required system capacities has motivated the community to develop and implement a program of long-term adaptation.

The study found that rates of undersized culverts, and adaptation cost, are insensitive to increases in precipitation and, along with other factors, provide financial incentive to incorporating a significant safety factor into future culvert design. A long-term program to upgrade the stormwater management system, utilizing Low-Impact Development strategies and managing uncertainty and costs, may maintain historically acceptable risk levels. To enable widespread adaptation, the federal government, and civil engineering and climatological professions should promulgate a single set of TP-40-like isoplubial maps, based on best-available climate model output. Multiple climate models and ensembles should continue to be maintained for research purposes. This study makes a significant contribution to establishing the manageability of uncertainty, in support of programs to adapt civil infrastructures.

Contents

Executive Summary

Schedule of key findings:

1. Introduction

This report describes methods and results of an integrated assessment and outreach project funded under the ninth competition of NOAA's fiscal year 2009 Climate Program, *Sectoral Applications Research Program* (SARP), *Water Resource Management.* The overarching purpose of this study was to promote stakeholder-driven adaptation of vulnerable stormwater management systems, by demonstrating a local-scale, quantified, and actionable protocol for maintaining historical risk levels for communities facing significant impacts from climate change and population growth. The study also committed to a research aim of examining several unresolved issues in the stormwater adaptation literature pertaining to uncertainty. The analyses, resulting adaptation tools, and associated outreach program provide new and consequential science-based knowledge; identify impacts and societal vulnerability; provide practical information to support decision-making; and provide a transferable template for stakeholder-driven implementation of adaptation programs.

The report is comprised of this primary document, and the appendices which contain detailed reports of the various activities performed during the project, that were deemed too lengthy for inclusion in the primary document. These pertain to:

- Technical track:
  - Precipitation modeling;
  - Runoff and culvert capacity modeling;
  - Buildout of the watershed to incorporate population growth into projections;
  - Low Impacts Development;
  - Cost analysis.
- Outreach program

Problem Statement, from Funding Proposal

It is now generally accepted that mitigation of greenhouse gas emissions must be accompanied by adaptation of civil infrastructures. As noted in the Fourth Assessment Report (AR4) of the IPCC (IPCC, 2007), adaptation can no longer be postponed pending perfect science, i.e. the effective elimination of uncertainty in coupled-climate model output and subsequent downscaling. Rather, we must learn to manage residual uncertainty in current-generation output and methods, enabling community leaders to make the myriad local-scale decisions that comprise the development and implementation of infrastructure adaptation plans.

This study proposed that an efficient path to this learning derives from moving beyond the regional vulnerability assessments that still typically characterize published literature, to local-scale assessments of the significance of climate uncertainty. These serve as a foundation for the development and implementation of local-scale adaptation planning studies, that utilize best-available information and methods to manage uncertainty: learning-by-doing.

Hydrology provides a precedent for this strategy, in modeling the rainfall-runoff relationship from which drainage system capacities are specified. Significant uncertainty in the ability to quantify this relationship persists today, even after roughly 100 years of developing modern runoff modeling theory, for example, "…Recognizing the high degree of error or uncertainty inherent in many aspects of stormwater modeling…generally, the goal of stormwater modeling is to provide a reasonable prediction of the way a system will respond to a given set of conditions" (MPCA, 2006). Yet the construction of drainage systems, engineered with best-available knowledge and methods, has always proceeded in parallel with the development of theory. This strategy has been justified because the risks from implementing less-than-perfect systems are less than the risks from waiting for more-perfect knowledge. The urgency of adapting systems to already-manifesting climate change justifies a similar strategy. The alternative to commencing adaptation, standing by as lives are lost and communities damaged from no-longer-adequate systems, while we wait for the chimera of perfect science, is neither acceptable nor necessary.

General Relevance

Studies have found that the historical precipitation intensity/return-period relationship across the coterminous United States exhibited a rising trend over the 20th century (Karl and Knight, 1998; Kunkel et al., 1999). The potential vulnerability of civil infrastructure to climate change-intensified precipitation has remained a core finding in research literature (Hennessy et al., 1997; Zwiers and Kharin, 1998; Groisman et al., 1999; Meehl et al., 2000; Semenov and Bengtsson, 2002; Voss et al., 2002; Watterson and Dix, 2003; Tebaldi et al., 2006). Projected increases in storm intensity will significantly increase runoff and flooding, and degrade water resources, compounding impacts from land-use change driven by population growth.

Local relevance and timeliness

In New England the presence of a climate-change signal for precipitation has already been detected (Wake, 2005; Hayhoe et al., 2006; Henderson and Shields, 2006). As with many communities in the northeastern United States, the region proximate to the study site is experiencing an unusual and ongoing period of extreme or record precipitation events. Since 2005, central New Hampshire has annually experienced an extreme storm with an intensity/duration at, or above, the historically 1-in-75 year return period. Two of these directly impacted the study site on October 8, 2005 and April 16, 2007, overloading stormwater management systems and causing hundreds-of-thousands of dollars in damage (Newbury NH, 2007). These events also increased turbidity and pollutant loading, degrading drinking water resources for communities in, and downstream from, the study site. A 1-in-75-year event equates to a 1.3% likelihood of occurrence in a given year.. The joint probability of a 1-in-75-year event occurring in six consecutive years is vanishingly small.

The vulnerability of current drainage systems to current storm levels has been detected in previous work by the study team. Studies of Keene, NH, and the Oyster River watershed on coastal New Hampshire found that 26% and 10%, respectively, of culverts are currently undersized for the recent (1971-2000) intensity/duration precipitation designated by the State as the design storm for common culverts (Simpson et al., 2005, Stack et al., 2010). By the mid-21st century, 39% of culverts in Keene are estimated to be undersized, based on an 18% increase in the design storm under the A2 scenario (ibid.). For the Oyster River watershed, 20% and 24% of culverts are projected to be undersized based on 30% and 59% design storm increases estimated for the B1 and A1fi scenarios (ibid.). These current and projected vulnerabilities indicate the need of policy and implementation responses that presently are not available.

At the state-level in New Hampshire, the institutional responses to climate change target mitigation, with minimal attention to adaptation (NEG/ECP, 2001; NHDES, 2001; RGGI, 2005; SPNHF, 2007; TNC, 2007). Among local leaders, although recent extreme storms are increasing awareness of the vulnerability of stormwater management systems (Simpson, 2007), with no available alternative to TP-40 the generally response has been to rebuild destroyed infrastructure to previous capacities (Cedarholm, 2008).

However, we are aware of an emerging trend, by road agents and other public works managers, to rebuild post-flood culvert damage with larger-capacity components, on an ad hoq basis with neither formal design nor direction from leaders (Throop, 2006; Anthony Bergeron, 2011). These laudable efforts typify communities struggling to cope, in the absence of guidance from the scientific and engineering professions, with an observed increase in precipitation intensity. These decisions are being made without support from professionals, scientists, and government standard-setting bodies, based solely on empirical observation that components are repeatedly failing, and that post-failure repairs are more costly than pro-actively increasing capacity (Watson, 2006; Durfor, 2007). This approach is inadequate: it depends on road agents or public works managers being both willing and able to modify past practices; the lack of climate change-informed planning may result in these incrementally up-sized components themselves becoming undersized prior to the expiration of service life; and components are only upsized after they've failed either dramatically- or frequently-enough to attract attention.

Outside of New Hampshire, reductions in runoff and peak flow are secondary benefits of stormwater programs being undertaken for other objectives, however the extent of these benefits are not being specified to achieve climate change readiness. Locally-acknowledged changes in run-off amounts and the need to protect adjacent sensitive natural systems have resulted in certain private-sector development projects limiting water quality impacts from storm events, with a resulting reduction in impacts to stormwater systems (Gunderson et al., 2011). Similarly, the need to economically minimize the release of untreated stormwater and wastewater from combined sewer overflow systems has motivated cities such as Portland, Oregon, Kansas City, Chicago, and New York City to establish green-infrastructure strategies to reduce flow, with a resultant decrease in stress to built infrastructure (Houle et al., 2011).

Gap in knowledge to inform adaptation decisions

This challenge is not confined to northern New England, stormwater line-managers in many parts of the country are being asked to respond to unprecedented increases in the frequency of extreme or record events (Oberts, 2007). Though communities have both an urgent need and an emerging desire to adapt stormwater management systems, the dearth of sufficiently specific and quantified information to support adaptation projects, identified in previous publications, persists (Dore and Burton , 2000; Wittrock, 2001; McGuire, 2003; Semadeni-Davies, 2004; Atkins PLC, 2004). In consequence, communities are vulnerable.

Three studies estimating climate-change impacts and specific adaptation requirements for stormwater management systems have been published, none recently (Kije Sipi, 2001; Waters et al., 2003, based on Waters' earlier Masters thesis, Waters, 2001; and Semadeni-Davis et al., 2008). Kije Sipi (2001) and Waters (2001) modeled climate change effects by applying a North America-wide rule of thumb proposed by Zwiers and Kharin (1998), developed from 1992-era, second-generation general circulation model output. Semadeni-Davis et al. (2008) projected climate change impacts for the 2071-2100. period, a time horizon that yields less precise results because of its distance in the future, and that also is of reduced adaptation utility for drainage system components that typically have useful lives of 50 to 70 years (for galvanized and concrete pipe, respectively).

The lack of published research on factors influencing stormwater infrastructure adaptation has become more urgent recently, as engineering firms have begun to plan adaptation projects. For example, the City of Alexandria, Virginia has contracted with a national firm to perform a five-year study of climate change-cognizant storm sewer capacity requirements (van der Tak, et al., 2010). In addition, the Comprehensive Stormwater Plan of Keene, NH (Keene NH, 2011) specifically commits to "Change design requirements for new or refurbished roadways,…Foster innovative stormwater design requirements,…Identify areas where increased infrastructure capacity is needed to hold/divert water, and include replacement or upgrade in [the] Capital Improvement Program."

Political and organizational challenges

In addition to the lack of published information and design specifications to guide adaptation, for New Hampshire the political will to adapt is obstructed by the presence of institutional inertia. The State legislature mandated the formation of a Stormwater Commission in 2008, to which testimony was presented on the projected changes in storm intensity and frequency and the potential impacts on built water-conveyance, and associated road, infrastructure (Simpson, 2008). However, the final summary brief to the public solely focused on water quality and water quantity impacts from an increasing percentage of imperviousness area, omitting any mention of the aforementioned testimony on already-manifesting and projected increases in precipitation intensity (NH Stormwater Commission, 2010). More recently, the passage of Hurricane Irene, which resulted in widespread impacts to culverts and bridges, has generated discussion at both the local- and state-levels of vulnerability of road infrastructures. However, the focus has been on improving emergency response and disaster relief preparedness, rather the longer term vulnerability analyses and broader adaptation planning (Simpson 2012).

It has been shown that even short-term forecasts are not included in water resource planning and management decisions (Callahan, 1999; Lach et al., 2005; Rayner et al., 2005; Hartman, 2005). At the local-scale, social and institutional constraints, and a tendency to discount events far-removed in time or space, create barriers to incorporating adaptation into future plans (Broad and Agrawala, 2000; Patt et al, 2005; Hillerbrand and Ghil, 2008). Socio-ecological systems (SES) have self-reinforcing mechanisms that work to resist adaptive behavior (Gunderson and Holling 2002), due in part to a lack of perceived legitimacy of scientific information (Walker et al, 2002). This perception is often influenced by the media to which decision-makers attend, and by the particular sources that inform reporting (Speth 2004; Grundman, 2007; Staut, 2008). Our experience, with facilitating environmental policy development and implementation initiatives, indicates that the motivations underlying resistance to change also include: potential conflicts with local knowledge and traditions; initial negative political response and resistance; competing internal organization needs; and public and official apathy. In order to mitigate these obstacles, and promote utilization of the technical results of this project, a program of education and participative decision-making was conducted with local stakeholders.

Project overview

The project performed an integrated assessment of local-scale stormwater system vulnerability to climate and landuse change, and resulting design requirements. From this foundation the project provided a planning-scale, risk-based, prioritized schedule for adaptation of individual components and sub-catchments, and estimated costs associated with adapting the infrastructure to required capacities. Through stakeholder participation, and community education and outreach efforts, the project also provided a forum and process to empower communities to translate knowledge gained in the technical activities into action. Because participatory approaches and transparency in decision-making activities and stakeholder actions are critical for the legitimacy of initiatives (Gruber and Clark, 2000; Walker et al., 2002; Campbell and Vainio-Mattila 2003), all activities of this proposal were framed with transparency and public participation in mind.

The integrated assessment drew on a multi-disciplinary team with expertise in adaptation policy and scenario generation, stakeholder outreach and participative decision-making, civil engineering, finance, landuse, Low Impact Development (LID), and statistical downscaling methods. The primary stakeholder organization, the Lake Sunapee Protective Association (LSPA), participated on the investigative team.

Project Aims

The funding proposal committed to four aims:

1. Develop reliable, quantified, best-available estimates of likely local-scale impacts on runoff and peak flows, Q_P, resulting from mid-21st century climate change and build-out, based on probabilistic estimates of the climate-changed design storm and population growth;
2. Model the required capacities, and associated upgrade costs, for existing water-related infrastructures to convey current and future Q_P from stormwater runoff, and model the climate-changed one-percent (100-year) flood plain;
3. Develop a risk-based strategy for economically managing Q_P, incorporating Low Impact Development (LID) principles, and system upgrade costs derived from analyses of replacement-cost, cost-avoidance, and substitution cost;
4. Catalyze local and national adaptation by developing and applying a program of citizen and stakeholder outreach and education; facilitate a participative decision-making process that implements the results of the technical analyses; disseminate results regionally, and nationally;

A fifth research aim studied the sensitivity of drainage system capacity and construction cost to uncertainty in the design parameters landuse, soil moisture, and precipitation.

2. Methods

(Note: to manage the file size of this report, Appendices provide additional information supplementing the Methods section.)

An effective response to the increasing inadequacy of civil infrastructures must address uncertainty in climate model projections of future precipitation regimes, provide adequate estimates of local-scale impacts and required system capacities, and address institutional inertia to adaptation. Sufficient infrastructure adaptation plans must also be cognizant of projected population growth.

As noted above, project activities can be divided into technical and Outreach tracks. Technical activities transferred coupled-climate model projections to the stormwater infrastructure, in a form understandable to planners, resource managers and decision-makers. These analyses modeled capacities required for the infrastructure to convey peak flows from a range of projected mid-21st century climate-changed precipitation and population growth scenarios; the potential for LID methods to provide a more economical management of peak flows than drainage system upsizing; and planning-scale estimates of adaptation costs. An overview of the study protocol for technical activities is provided in Figure 2-1.

One hundred twelve (112) culvert locations were identified within the study site and modeled. The response of each culvert to 300 combinations of precipitation, landuse, and soil moisture conditions was estimated. This yielded a total of 33,600 records of culvert response, comprised of:

• Twenty (20) precipitation levels, which were directly input to the runoff/culvert models: seven (7) mid-21st century GCM/SRES combinations; recent NCDC observed records for 1971-2000; and the TP-40 value increased in 25% increments from 100% to 300% of TP-40. For GCM/SRES and observed scenarios, estimators included *most likely* (*ML*) values and upper and lower 95% confidence bounds. Impacts for an additional four (4) GCM/SRES combinations, including *ML* estimators and 95% confidence bounds, were derived by overlaying precipitation estimates for these onto the precipitation-hydrology-hydraulic response curve established from the TP-40-plus-arbitrary increments information;

• Five (5) landuse scenarios were modeled: current, buildout, buildout with steep slopes excluded, buildout with LID, and buildout with LID and steep slopes excluded;

• Three (3) antecedent moisture conditions (*AMC*) were modeled: dry, average, and wet.

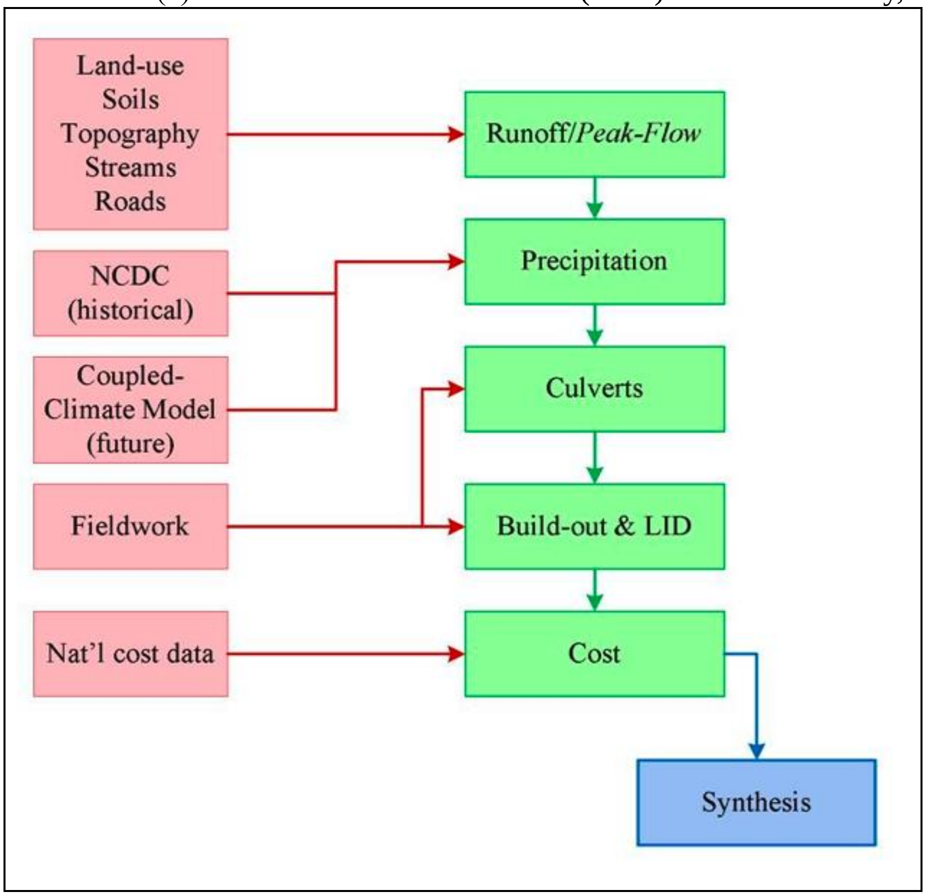


Figure 2-1. Major data sources, and flow of technical activities

<u>The Study Site: Physical and Political Features</u>

Physical features

The Lake Sunapee Watershed is a largely undeveloped watershed with good water quality and small amounts of development. This watershed is a medium-sized drainage basin in the Sugar River Watershed of the upper Connecticut Basin (Hydrological Unit HUC 12 # 010801060402), a sub-watershed of the Connecticut River basin. The watershed encompasses 13,470 hectares (30,948 acres or 48.36 square miles), and 24 micro-watersheds, with 275 km of roads and 125 km of riparian corridors.

There are 13 lakes and ponds in the watershed. Lake Sunapee is the largest, at 4,088 acres, with a mean depth of 37 feet and a maximum depth of approximately 105 feet. The lake is relatively long and narrow, with a perimeter of 32 miles. The shores are largely developed with both year-round and seasonal residential development. Lake Sunapee is designated Class "A" for drinking water resources, serving as a primary source for residents living around the lake, and a back-up source for the town of Sunapee. The Lake is considered one of the cleanest in the country, the result of nearly 100 years of water quality monitoring and advocacy by the Lake Sunapee Protective Association (LSPA). Outflow from Lake Sunapee occurs through a flood control dam into the Sugar River, which drains into the Connecticut River and subsequently into the Atlantic Ocean.

Wetlands represent a relatively small portion of the watershed. Excluding lakes and ponds, 1,116 acres (3.6% of the watershed) are comprised of palustrine (freshwater) wetlands dispersed throughout the watershed. Terrain within the watershed ranges from steep slopes (greater than 25%) to rolling terrain, and 7.6% (2,352 acres) of the watershed are considered steep. Elevation ranges from over 2,760 feet at the summit of Mount Sunapee to 1,093 feet at the Lake Sunapee dam outflow. 23% (7,202 acres) of land area is in conservation, however only small portions of shoreline are permanently protected from development. Impervious surfaces, an important factor determinant of runoff rates, were estimated in 2004:

- Total Impervious Surface within the Lake Sunapee Watershed: 5.8%
- Total Impervious Surface within 250 ft. of the shore: 28.2%

Table 2-1. Towns in the study site

Town	Acreage	Percent of watershed area
Newbury	9,395	30%
Springfield	7,704	25%
Sunapee	7,446	24%
New London	5,310	17%
Sutton	828	3%
Goshen	266	1%

The watershed includes portions of Merrimack and Sullivan Counties and portions of the six towns of Newbury, Springfield, Sunapee, New London, Sutton, and Goshen (Table 2-1). Sutton and Goshen have no culverts within the study site, therefore project analyses conducted at the town-level have no results for these towns.

Political features

New England and New Hampshire have a long tradition of home rule, of which the town meeting is the outward manifestation. This is balanced by legislatively implemented mandates at the state level (Walker DB, 1972; State of NH, 1979; Barron, 2003). These comprise a series of nested relationships, each of which influences climate change adaptation decisions (Figure 2-2.).

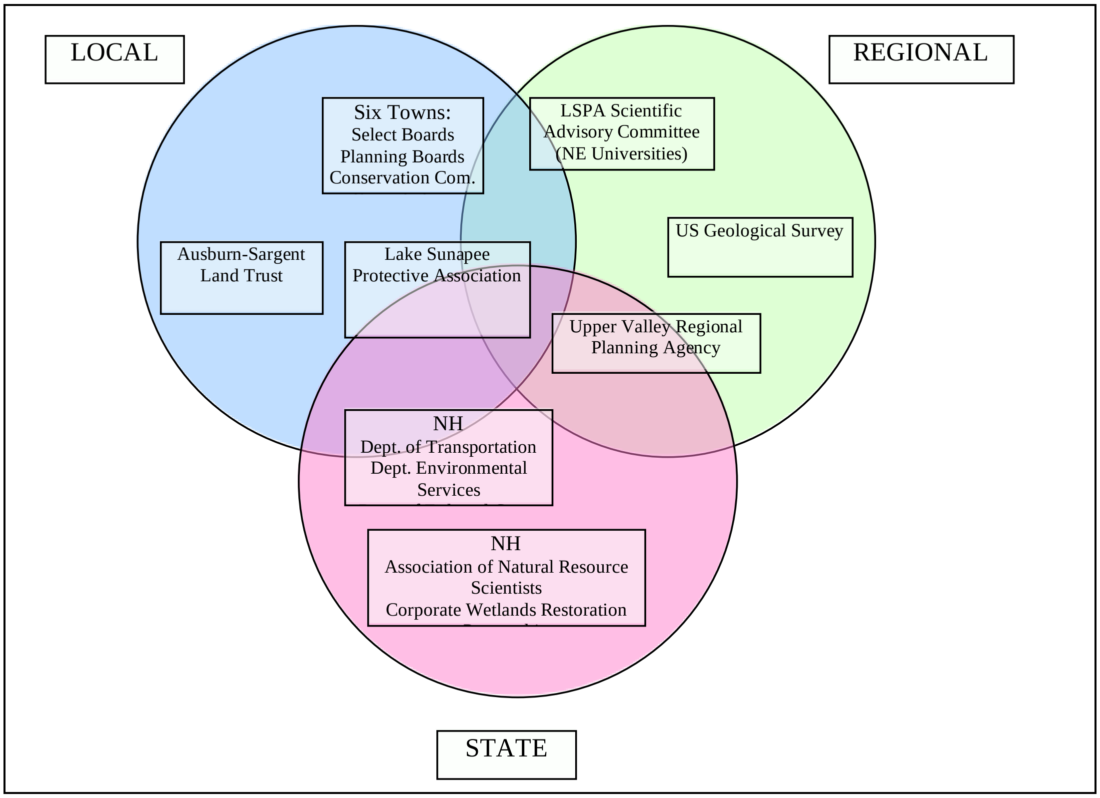


Figure 2-2. Nested decision-making relationships affecting the study site

<u>Precipitation model</u>

Commitment from the funding proposal

<u>Aim 1, Activity 2</u>: Utilize down-scaled coupled-climate model precipitation output for gridpoints in the northeastern US, and historical precipitation records for the study site and proximate stations, to derive probabilistic baseline and mid-21st century climate-changed design storms for the study site.

<u>Technical Approach</u>: The design storm will be the 24-hour duration, 25-year return period (4 percent probability), as specified for simple culverts by the New Hampshire Department of Public Works & Highways Manual. Establish intensity/return-period relationships for the design storm by fitting National Climate Data Center (NCDC) historical precipitation records for the study site, and coupled-climate model output for gridpoints surrounding the study site, to a *point process* model of *peaks-over-threshold*. Fit data to a bivariate model, for which the second variable is time, to model the non-stationary character of near-term climate change impacts. Utilize stepwise regression to transfer percentage changes in the *point process* parameters location, scale, and shape, from coupled-climate model gridpoints to the study site. Utilize the current-generation World Climate Research Programme's Coupled Model Intercomparison Project phase 3 multi-model dataset prepared for the IPCC AR4

(Meehl et al., 2007), for the SRES emissions scenarios A1B and A1Fi, and for the 3-month periods March-May (Spring), June-August (Summer), and September-November (Fall). Use thirty-year data records for all analyses, and regionalize the shape parameter for the study site, to provide a reliable estimate of the intensity/return-period relationship (Figure 3). Results will include most-likely estimators of design storms, and 95% confidence intervals.
Deliverables: Probabilistic estimates of the baseline (1971-2000) and mid-21st century 24-hour, 25-year design storm, and of rates of change in the design storm during the intervening period.
Evaluation: Assess the effectiveness of the specific methods for estimating design storm values. Validate the model by determining skill at estimating the design storm for a known historical period.

Methods (Also see Appendix 2)

Future precipitation was estimated by applying, to the design-storm level of intensity-duration-return-period determined from recent historical records for the study site, a percentage increase derived from general circulation model output. Salient features of this process include:

• Because historic New Hampshire guidelines specify that culverts be designed to accommodate peak flow from a once-in-twenty-five-year precipitation event lasting for 24 hours, the percentage change in this specific event, from recent to mid-21st century, was estimated. 24-hour results were obtained by converting daily GCM output and daily historical records;

• Based on generally accepted hydrological practice, the 25-year 24-hour event was estimated for both historical and GCM output;

• To measure the impact on study results from uncertainty in climate change projections, a range of GCMs, emissions scenarios, and downscaling methods were used. To establish the relationship between watershed hydrological characteristics and engineering hydraulic design methods, the response of the combined hydrologic/hydraulic system to arbitrary increases in precipitation from 100% to 300% of TP-40 was determined;

• A *point process, peaks-over-threshold* statistical method was used to derive the 25-year 24-hour value for each set of sample data.

Model output was statistically downscaled using a variation of the Change Factor (Diaz-Nieto and Wilby, 2005), also known as the Delta, or Perturbation Factor, method. This was applied using a direct, multi-site approach (Haylock et al., 2006). Change factors were derived using extreme value statistics to model the low frequency (high return period), more hazardous events residing at the tail of the precipitation distribution. Civil infrastructure is generally designed to accommodate a specific low-frequency/extreme-value event. As noted above, New Hampshire design guidelines has specified that common culverts be designed to accommodate peak flow resulting from the once-in-twenty-five year event (i.e. the event having a 4% probability of occurring in any given year), specified by the TP-40 standard established in 1961 (Hirshfield, 1961). Recent studies have applied *point process* theory to extreme value statistics in the modeling of precipitation (Coles and Pericchi, 2003), and the present study fit data to a *point process* model of *peaks-over-threshold*, 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.

Thirty years of continuous daily precipitation records for GCM output and observed NCDC station data, for GCM gridpoints and stations proximate to the study site, was extracted from the full datasets. The thirty-years of records were conditioned for comparability between GCM and NCDC data, and between that data and design storm requirements:

• Units of measure were converted to inches of rainfall;

• In order to convert daily rainfall totals, from GCM output and NCDC historical records, to the 24-hour totals required per New Hampshire culvert design guidelines, daily records were multiplied by 1.13, following the results of Young and McEnroe (Young and McEnroe, 2003). This multiplier must be applied to compensate for the difference found between daily precipitation totals obtained from measurements taken at a specific time of day (or daily totals in the case of GCM output), and totals obtained by taking 24-hour totals regardless of when the 24-hour period occurs. For example, a 24-hour event might occur from 8:00 p.m. to 8:00 p.m. the following day. If cumulative precipitation measurements are taken at 9:00 a.m. every morning, for this rainfall event precipitation would be divided between that accumulated between 8:00 p.m. and 9:00 a.m., and that accumulated between 9:00 a.m. and 8:00 p.m. Studies have shown that multiplying daily records by a factor 1.13 accurately converts daily totals to 24-hour totals (ibid.).

• Rain gauges used for NCDC records have a detection limit of 0.05 inches, with precipitation amounts of less than 0.05 inches recorded as “Trace”. Generally accepted hydrological practice converts “trace” records to 50% of the minimum detectable value, in this case 0.025 inches (Mitsch and Gosselink, 2000). For NCDC records, 0.025 inches was substituted for all notations of “Trace”. For GCM output, 0.025 inches was substituted for all values less than 0.05 inches.

General Circulation Model output:

Data used to estimate the impact of climate change on precipitation were taken from the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset. Downscaling was achieved by two methods: the modified delta method described below and used in previous studies by the project team; and, for comparison with other downscaling methods and previously published results, a subset of the NECIA downscaled dataset used for a set of 2007-published studies of climate change impacts on New England (Hayhoe et al., 2007).

The selection of GCMs used for the modified delta method downscaling was based on the common international practice of national adaptation programs utilizing the GCM supported by that country, e.g. United Kingdom uses the HadCMx series of GCMs, and Canada uses the CCCma CGCMx series of GCM. Therefore, two of the three potential candidates for a hypothetical future United States adaptation program were selected for this study. The Geophysical Fluid Dynamics Laboratory GFDL-CM2.1 model (Delworth et al., 2006) was selected based on its skill at modeling the North American climate-changed and 20th century climates (Tebaldi et al., 2005; Knutson et al., 2006). In addition, the NCAR PCM model (Washington et al., 2000) was selected due to its frequent use in climate impacts studies, and it's representation of a "drier" climate than that predicted by the GFDL. A six-gridpoint sample was used, representing gridpoints encircling and closest to the study site.

The NECIA dataset from the 2007 studies cited above utilized the PCM and HadCM3 GCMs, and both sets of output were obtained for this study. The NECIA dataset has a resolution of ⅛° for both longitude and latitude a grid-spacing of about six miles, with a gridpoint located in the study site.

The study's schema for the GCM/SRES combinations is presented in Table 2-2. For the modified delta method ("present study" on Table 2-2), the A1fi, A1b, and B1 SRES pathways were used for the GFDL 2.1. The A1b and B1 SRES pathways were used for the PCM, however PCM data for the A1fi pathway was not available from the ESG data portal. For the NECIA-downscaled records, data for the A1fi pathway was used for both the PCM and Hadcm3 GCMs. For all GCMs from each downscaling method, data for the 1971-2000 period, from the Climate of the Twentieth Century scenario was utilized as the baseline from which to estimate the percentage change in the design storm.

Where multiple runs of GCM/SRES combinations were uploaded to the ESG portal by the modeling groups, all runs were downscaled for this study. However, for each combination only a single, mid-point design-storm estimate was selected for use in drainage system capacity studies. Cells in Table 2-2 that contain numbers indicate the number of runs uploaded to the ESG portal. Figure 2 in Appendix 2 shows design storm modeling results for all runs, for all GCM/SRES combinations, and indicates the mid-point run selected for this study.

Table 2-2. GCM/SRES pathway combinations used, for each downscaling method. For combinations using the modified-delta method of the present study, the number of model runs available on the ESG data portal is indicated, all runs were used in this study.

		NCDC Historical	GFDL 2.1		NCAR PCM		HadCM3	
SRES	Period	(baseline)	Present-study	NECIA	Present-study	NECIA	Present-study	NECIA
A1fi	2046-75		1					
A1b	2046-75		3		1			
B1	2046-75		1		2			
Cli20th	1971-00		3		2			
Recent observed	1971-00							

Downscaling model

Thirty year-long records of data for each GCM, SRES pathway, model run, time period, and gridpoint (comprising 978 sets of data), were fit to a *point process* model of *peaks-over-threshold*, using *maximum negative log-likelihood* (*NLLH*) to estimate the three parameters location μ, scale σ, and shape ξ, which established the curve of the distribution. Probability and quantile diagnostic plots of estimated/modeled versus actual/empirical precipitation, were used to assess the goodness of fit of the *point process* curve generated from parameters at the *NLLH* (Figure 2-3). Note, on the Quantile plot in

Figure 2-3, that the most extreme observed value, a bit more than 3.5 inches, is above the line of perfect fit. This means that the best-fit model according to *NLLH* under-estimated this value. Although fairly often this underestimating occurred, occasionally the divergence was large. For these cases a better fit was sought across a range of *NLLH* values. For several datasets a local maximum *NLLH* yielded better fit of extreme values than the global maximum, in this case the local maximum was selected.

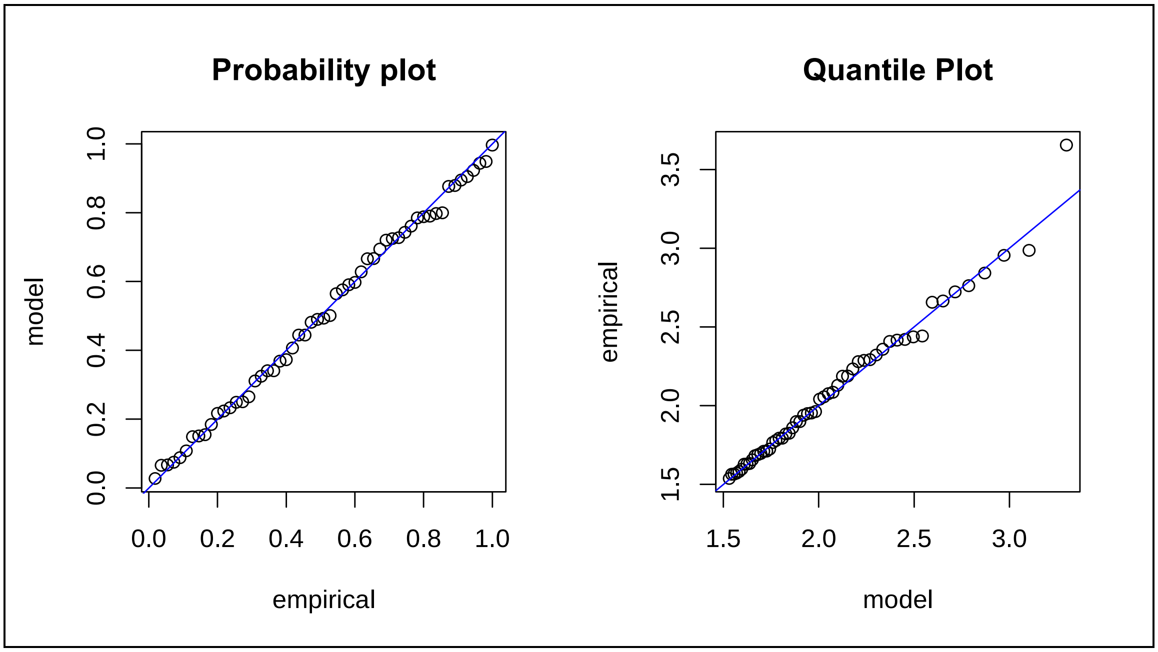


Figure 2-3. Example of diagnostic plots used to assess goodness-of-fit of the point process model computed for each 30-year data record.

The parameters μ, σ, and ξ, were used to estimate the 25-year return period (4% annual probability of occurrence) event for each gridpoint. The percentage change in this value, from recent to climate-changed periods, was computed, and transferred to the study site. For this purpose we modified a method proposed by Shamseldin et al (2006), whereby relationships between GCM gridpoints and observed NCDC stations are established via least-squares regression. At each gridpoint, Δ% in the 25-year event, from the baseline to the mid-21st century periods, was calculated. Stepwise regression identified sets of significant factors ($p = 0.05$) able to predict, at a high r^2, Δ% in the 25-yr event across the six GCM gridpoints. The resulting regression equation was used to transfer the Δ% from GCM gridpoints to NCDC stations. In order that regression equations derived from GCM gridpoints could be applied to NCDC sites, candidate factors included in the stepwise regression analysis needed to be available for both GCM gridpoints and NCDC sites. "Physical" factors tested were elevation, latitude, longitude, and probability of precipitation P_p. Statistical factors tested were, from the *point process* fit, *NLLH*, number of records exceeding the *threshold* value, baseline μ, σ, and ξ, and baseline 25-year event estimates. Residual values were assumed to be independent and normally distributed. Regression transfer functions derived from the GCM gridpoints were used to estimate Δ% in the 25-year event, from baseline to mid-21st century, for NCDC stations. In accordance with common hydrological practice, the shape parameter ξ

was regionally averaged to increase the reliability of results. The method of L-Moments identified 12 New England NCDC stations as regionally similar to the Mt. Sunapee (Table 3-18). For these stations, the mean historical ξ was computed, and increased by the mean $\Delta\xi$.

The above analysis estimated mid-21st century *point process* parameters for the study site. These were input to the equation for the *generalized extreme value* distribution (Shamseldin et al., 2006), to estimate the mid-21st century, 24-hour, 25-year design storm for the study site. This value was used by the runoff and culvert models to estimate *peak flow*, Q_p, and culvert capacity expected under mid-21st century climate-changed conditions. Extreme value statistical analyses were performed using the ISMEV and EVIR packages in "R" (R Development Core Team, 2005), regression analyses were performed in JMP 8.0 (SAS Institute, 1989-2005). Note that statistical analyses described elsewhere in the project were also performed in JMP.

Model validation

The validity of the downscaling model, described in detail in the *Results/Discussion* section of this report, was established in previous studies, most recently Stack et al. (2010). That study tested the methods skill at deriving the 25-yr event for a known historical period, 1971-200, from data for the baseline period 1926-1955. Across twelve NCDC stations, including the study site, that were homologous based on Hoskins' and Wallis' (1997) L-moment regionalization method, the average error in predicting the 25-yr event was −0.3%, with a range of −20.0% to +19.3%, all of which were within the 95% confidence bounds of the *most likely* estimator.

Runoff, Buildout, and Culvert models (Comprised of three study activities)

Commitment from the funding proposal:

Aim 1, Activity 1: Develop a GIS and spreadsheet-based model of runoff and peak flow for each sub-catchment draining into a culvert.

Technical Approach: Model runoff rates using the National Resource Conservation Service (NRCS, formerly SCS) *Curve Number* (*CN*) method. Identify locations of drainage system components, and delineate individual sub-catchments for each component to route runoff flow through the terrain. Derive a composite *CN* number for each sub-catchment, and estimate runoff volumes at each component. Peak flow, Q_p, the parameter to which drainage system components are designed, and Times of Concentration, will be estimated using the standard urban drainage design methods. Create a template to overlay each build-out and climate change scenario onto the model and integrate this with the runoff model to allow for scenario selection. Initialize model run using a baseline scenario of the TP-40 design storm and existing build-out.

Deliverables:

- A GIS project file with all relevant spatial information for data storage and retrieval;
- A database of *CN* runoff coefficients and Q_p, values for the component sizing model;
- A spreadsheet-based model of runoff and Q_p, accommodating user-selectable scenario input.

Evaluation: Assess the effectiveness of the technique at generating the GIS project file. On a sample basis, test the accuracy of the project file against actual components of the watershed. Validate the model by comparing output with historical precipitation and flood record.

Aim 1, Activity 3: Model impacts of population growth on runoff, peak flow, and drainage system capacity, by performing a build-out to existing planning/zoning regulations.
Technical Approach: Derive develop-able land within the study site by excluding, from the total study site area, riparian corridors, conservation easements, steep slope ordinances, and other limitations to development as formally reflected in town ordinances and/or overlay maps. Based on current zoning and standard development methods, apply percentages of impervious, lawn, forested, etc. for the build-out scenario to each subcatchment. Develop regulation/overlay GIS layers at a planning resolution scale as needed to input build-out scenario information to the runoff/*Qp* model.
Deliverables:
• A table of assumptions for the standard build-out scenario;
• A table of curve numbers for each sub-catchment, area-weighted for the standard build-out scenario;
• GIS layers at a planning scale, formatted for input to the runoff/Q_p model.
Evaluation: On a sample basis, test the accuracy of the map against actual impervious areas.
Aim 2, Activity 1: Perform fieldwork to collect specifications of the existing stormwater management system and, at a planning scale, reverse-engineer components to provide estimates of the capacities of existing components, in order to evaluate current and required system adequacy under the various build-out and climate change scenarios.
Technical Approach: Employ fieldwork to collect specifications for existing drainage system components. Develop a spreadsheet-based model to determine the capacity of existing components by reverse-engineering their design using standard engineering flow capacity design methods. These methods will meet or exceed New Hampshire Department of Public Works & Highways Manual regulations for sizing of drainage components.
Deliverables (See Table 1., Figures 4., 5.) :
• A map layer and database containing all of the field and spatial information for system components;
• Schedules of model sizes and capacities for each component;
• A spreadsheet model to estimate, at a planning scale, adequacy of present capacity under the various climate change and build-out scenarios, and to estimate required capacities under each scenario.
Evaluation: Field assessments will be quality assured through independent spot checks and comparison with any available design documentation on file at town offices.

Methods (Also see Appendix 3)
Runoff model

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, well-validated, and it's transparency enabled facile diagnosis of the various sensitivities impacting results. Data providing inputs to the *CN* calculation were obtained from the New Hampshire GRANIT database (Figure 2-4).

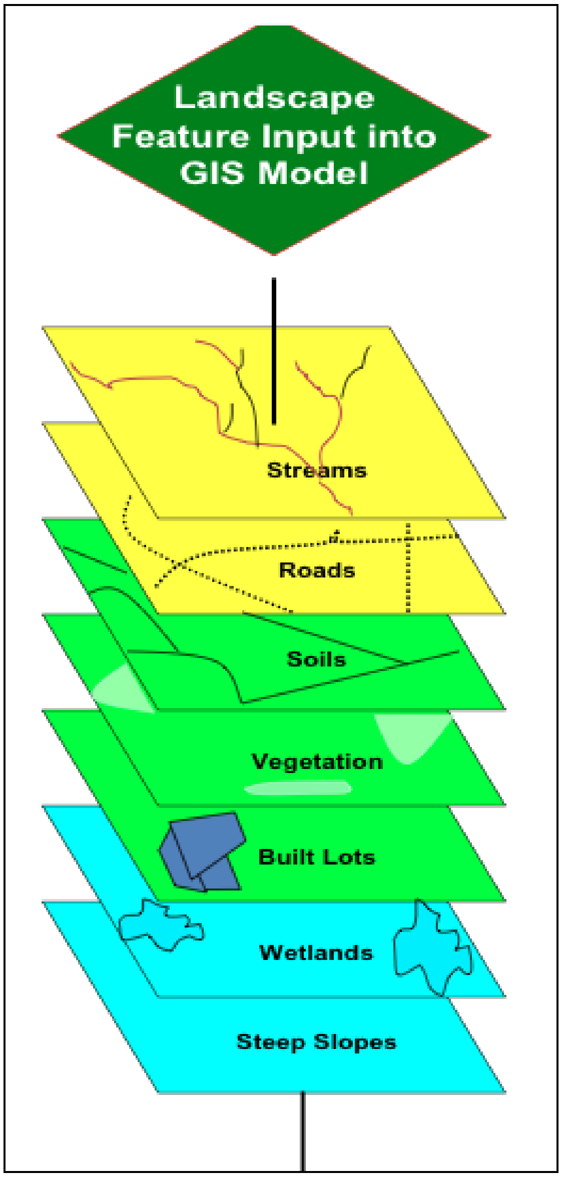


Figure 2-4. Data layers prepared for computation of subcatchment Curve Numbers

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 landuse 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*.

Subcatchments and corresponding culverts were identified using a coding schema that assigned a letter to each primary drainage channel, and a number to each subcatchment/culvert in the drainage channel. Numbering started with the subcatchment/culvert at the bottom of the channel, and increased to the top of the channel A map of the study site, showing this identification schema, is provided as Figure 3-2.

Exceptions & difficulties in runoff modeling

All catchment delineation was performed using WMS 8.3. Using the 10m DEM available for the watershed provided a reasonable method for creating drainage segments for each culvert. There were areas within the watershed in which WMS was unable to create a catchment however and there was no backup method employed. The culverts for which catchments could not be created using WMS were simply dropped from the model.

There are a couple of reasons that WMS might not be able to delineate a catchment. The first and simplest is that there is not a catchment. Since we use the GIS stream and road layers to determine potential culvert locations, in some cases, the digitized stream lines may not accurately depict a flow path on the landscape. The next reason is that the DEM lacks sufficient resolution for a flow path to be determined based on the elevation cells. There are many examples of this within the watershed.

In general, when a particular location was unable to generate a flow path, the first course of action was to change the stream threshold level within the model and see if a smaller threshold could generate a flow path through or near the culvert location. If that failed the *DEM* was reviewed to see if minor changes would create a flow path. If all of this failed, the location was abandoned. An example of a location where the flow path could not be determined is I01: this area lies between contour lines and the I01 location is at the top of a drainage area. For locations for which ambiguous flow paths could not be resolved within the GOS and WMS, fieldwork teams physically determined the direction of drainage. Several areas at the top of the watershed, for example the waters exiting Ledge Pond, and areas north of I-89, required fieldwork to establish flow direction.

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 Lake Sunapee watershed. The inventory process was managed by the Lake Sunapee Protective Association. 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 (Figure 3-7).

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 (ibid.).

Determining flow regime and pipe size

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). Culvert capacity was computed for the culvert currently in place, and for the size required to convey *peak flow* for the various climate change and buildout scenarios. If the required capacity was greater than that of the current size, the culvert was undersized; even though, the actual culvert had installed head and side walls and adequate upstream floodplain storage capacity to handle the ponded water during weir conditions.

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. Using stock sizes resulted in the capacity for a specific culvert increasing as a step function, so that, once a culvert became undersized, the replacement would be adequately sized for a range of increases in *peak flow*. For box culverts, replacements and upgrades were not sized for stock sizes, though these were available for smaller box culverts, because on-site construction of box culverts is more economical according to national construction cost data references (Means, 2011).

Buildout 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 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.

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.

The buildout calculation methods used were created by the team and are perhaps unique. The method begins by creating a modeling point grid. The grid is a regular grid with a point spacing of 46.75 ft. square covering the entire watershed. The baseline landuse layer has a grid cell size of 93.5ft square and the model grid has 4 points per landuse raster cell providing an oversampling. The reason for the oversampling is that the soils are polygons and the elevation grid has a cell size of 24.9 ft. square which means that the landuse grid has the lowest resolution of all the layers. It would be simpler perhaps to set the model grid equal to that of the landuse, but we chose the higher resolution to allow us to construct base information at the higher resolution and then downsample to the landuse resolution for making the final CN raster layers. This provides better edge resolution at the polygon edges.

The method starts with intersecting the model grid with the soils and landuse layers. From the combination of soil hydrogroup code and landcover code the CN (baseline) is calculated for each grid point. The point grid is then converted to a raster using the CN value which created the baseline. Once the baseline CN is calculated, the additional CN raster information is added to begin created the buildout. The model grid is then intersected with additional layers:

1) NWI Wetlands
2) Conservation Easements
3) Soil-slope classes
4) Zoning (Min-Sqft classes)
5) Towns
6) Watershed and Waterbodies

A field is added to the model grid after intersecting with all of the exclusion layers. This field is used to write a "buildable" or "not buildable" attribute to each point in the model grid. This is done using a series of queries that look at the fields for wetlands, conservations easements, soils & slope classes to determine whether each point falls in a buildable or not buildable area. Examples: if a point falls inside an existing conservation easement, it was not buildable, if a point has a slope > 25% then it was not buildable, if a point fell inside a waterbody, it was not buildable, etc. etc. Other such exclusions included: all existing impervious area, poorly or very poorly drained soils.

Two layers were made:

1) Excludes Steep Slopes (ESS): excludes all points with soil slopes > 15%.
2) Allows Steep Slopes (ASS): excludes all points with soil slopes > 25%.

Based on a 2006 Technical Memoranda from UVLSRPC on expected growth within the region, we used the number of homes at buildout as targets for this project. Since our goal was to model conditions at 75% of full buildout, we then reduced the number of homes to 75% of the full value. Once the approximate buildout density was achieved, the CN values for the ASS and ESS conditions were calculated for all "buildable" cells. Baseline CN values were translated for the "not buildable" cells. Two new CN rasters were then created, using the ESS and ASS CN values.

Low Impact Development (LID) model

Commitment from the funding proposal:

Aim 3, Activity 1: Evaluate the capacity of a build-out scenario incorporating Low-Impact Development (LID) principles to manage Q_p more economically than increasing the size of drainage system components.
Technical Approach: Develop a set of LID development standards that would be feasible for the study site, given current zoning standards and the character of existing development. Estimate impervious ratios, under a LID development scenario, for the zoning types within the study site, and apply these ratios to build-out currently undeveloped areas of the study site. Apply these ratios to redevelop currently built-out portions of the study site, based on recent census numbers and applied to the 50-year horizon. Input LID factors into the runoff and component capacity models. Evaluate the change in runoff and peak flow achieved by the application of LID principles.
Deliverables:
• A set of build-out assumptions, consistent with current zoning and the character of current development at the study site, utilizing commonly accepted and feasible LID techniques;
• A table of percentage changes in impervious rates and NRCS *CNs* under the LID scenario;
• Comparisons of the change in drainage system upgrades required under standard and LID development;
• A series of GIS map layers in either raster or polygon vector format illustrating the end result of the LID-based development scenario.
Evaluation: Assess the specific effectiveness of the methods used to model LID impacts. Using published literature, determine the reasonableness of estimates of rates of reduction in runoff and Q_p resulting from the application of LID principles.

Methods (Also see Appendix 4)

The LID Curve Number Analysis was applied using a method developed by McCuen (1983) and formalized in practice by the Maryland Department of the Environment (2008). The method adjusts curve numbers based on the amount of storage designed using LID practices for the 1” water quality event. Because there are a limitless variety of applications of LID systems in a design context, the CN analysis performed here is based on providing a 1” WQV volume for all impervious surfaces. For the CN analysis, the practice type (i.e. bioretention, sandfilter, infiltration trench, etc.) is unimportant, but rather the storage volume is critical.

This analysis applied the use of bioretention for all sites. 1 acre lot sizes and above incorporated the use of porous pavement which adds substantial additional storage. For commercial and industrial sites designs included parking (porous asphalt) and roads (standard asphalt and bioretention), and rooftop infiltration. In this instance, professional judgment was used as to when and where porous pavements might be used. The common practice of limiting porous pavement usage to parking areas was applied.

The runoff curve number (CN) reduction is analyzed using the method outlined in the Environmental Site Design Sizing Criteria (MDE 2008) which is a modification of the TR-55 Method (NRCS 1986). This method applies an adjusted curve number based on the amount of storage built into the landscape using structural LID approaches that will result in runoff volume reduction by recharge. The goal is to achieve a condition equivalent to predevelopment however the method is sensitive and can be used in conditions where both more or less than storage for a 1" WQV can be achieved. It may be desirable to oversize a system to compensate for locations where less storage is possible. Drainage areas with multiple land uses will have composite curve numbers identical to the TR-55 methodology. For sites where equivalent storage for a 1" water quality event or more cannot be achieved then an additional design for the channel protection volume is required. The LID practices should be distributed uniformly throughout a drainage area.

The principle step in the curve number adjustment is the calculation of the rainfall amount captured. For details of the formulas and relationships utilized in the analysis, see Appendix 4.

Cost model

Commitment from the funding proposal:

Aim 3, Activity 2: Perform a planning-scale analysis of marginal upgrade costs for upgrading the system of drainage components to sizes adequate for conveying peak flows from current and mid-21st century climate-changed conditions, and build-out under standard and LID principles.

Technical Approach: Apply a combination of replacement-cost, cost-avoidance, and substitution cost analyses (King and Mazzotta, 2007). The replacement-cost method estimates costs to restore drainage system components and surrounding areas after component failure. The cost-avoidance analysis considers the costs of upgrading infrastructure components to avoid damages from increased runoff and Q_p. The substitution-cost analysis estimates the cost of replacing infrastructure components that have reached their design life, with similar, but adequately-sized, components. Analyses will include cost impacts associated with water conveyance, built infrastructure impacted by increased run-off, damage to built infrastructure along riparian and lacustrine corridors, and the net costs of mitigating or avoiding such impacts. Analysis of water conveyance structures may also include a selected dam along the Sugar River corridor. An optional additional analysis would estimate flood damage within a climate-changed one-percent (100-year) flood zone.

Deliverables:

• A net cost-analysis for upgrading components and other water conveyance structures within targeted micro-watersheds to accommodate Q_p resulting from each scenario;

• A cost analysis of potential damage resulting from a climate-changed 100 year flood zone along the Sugar River in Sunapee, NH;

• A net cost analysis of instituting LID alternatives for projected build-out within targeted micro-watersheds, which will include such costs in zones that are likely candidates for re-development.

Evaluation: Quantify the confidence interval for cost estimates under each scenario, and measure the significance of uncertainty. Compare results with historical records. Assess the effectiveness of study methods for modeling costs and providing meaningful information to decision-makers.

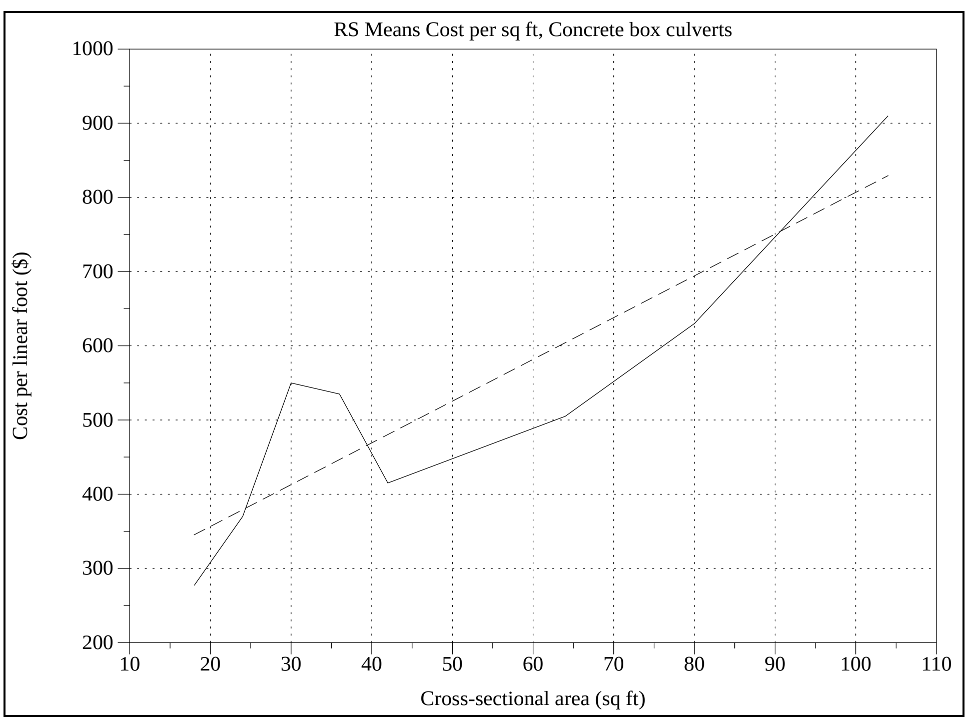
Methods (Also see Appendix 5)

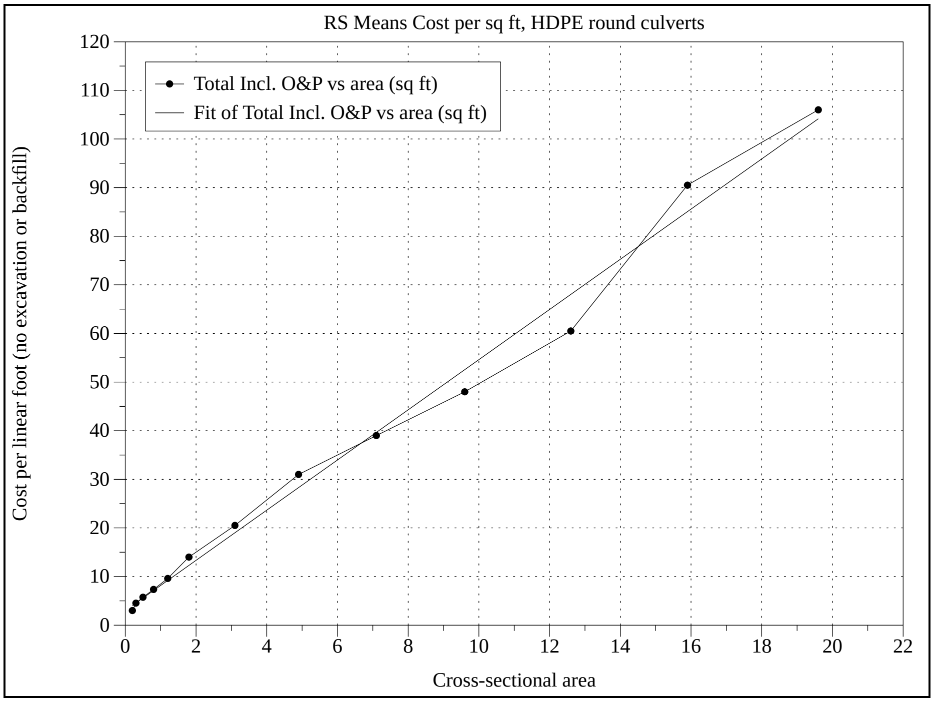
For culverts under-sized for the various climate change and build-out scenarios, the goal of this analysis was to determine the cost of removing the existing culvert and replacing it with one that is adequately-sized. Quantities of materials required for each upgrade were calculated based on field data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

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.

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.

As with the runoff and culvert capacity models, costs were estimated for providing an adequately-sized capacity, for each of the 112 culverts modeled, for each combination of 20-precipitation scenarios, five landuse scenarios, and three Antecedent Moisture Conditions, plus the replacement cost for re-installing a similar-sized culvert as that in place at the time of fieldwork. Thus the cost model generated results for over 34,000 records.





Outreach program

Commitment from the funding proposal

Aim 4, Activity 1: Disseminate results from the technical analyses through the development and distribution of targeted educational materials, public awareness and engagement process, and a stakeholder capacity building campaign; Promote the incorporation of study results, including innovative local land use policies and regulations, into future municipal infrastructure asset management master plans and capital planning/budgeting processes for at least one community within the study site.

Technical Approach: The results of precipitation, engineering, and costing analyses, along with targeted printed and electronic educational materials, will serve as a precipitating event to convene a well-publicized multi-community Regional Forum, to include a broad range of individuals representing both the formal and informal leadership of the communities within the study site. The forum will provide a vehicle to communicate study findings and the importance of local governments' initiating an adaptation planning and action process. The forum will also initiate the first steps of a strategic planning process through participant visioning, goal setting, developing next action steps, and selecting representatives from each of the local governments to serve on an Upper Sugar River Task Force (Task Force). The Task Force will serve as the primary inter-governmental communication resource and will participate in the evaluation component of this work.

Following the Regional Forum, local "Cluster Workshops" will be held in each of the communities. These will include representatives of the Boards of Selectmen, Planning Boards, Zoning Boards, Conservation Commission, local NGOs, and Businesses. Collaborative dialogue between these stakeholders is historically rare, but is critical in building local knowledge, awareness, trust, and future broad local support for proposed changes to land use regulations and capital improvement plans. "Cluster Workshops" will be structured to move the strategic planning process toward assessing barriers to action, identifying potential strategies, and potential next steps. We will promote each community agreeing to "next steps", and will identify future needed assistance prior to adjourning. Future assistance may include public information dissemination and additional working sessions, provided through project staff, Antioch University New England graduate students, the regional planning agency (UVLSRPC), applicable state agencies (DES, OEP, DOT), and stakeholder organizations.

Deliverables:

• Develop and locally-disseminate results of the technical analyses through printed and electronic materials and mass media, including a "citizen-friendly" executive summary of the study (approximately 8 pages), and an Upper Sugar River newsletter (two issues) that gives updates on the initiative's progress at the end of months 12 and 18. (Months12-18);

• Hold the first Regional Forum for board representatives and other key stakeholders for all communities in the study site. This forum will serve as the initial steps in a strategic planning process. (Month 9);

• Conduct a Cluster Workshop with each local community in the study site. (Months 12-16);

• Provide follow-up assistance to each community. (Months 15-18);

• For at least one community within the study site, achieve the incorporation of climate change adaptation into master planning procedures and documents (Month 18).

Evaluation: Establish a qualitative and quantitative instrument that evaluates task outputs including effectiveness of engagement and information dissemination, and that assess progress towards overall objectives that include near term actions of policy makers. The Task Force, serving in the role as the primary inter-governmental communication resource, is well suited to provide assistance to the project management team in this overall evaluation process. Deliverables will be evaluated by the stakeholders involved in each activity at the point of delivery. The evaluation instrument will be tailored to the each of the deliverables, and will assess the levels of knowledge, awareness, and understanding of the future risk and impacts to water related infrastructure and potential actions that can be taken. Evaluation will also assess the readiness of stakeholders and decision-makers to make change, and the actions taken prior to, and by the end of, the study, that improve community infrastructure, enhance land use regulations, and adopt innovative land use practices. This assessment will examine the readiness of local elected and appointed municipal leadership, other stakeholders that are influential in local decision making, and the general public. A survey instrument will be developed to gauge "readiness" and "actions taken to date", using a logic model to identify indicators of progress towards these goals. This instrument will analyze specific stakeholder groups in order to identify potential barriers or leverage opportunities in implementing actions.

Methods (See Appendix 6 for the full Outreach report)

The Lake Sunapee Watershed Infrastructure project was designed to assist local communities in mitigating their current and anticipated future adverse impacts from increased storm water run-off due to climate change. The focus of the public engagement and participation component of the project was to incorporate members of the public and local leadership in the planning, development, and implementation of adaptation actions in response to a) increasingly severe storm events b) flooding caused by undersized culverts, and c) changes in land use practices.

The project included three over-lapping phases: 1) engaging the public, across town boundaries, on identifying current observed changes within the watershed including flooding, increase in erosion and siltation, and conditions of existing storm water infrastructure, 2) researching and presenting the scientific findings to the public, in cluding individual meetings with key public officials in each of the individual towns and 3) supporting formal and informal community leaders in assessing priorities and creating action plans in response to the findings and their priorities.

The overall project was introduced to the public in a stakeholder forum in the fall of 2009, and as a result of that Fall Forum, three Task Forces were formed and met in early 2010 to address publicly identified issues of primary concern. An Advisory Committee was formed to oversee the public involvement of the entire process and provide feedback to the Project Management Team. Also beginning in the fall of 2009, a scientific research team started gathering and analyzing field data on current water management infrastructure, as well as forming predictions of changes to storm frequency and strength in the region. A second Forum was held in the spring of 2010 to update the public on progress made by the Task Forces and researchers. A public talk on climate change was also held at this time. The first of three newsletters (the "Sunapee News-Stream") was published to update the public and stakeholders on progress on the initiative (see Appendix ?). Watershed and flood mitigation related policy recommendations were development during Town workshops that were held during the winter of 2011 at each of the four towns that abut Lake Sunapee. A second newsletter was published in the winter of 2011 to inform the public of Task Force meetings highlights and provide other updates on the project. A third newsletter was published and technical consultation was provided during the spring 2011. The final (third) public Forum and final Advisory Committee meeting were held at the close of the project in June of 2011.

The project's public participation component described in this report was directed by James Gruber of Antioch University New England. The management team for this component included Robert Wood and June Fichter of the Lake Sunapee Protective Association, Michael Simpson of Antioch University New England, and Latham Stack of Syntectic International LLC. Primary staffing for the public participation component was provided by graduate students at Antioch University New England (Marielle Decker, Sarah Demers, Oxana Fartushnaya, Reeve Gutsel, Angela Mrozinski, Jason Rhoades, Jennifer Rootes, and Wendy Stott).

A number of specific evaluation techniques were drawn upon in order to achieve the evaluation goals of this project. These included surveys, feedback from the Advisory

Committee, developing and assessing indicators, and reviewing each of the deliverables. These techniques were drawn upon to assess the *process*, the project stated *deliverables*, and the indicators of *longer-term outcomes.* Surveys were issued at the end of almost every meeting (including the Task Force meetings, Town Workshops, Forums, and Advisory Committee meetings), to help the project management team in the assessment process. Town workshop surveys utilized a five-stage ranking scale (strongly agree, agree, neutral, disagree, strongly disagree) to respond to three statements:

1. The information I received during this meeting was useful and clearly communicated current and future storm water issues facing our town.
2.The workshop was effective at sharing information and facilitating communication among the town officials.
3. As a result of this workshop, I anticipate that my town will likely proceed to plan and develop priority actions to mitigate flooding and other adverse impacts from storm water.

A fourth, open-ended question was also posed: "What issues regarding storm water infrastructure and related planning would you like to learn more about or receive additional technical assistance?" In addition to the surveys at these meetings, the team utilized the Advisory Committee to help assess progress towards meeting the project's stated goals. There were two formal Advisory Committee meetings that focused on assessment. One was in October 2010 and the second was in June 2011. In addition to surveys and the Advisory Committee input, the team developed its own list of indicators to assess stakeholder engagement and readiness for action in the arenas of improving community infrastructure, enhancing land use regulations, and adopting innovative land use practices.

Dissemination of results

Commitment from the funding proposal

Aim 4, Activity 2: Disseminate results to at least four regional and national conferences, in two peer-reviewed publications, and on one internet site, in partnership with existing regional and national adaptation organizations.

Technical approach: Hold a second Regional Forum to share progress in each of the communities and to work towards areas of mutual interest and other regional concerns. Collaborate with existing climate change adaptation organizations to develop and disseminate one instructional booklet nationally (e.g. Cities for Climate Protection, The Pew Center on Global Climate Change, etc.). Prepare and disseminate maps, video and photographs to communicating results. Inform the scientific community of project results by publishing two peer-reviewed papers on study methodology and results. Inform the regional and national professional communities and leaders by presenting results at four regional and national conferences.
Deliverables:
- The second Regional Forum (Month 16);

- Presentation of results at 2 regional and two national conferences (Months 16-24, and beyond);
- Educational booklet disseminated in partnership with an existing adaptation organization (Month 16-24);
- Two peer-reviewed publications (Months 14-24);
- Maps, video and photographs, communicating results, for use by NOAA and for dissemination at conferences and via the internet (Months 14-24);
- Analysis of future research needs (Month 18);

Evaluation: Develop and implement a survey-based instrument to assess the effectiveness of regional and national educational media.

Methods

To-date, activities for this component are still in-progress. The second Regional Forum has been held; future research recommendations compiled in this report; and maps, photographs, and presentations provided to the Climate Program Office.

Five conference presentations have been given, two at national conferences and three at a New England regional conferences. At least two papers, to be submitted for peer-reviewed publication, will follow issuance of this report. A report targeted for non-technical audiences will also utilize the results and discussions compiled in this report.

3. Results and discussion of individual activities

Precipitation model

Results

For the study site, Table 3-1 lists the downscaled percentage increase, from the baseline of the recent historical 24-hour, 25-year event, of the *most likely* estimators for each GCM/SRES combination selected (see Appendices for details). NCAR PCM model results match GFDL CM2.1 for the B1 trajectory. However, PCM results are increasingly dampened, for A1b and A1fi, compared with the GFDL CM2.1 and HadCM3 models. This damping is exhibited whether the downscaling source is this study or the NECIA dataset. These results conform to the PCM's reputation as a "dry" model.

For A1fi, the HadCM3 result computed from the NECIA dataset is lower than the GFDL CM2.1, however, when 95% confidence levels are reviewed (Table 3-3), results are more comparable. The percentages of change from B1 to A1b, and from A1b to A1fi, increase for both the CM2.1 and the PCM. This increasing divergence has repercussions for changes to the return-period/intensity curves, as noted in Figure 3-1.

Table 3-1. Estimated percentage change in the "most likely" 24-hour 25-year event.

		GFDL 2.1		NCAR PCM		HadCM3	
SRES	Period	Present-study	NECIA	Present-study	NECIA	Present-study	NECIA
A1fi	2046-75	64%			12%		53%
A1b	2046-75	20%		8%			
B1	2046-75	5%		5%			

For the study site, *"most likely"* estimated precipitation values, in inches, for the 24-hour 25-year event, are shown in table 3-2. Table 3-2 also includes the TP-40 design storm value (Hershfield, 1961), still used for most drainage system design in New England, and the "most likely" estimator calculated from NCDC historical observed records for the 1971-2000 period. Note that the value for the recent 25-year event is significantly less-than the value for TP-40. A generally consistent finding from this and previous studies by the project team is that TP-40 values exceed those computed from NCDC historical values. This may be due to a safety factor having been incorporated into TP-40. Values for the B1 and A1b scenarios are also less than TP-40. This has important implications for adaptation: although certain culverts are currently undersized even for TP-40, any culvert that is adequately sized for TP-40 will be adequately sized for future changes that conform to B1 and A1b rates (see Table 3-17).

Table 3-2. Downscaled "most likely" estimators of baseline and climate-changed 24-hour 25-year precipitation (inches).

		NCDC & TP-40	GFDL 2.1		NCAR PCM		HadCM3	
SRES	Period		Present-study	NECIA	Present-study	NECIA	Present-study	NECIA
A1fi	2046-75		*6.65*			4.55		6.21
A1b	2046-75		*4.87*		*4.40*			
B1	2046-75		*4.25*		*4.25*			
Recent observed	1971-00	*4.06*						
TP-40	ca1926-1955	*5.10*						

Table 3-3a adds estimators of the 95% confidence limit to the *most likely* values in the previous table. For all GCM/SRES combinations, the range from the *most likely* value to the lower 95% limit is smaller than the range from *most likely* to upper 95% limit. This is a statistical feature of rainfall and the distributions used to model it (e.g. *general extreme value*, *generalized pareto*, *weibull*, *etc*.): the lower-bound for rainfall is 0.00, i.e. no rainfall, while the upper-limit is much less bounded.

Although the precision (i.e. range of estimates) for B1 is essentially the same for the PCM and the CM2.1, for A1b the PCM is less precise than the CM2.1 (also see Appendix 2, Figure 2). For A1fi, the CM2.1 is less-precise than the HadCM3 at the high-end of the confidence range.

Table 3-3a also provides multiples to compare modeled values with TP-40. Because certain scenarios are smaller than TP-40, multipliers for these are less than one. The use of multipliers is a simple way to incorporate climate change into the design process. The Discussion section of this report compares these multipliers to several published multipliers in use, or proposed as a rule-of-thumb, for climate change-cognizant design. Unless otherwise specified, climate-changed analyses and graphics described in this report show results for the GFDL 2.1 A1fi *most likely* estimator, and the A1fi +95% confidence limit. The decision to limit most work to these scenarios was made to simplify understanding and communication of relationships and results. From Table 3-3a and Figure 3-11, the representativeness of the GFDL A1fi and A1fi +95%c.i. is apparent. The representativeness of the GFDL B1 and A1b results can also be seen, and certain graphics and results include the A1b value. However, because the B1 and A1b values are less than the TP-40 value, it is more relevant to discuss adequacy and adaptation in the context of TP-40 rather than these scenarios. It is also pragmatic to discuss adaptation to A1fi, in the context of recent observed emissions and the lack of meaningful progress in emissions control treaties.

Tables 3-3a. For recent observed and all climate-changed scenarios, "Most likely" and 95% confidence limit estimators of downscaled 24-hour 25-year return period precipitation for the Mt. Sunapee NCDC station.

Downscaling method	SRES	Data Source	Period	25-year precip (in.) -95%c.i.	25-year precip (in.) Most Likely	25-year precip (in.) +95%c.i.	Multiple of TP-40 -95%c.i.	Multiple of TP-40 Most Likely	Multiple of TP-40 +95%c.i.
		TP-40			5.1				
Modified Δ	Observed	NCDC	1971-2000	2.70	4.06	6.65	0.53	0.80	1.30
Modified Δ	B1	GFDL CM2.1	2046-2075	2.63	4.25	7.47	0.51	0.83	1.47
Modified Δ	B1	NCAR PCM	2046-2075	2.71	4.25	7.27	0.53	0.83	1.43
Modified Δ	A1b	GFDL CM2.1	2046-2075	3.23	4.87	8.00	0.63	0.95	1.57
Modified Δ	A1b	NCAR PCM	2046-2075	1.88	4.40	9.77	0.37	0.86	1.92
Modified Δ	A1fi	GFDL CM2.1	2046-2075	4.34	6.65	11.10	0.85	1.30	2.18
NECIA	A1fi	HADCM3	2046-2075	4.13	6.21	9.91	0.81	1.22	1.94
NECIA	A1fi	NCAR PCM	2046-2075	2.89	4.54	7.78	0.57	0.89	1.53

Table 3-3b. Return period computed for selected scenarios, for extreme return periods, and for the 11.1" event estimated as the GFDL A1fi +95% conf. limit of the 25-yr event.

Precipitation scenario	Return Period 25	Return Period 100	Return Period 500	Return Period 1000	Return period for 11.1" event
GFDL A1fi +95%ci	**11.1**				
TP-40	5.1	6.2	8.3	9.4	2,500
Recent historical	4.06	5.08	6.44	7.09	10,000
GFDL A1fi	6.65	8.33	10.56	11.63	750

Figure 3-1 shows the change in precipitation across return periods, from the recent historical to the GFDL A1fi mid-21st century estimates. The steepening slope observed here has remained a consistent finding of studies of the impact of climate change on precipitation intensity, dating to Hennessy et al. (1997), and is inherent in the statistical nature of rainfall. The rarer, and hence more extreme, an event, the greater the percentage increase from climate change. Although not shown, the response curve for TP-40 lies approximately half-way between these curves.

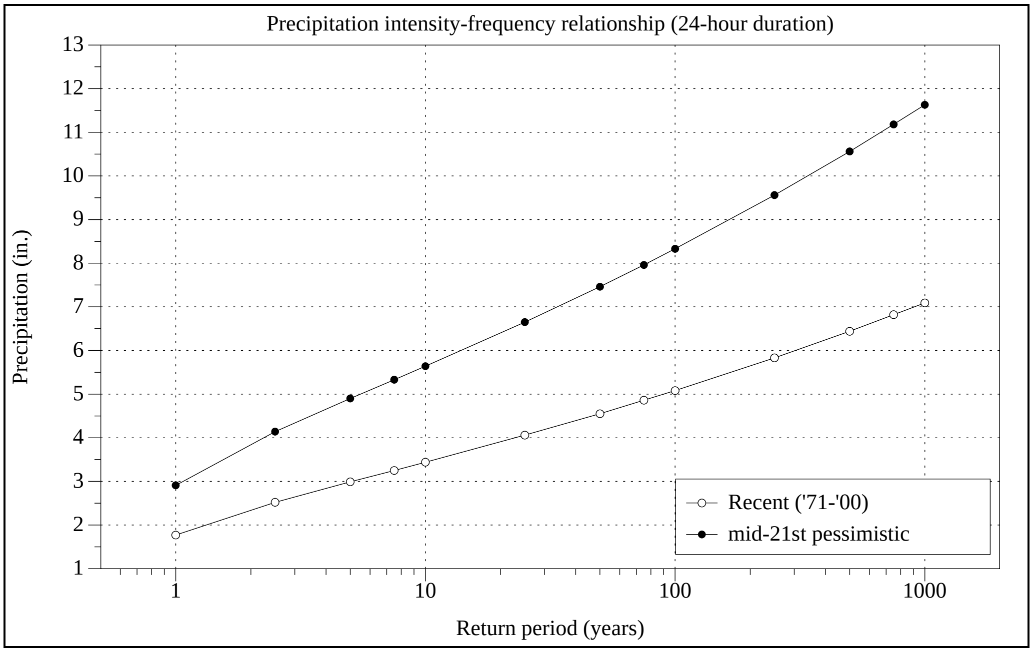


Figure 3-1. Changed slope of the intensity-return period curve, estimated to result from climate change. The "recent" curve was computed from NCDC historical records for the study site. The mid-21st century "pessimistic" curve was computed from output from the GFDL CM2.1, for the A1fi SRES pathway.

Discussion

As inputs to the runoff, culvert capacity, and cost models, the study applied a broad range of estimates for climate-changed increases to the 24-hr 25-yr design storm. The upper limit of this range, used in most analyses, was the +95% confidence limit estimate for the GFDL A1fi trajectory, which is 2.18-times greater than the *TP-40* 25-year design storm (Table 3-3a). The +95% confidence limit is 11.1" of rain over 24-hours, which has been experienced in the region of the study site twice in recent years: in Keane, New Hampshire in October 2005; and in several sites in central Vermont from tropical storm Irene in Fall, 2011. 11.1" of precipitation in 24-hours is comparable to a 750-year return period event for the GFDL A1fi scenario, a 2,500-year event for TP-40, and an over-10,000 year event for the recent historical climate (Table 3-3b). Thus, using the A1fi 11.1", +95% confidence limit event as the upper level in most analyses for this study incorporates a large degree of uncertainty, and yet may be an achievable adaptation target, as discussed later in this report.

The A1fi *most likely* estimator for the 25-year event, at 1.30 times greater than TP-40, is comparable to the 1.21-1.50 multipliers currently used in southwest Germany for climate change-cognizant flood protection planning (Hennegriff, 2006). At 1.30 times greater than TP-40, the A1fi *most likely* multiplier is larger than Zwiers' and Kharin's (1998) rule-of-thumb 1.15 design storm multiplier, that was used in both Jobin's (2001) and Waters' (2003) studies of required stormwater system capacity.

The modified delta method of statistical downscaling (Appendix 2), used in this and previous studies by the project team, appears to give results comparable in robustness to other methods reported in published literature. Literature generally has not found an advantage to dynamic versus statistical downscaling and, as described later in this report, validation work appears to support this method (Figure 3-24, Tables 3-18, 19).

Eight of the set of twenty (20) precipitation values that served as inputs to the runoff, culvert capacity, and cost models, consisted of TP-40, and TP-40 increased in 25% increments to TP-40 x 300%. These arbitrary increases established the response curves for undersized quantity and rate, adaptation cost, and marginal cost, to changes in precipitation (Figures 3-9, 3-16, and 3-18). The curves were fit to simple linear or power functions yielding r^2 values in the high 0.90s, and can be used to determine, with a high degree of reliability, the hydrologic/hydraulic response to specific precipitation levels. Note that the response for LID scenarios on Figures 3-16 and 3-18 diverges from the generic response curve, because LID assumptions alter subcatchment hydrology.

These response curves are solely a function of subcatchment hydrology and engineering design principles: it is immaterial for the response whether an input precipitation value is from TP-40, historical, or climate-changed precipitation. This is important in the context of discussions of uncertainty: within the standard qualifications of uncertainty in hydrological or climate change modeling, the response of the hydrologic/hydraulic system to a given precipitation value is unambiguous.

With the high r^2 values achieved, we relied on these curves to determined how precipitation for the PCM and NECIA scenarios impacted culvert capacity and costs (Figure 3-11), rather than running precipitation values for these scenarios through the models as we did for the GFDL scenarios. This saved labor and computational resources: each precipitation scenario that is run through the models generates 1,680 records, due to the combination of five landuse and three AMC scenarios, and 112 culverts. Modeling the *most likely*, and the -/+ 95% confidence limits, for the two PCM and two NECIA scenarios, would have added over 20,000 records to the 34,000 already being modeled.

Runoff model *(also see Appendix 3)*

Delineation of subcatchments

Digital data layers for roads and for streams were combined to identify road-stream intersections, the preliminary locations for culverts. GPS coordinates for these intersections were provided to the volunteer teams that gathered specifications for the culverts. The hydrologic modeling program WMS was used to delineate the subcatchment that drained to each road-stream crossing (Figure 3-2). Subcatchments that drained directly into Lake Sunapee by definition did not have a outlet point with a culvert, and thus were not modeled for these. Fieldwork teams found that the digitally identify road-stream crossing were sometimes inaccurate, with no culverts near the location specified. Several additional culverts were found by the fieldwork teams that were not revealed by the digital intersections.

Each subcatchment and associated culvert where assigned a three-character identification code. In Figures 3-3, 3-4, 3-7, and 3-8, subcatchment/culvert ID no. A04 is used to demonstrate the information generated by analyzing and identifying culverts and subcatchments. These maps and table were generated for each subcatchment/culvert, and provided to the Lake Sunapee Protective Association and to each town, as equivalent records did previously exist. Table 3-17 shows that A04 is adequately sized for all but the A1fi +95% confidence limit precipitation.

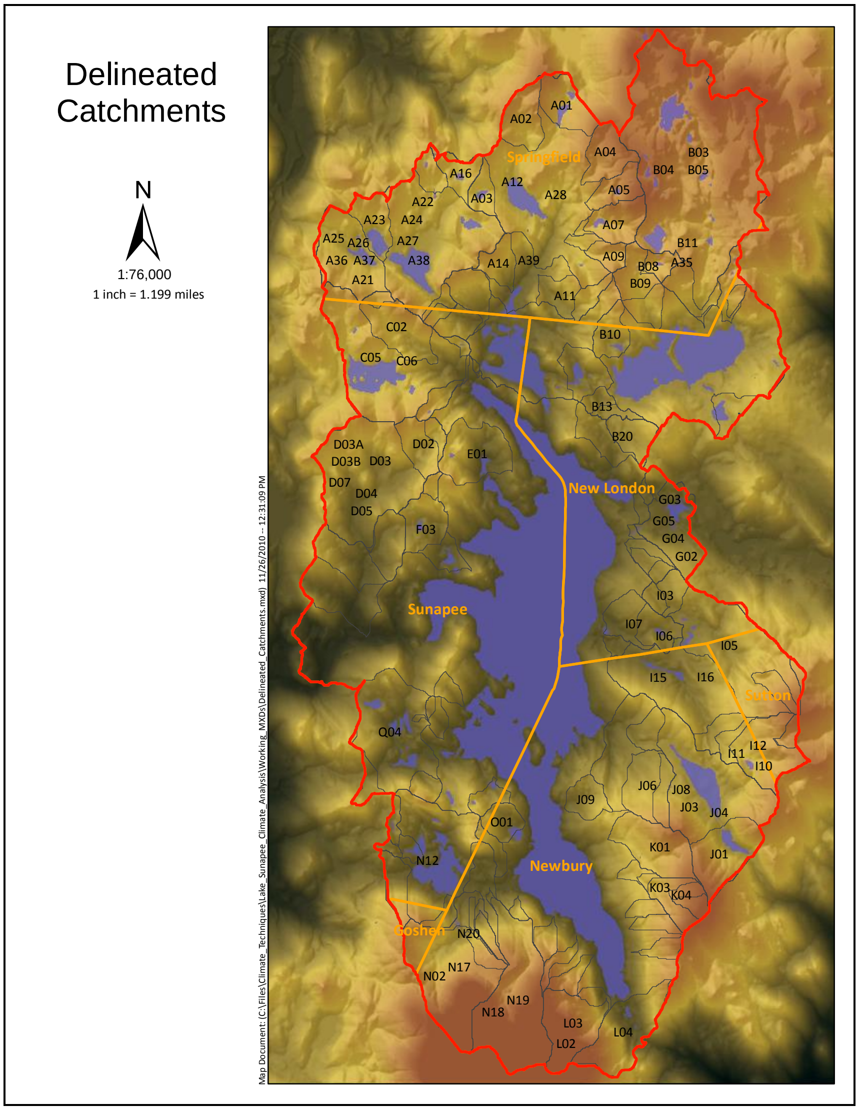


Figure 3-2. Modeled subcatchments identified and delineated. Note location of subcatchment/culvert A04, at the top center of the study site.

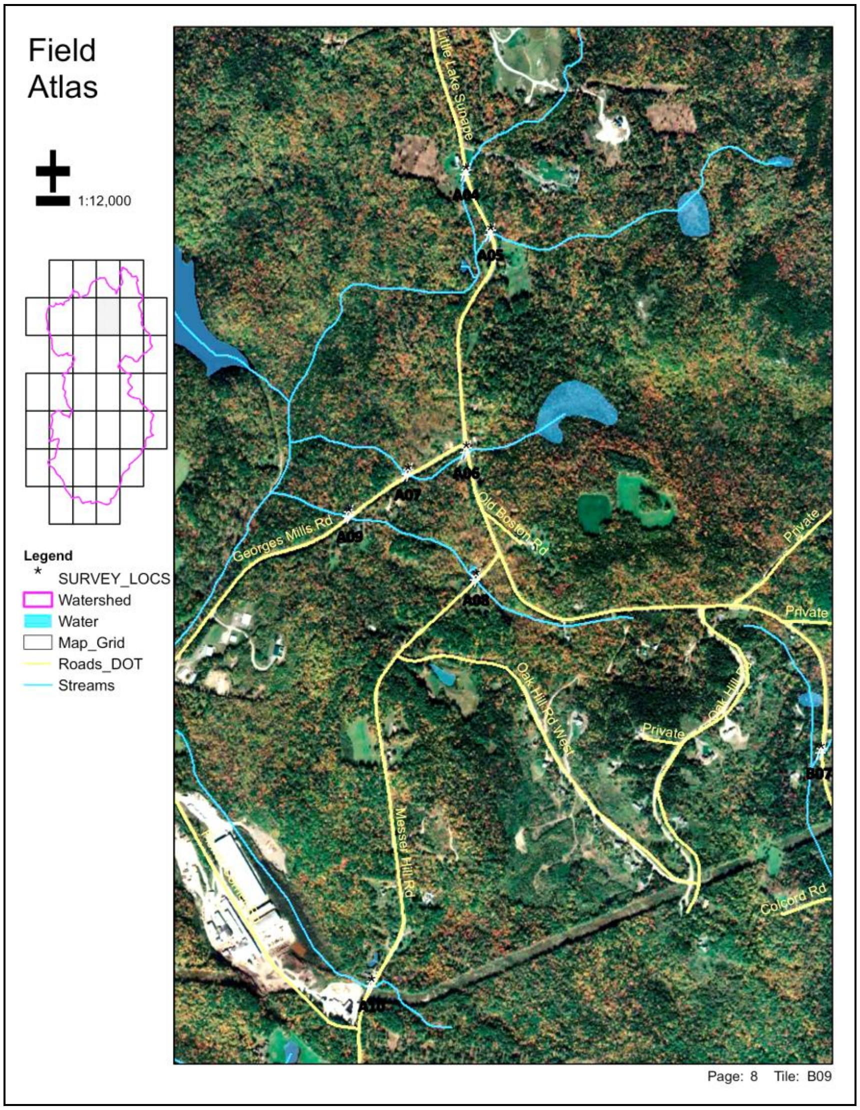


Figure 3-3 Map of road/stream crossings for quadrant "B09". Subcatchment A04 is located at the top right of map.

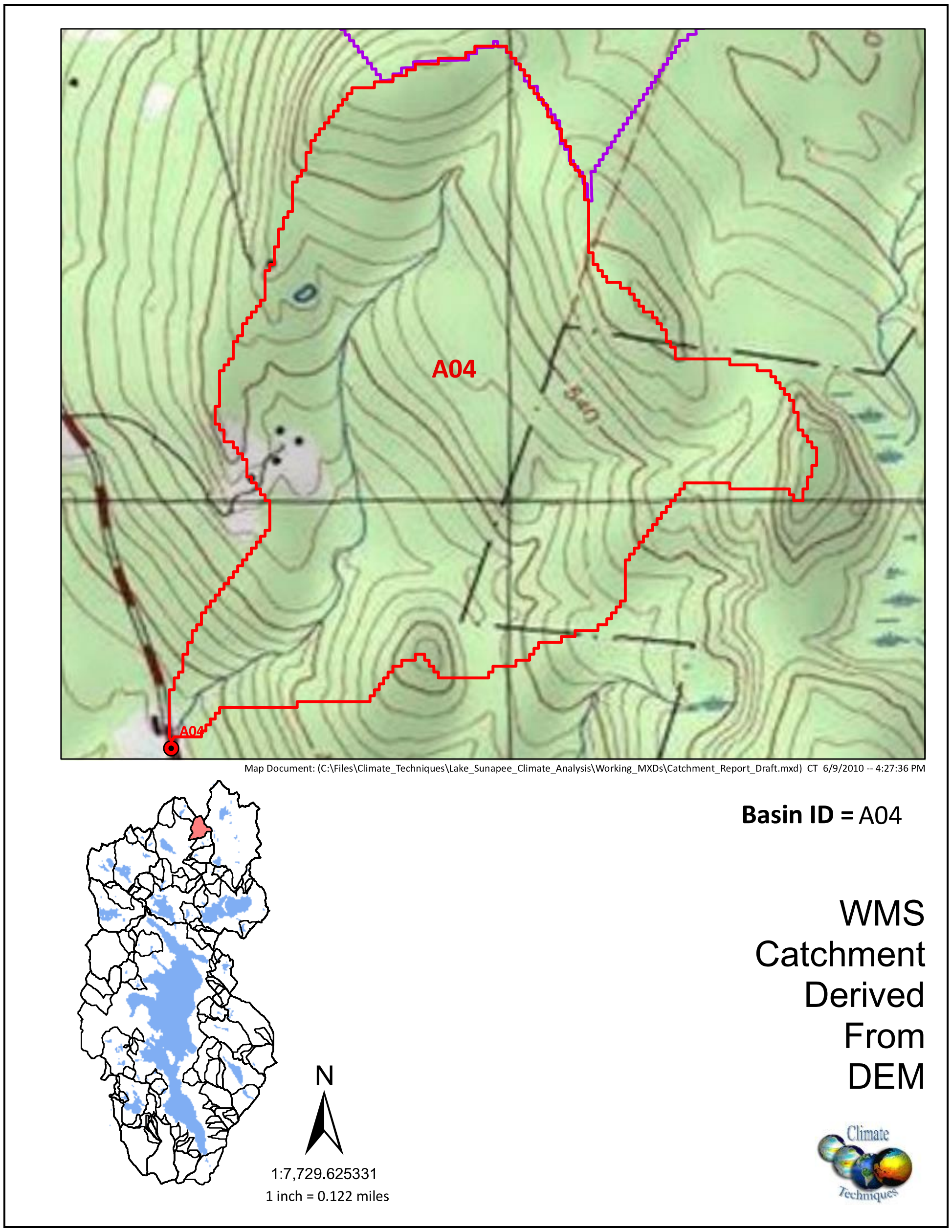


Figure 3-4. Topograph showing delineation of subcatchment A04.

Fieldwork

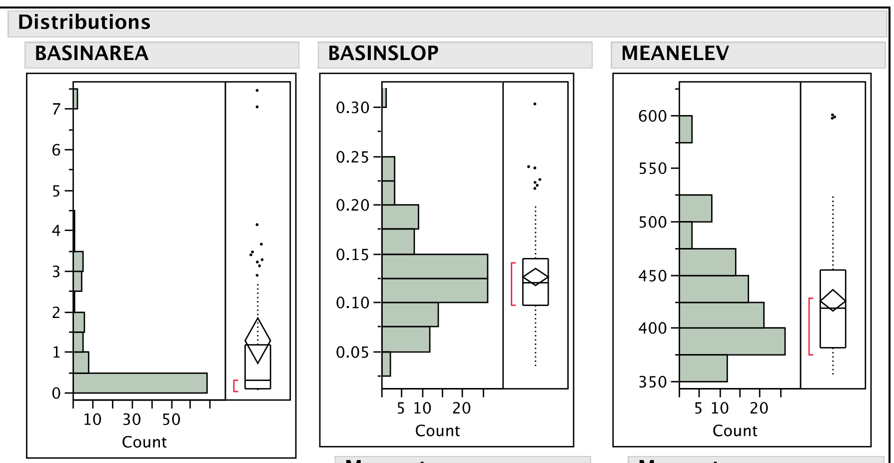
The program of fieldwork gathered detailed specifications on the one hundred twelve culverts within the study site, providing information for reverse-engineering to determine each culvert's current actual capacity, and estimating costs to replace or upgrade each culvert for a given landuse and precipitation scenario. This program utilized volunteers from the communities in the study site, under supervision of project investigators. Utilizing volunteers enabled accomplishing fieldwork with limited project budget, and complemented the Outreach program by promoting interest in the study's activities and results. Over 600 hours of mostly volunteer labor were required to perform and manage this work, and analyze returned datasheets for completeness.

The fieldwork protocol and forms (Figure 3-7, Appendix 1) were designed to comply with the New Hampshire program for assessing the adequacy of culverts for affording aquatic species passage. This increased the relevance of the study beyond climate change, and has promoted interest in the study at regional and state levels.

The timing of fieldwork was driven by season and project critical-path factors. As a result, it was crucial that fieldwork start quickly after project funding was confirmed in September, 2009, and completed prior to December, 2009. Successful completion within this interval was achieved by planning and scheduling. Paper forms used during fieldwork were scanned and saved as pdf files, and are available on request. Data from forms was manually entered into a Microsoft Access database for use in culvert modeling and cost estimation. During the data entry process, missing data was identified and fieldwork teams returned to culvert sites to complete records. A sample of datasheets were audited for quality assurance, as described in the Validation section of this report.

Results

Figures 3-5a, b are frequency distributions by subcatchment, for selected hydrological features. Mean subcatchment area is 1.30 acres, with 63% under ½ acre. Mean slope is 12.6%, with most between 5% and 20%. Mean subcatchment elevation is 426 feet, with most between 350 ft. and 475 ft. Mean lag-time is ¾ hr., with most between 15 min. and 1 hr. Mean time of concentration is 1¼ hr., with most between ¼ hr. and 1½ hr. 63% of streams are 1st order, with another 22% being 2nd order.



Moments (BASINAREA)

Mean	1.2991366
Std Dev	2.891424
Std Err Mean	0.2835275
Upper 95% Mean	1.8614465
Lower 95% Mean	0.7368268
N	104

Moments (BASINSLOP)

Mean	0.1262388
Std Dev	0.0468299
Std Err Mean	0.004592
Upper 95% Mean	0.135346
Lower 95% Mean	0.1171316
N	104

Moments (MEANELEV)

Mean	426.22735
Std Dev	51.981692
Std Err Mean	5.0972243
Upper 95% Mean	436.33649
Lower 95% Mean	416.1182
N	104

Figure 3-5a. Frequency distributions of key subcatchment features: area (acres), mean slope (%), and mean elevation (ft.).

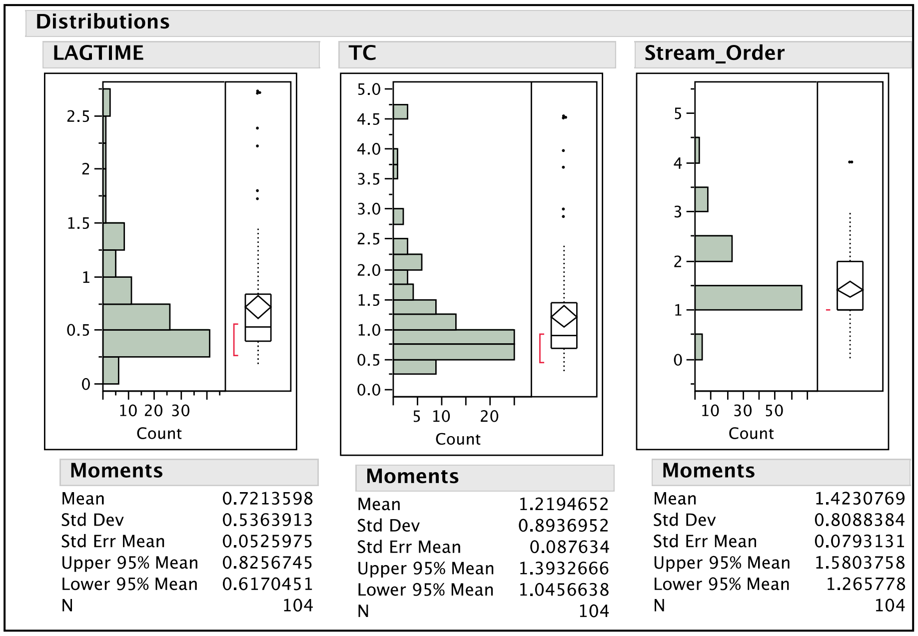


Figure 3-5b. Frequency distributions of key subcatchment features: lag time (hrs.), Time of Concentration (hrs.), and stream order.

Figure 3-6 shows the spatial distribution of *curve numbers (CN)* in the study site. Larger *CN* values have higher runoff rates. The small amount of red-shaded area indicates that little land area is commercial or higher-density residential, reflecting character of the study site as mostly rural, forested, or large-lot size residential.

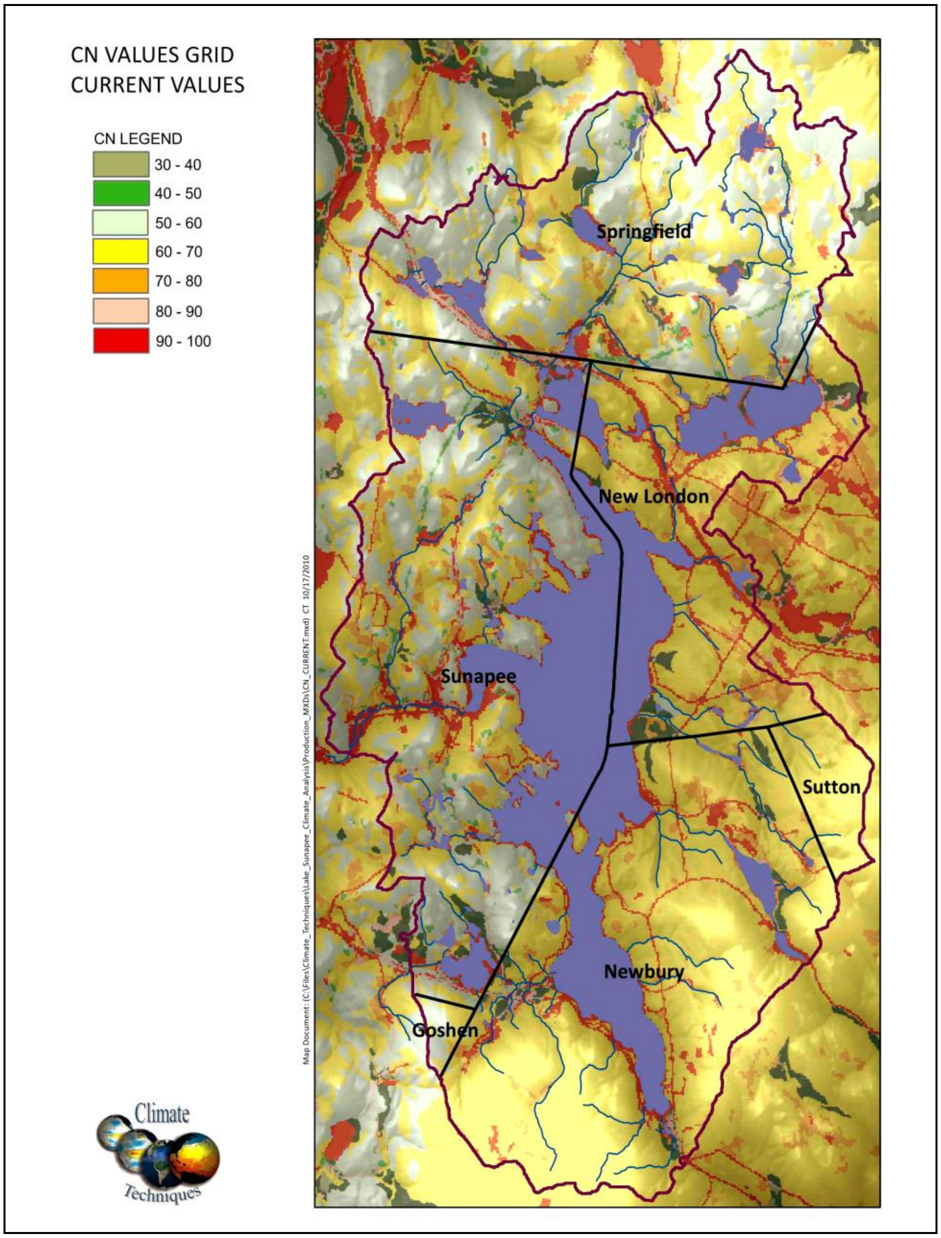


Figure 3-6. Pre-Buildout Curve Numbers, higher Curve Numbers have higher runoff rates.

Figure 3-7 is a sample of the four-page forms used to record data collected during fieldwork, see Appendix 1 for the full-size form.

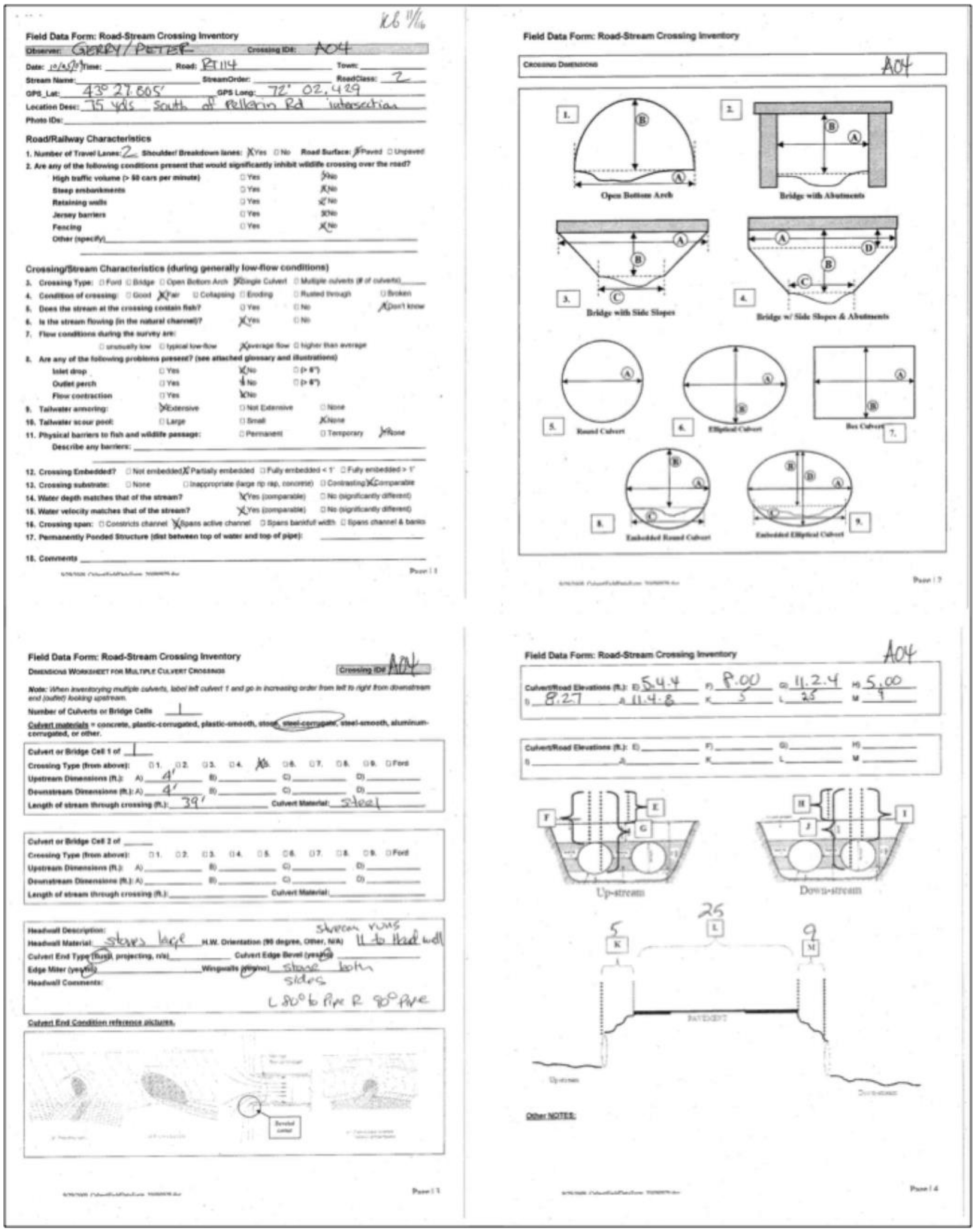
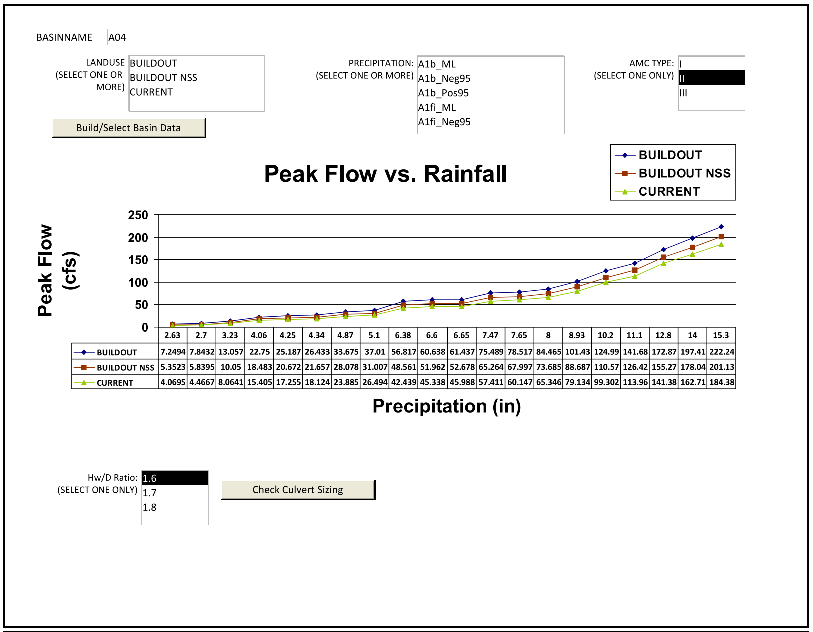


Figure 3-7. Data sheets for culvert A04. Specifications were used to reverse-engineer culverts to obtain present capacity, and for inputs to the cost model.

Figure 3-8 is an example of the runoff summary results report, created for each modeled subcatchment to show the relationship between *peak flow*, and precipitation and landuse. The custom Access database was programmed to generate these, for the landuse, precipitation, and AMC condition selected at the top of the report. Note, at the bottom-left of the report, that the ratio of headwall height to culvert diameter is selectable. This ratio specifies the minimum ratio permitted for a given culvert diameter. A minimum headwall height is required to adequately spread the load of traffic to the soil adjacent to the culvert.



	2.63	2.7	3.23	4.06	4.25	4.34	4.87	5.1	6.38	6.6	6.65	7.47	7.65	8	8.93	10.2	11.1	12.8	14	15.3
BUILDOUT	7.2494	7.8432	13.057	22.75	25.187	26.433	33.675	37.01	56.817	60.638	61.437	75.489	78.517	84.465	101.43	124.99	141.68	172.87	197.41	222.24
BUILDOUT NSS	5.3523	5.8395	10.05	18.483	20.672	21.657	28.078	31.007	48.561	51.962	52.678	65.264	67.997	73.685	88.687	110.57	126.42	155.27	178.04	201.13
CURRENT	4.0695	4.4667	8.0641	15.405	17.255	18.124	23.885	26.494	42.439	45.338	45.988	57.411	60.147	65.346	79.134	99.302	113.96	141.38	162.71	184.38

Figure 3-8. Sample of a catchment/culvert information sheet, for culvert A04.

Figure 3-9 shows the relationship between rate of precipitation change and percentage of undersized components. Note that the relationship is a curve, as precipitation increases, a smaller and smaller percentage of culverts become undersized. Note also that the curve flattens at higher percentages of increase in precipitation. Approximately 30% of components that we modeled are large box culverts, which remain adequately sized even at extreme precipitation levels 200% greater than observed recent rainfall. This results from the need to accommodate the grade of the road that passes over the stream crossing, which results in a higher culvert/bridge than necessary for conveying streamflow. This feature is advantageous for climate change adaptation, as it reduces the number of components that require mitigation.

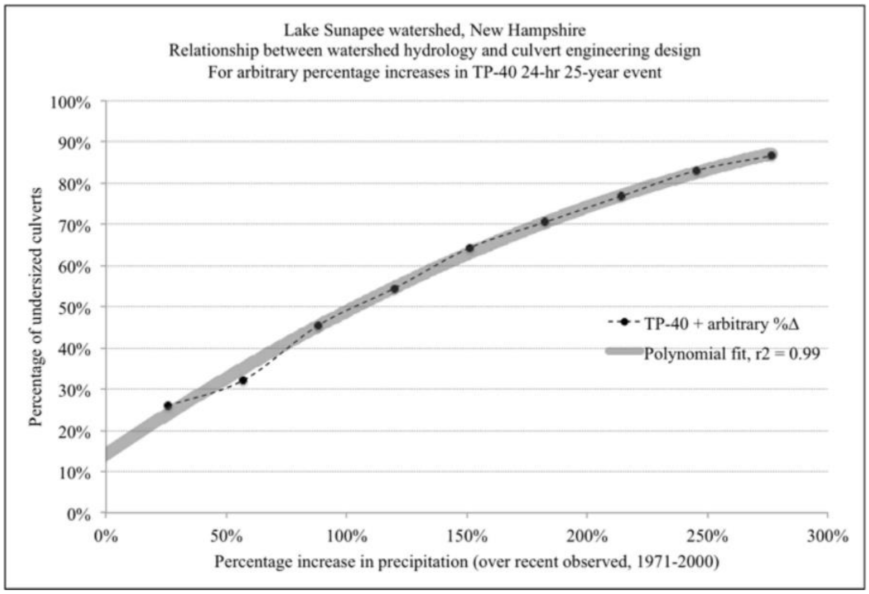


Figure 3-9. The hydrologic/hydraulic relationship between percentage change in precipitation and percentage change in undersized culverts.

Results for specific precipitation levels can be overlaid on the curve of the hydrology-culvert design relationship (Figures 3-10, 11). Figure 3-10 is simplified, overlaying only the three GFDL SRES trajectories, to demonstrate the method. Larger circles are the *most likely* estimator, and small circles the +95% confidence limit. Figure 3-11 maps results for all GCM/SRES/downscaling-method combination used in the study. Note that for the *most likely* A1fi precipitation, which is 64% higher than the recent historical design storm (and about 30% larger than TP-40), only 35% of culverts are undersized. This is a ratio of 1.8:1.

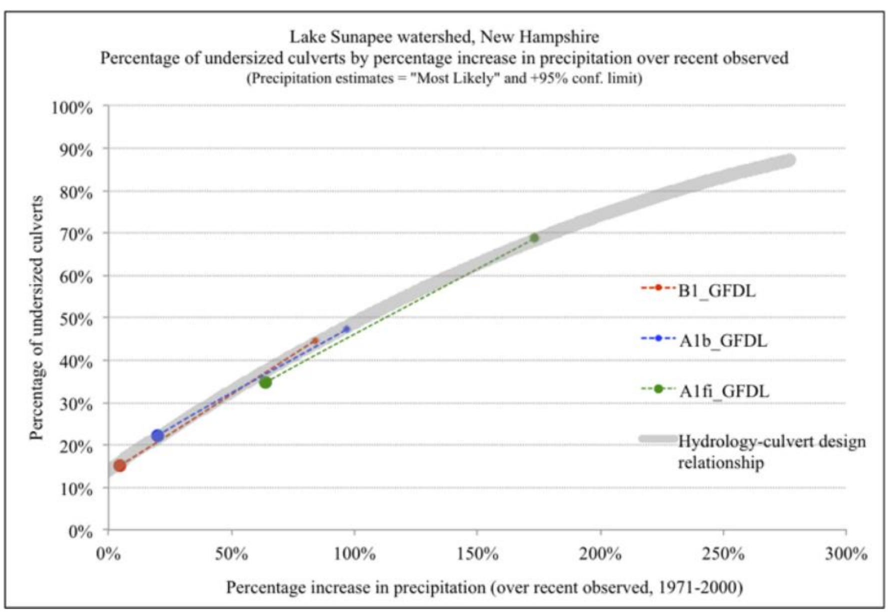


Figure 3-10. Mapping specific climate-changed precipitation scenarios onto the hydrologic/hydraulic relationship curve.

Figure 3-11 plots *most likely* and +95%c.i. data for all scenarios. Note that, for almost all plotted points, 50% or less of culverts are undersized.

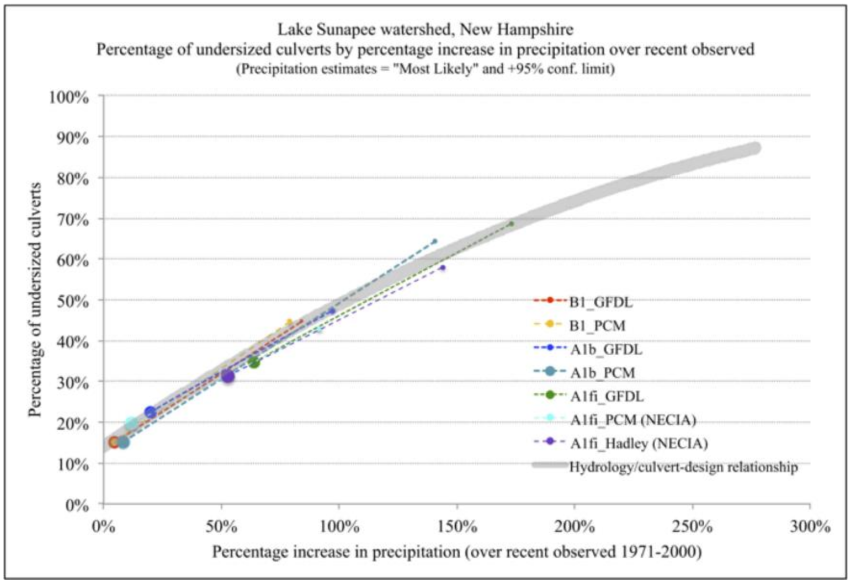


Figure 3-11. All climate-changed precipitation scenarios, mapped onto the hydrologic/hydraulic response curve, for "most likely" and +95%c.i. estimates.

<u>*Buildout model*</u>

Results

Figure 3-12 maps the various zoning standards found in the study site. The site is largely rural, with many vacation homes at medium to low density, and little high-density area. Zoning standards were used to determine lot size for the buildout and LID analyses.

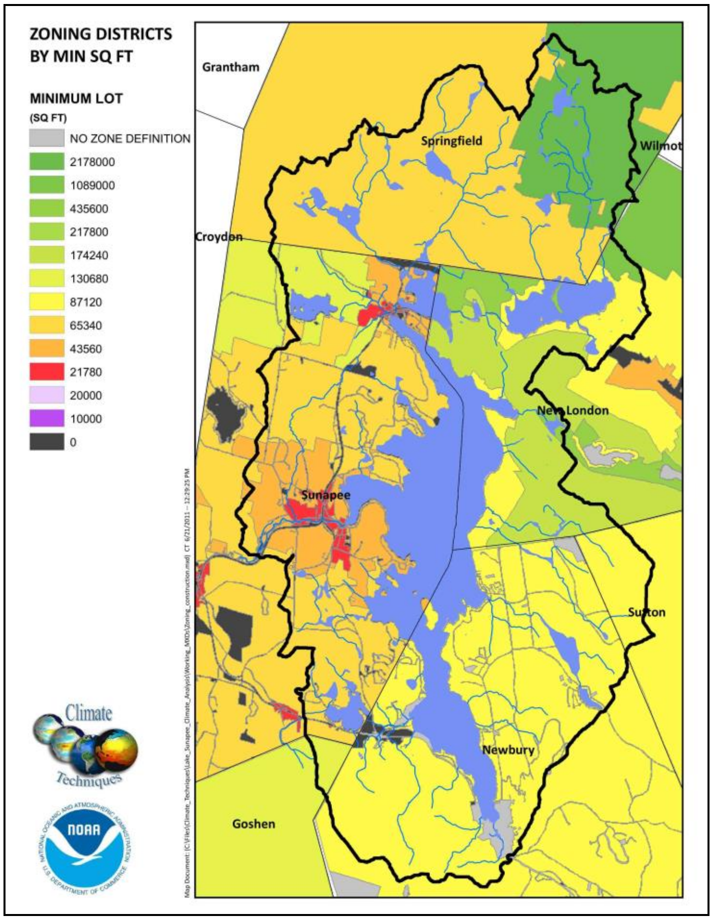


Figure 3-12. Zoning districts in the study site. Minimum lot sizes were the basis for the buildout model.

Table 3-5a shows *curve numbers* for combinations of zoning lot size and Hydrological Soil Group, for Buildout. Similar information, for LID-adjusted *curve numbers*, is shown in Table 3-7.

Table 3-5. Buildout-informed Curve Number (CN) values, by zoning and curve number

Runoff Curve Numbers (TR-55), except as noted below					
	Percent	HSG-A	HSG-B	HSG-C	HSG-D
	IC	38	55	70	77
Urban districts					
Commercial and business	85%	89	92	94	95
Industria	72%	81	88	91	93
1/8 acre	65%	77	85	90	92
1/4 acre	38%	61	75	83	87
1/3 acre	30%	57	72	81	86
1/2 acre	25%	54	70	80	85
1 acre	20%	51	68	79	84
2 acres	12%	46	65	77	82
5 acres*	7%	43	62	75	80
10 acres	3%	40	59	73	79
25 acres	1.3%	39	57	71	78
50 acres	0.7%	38	56	71	77
Undevelo	0%	38	55	70	77

Discussion

Table 3-6 shows that the impact on the rate of undersized culverts caused by population growth is small, at 3% and 5%. The effect of population growth is mildly sensitive to increases in precipitation, insofar as the difference between current and built-out landuse is 2% larger under climate-changed conditions.

Table 3-6. The impact of population growth on the percentage of undersized culverts

Percentage undersized culverts

	Landuse		Population
Precipitation	Current	Buildout	impact
NCDC recent	12%	15%	3%
GFDL A1fi	30%	35%	5%

Culvert model

Results

The standard engineering method for designing culverts was employed (Durrans, 2003), with no design modifications to accommodate specific site conditions. As such, culvert dimensions computed for a given scenario are not adequate to support actual construction, though sufficient for the planning-scale needs of this project. A sample of output from the culvert model is shown in Appendix 3, “Culvert model”, Table1. On this table, the CAP (CAPacity) ratio indicates whether the current culvert is adequately sized. The CAP ratio compares the modeled culvert size with the actual culvert size, for a given scenario combination of landuse, precipitation, and *AMC*. A ratio greater than 1 indicated that modeled size was greater than the actual size, so that the culvert was undersized for that scenario.

For each culvert we performed a linear regression to establish the relationship between CAP ratio and precipitation, holding landuse and *AMC* constant. The resulting equation, fit with an r^2 value in the high-90s, enabled determination of the exact precipitation at which a culvert's capacity is exceeded.

Figure 3-13 is a frequency distribution of the number of culverts that are undersized at a given precipitation. The plot has been truncated at precipitation = 15", to show in greater detail the precipitation range that most culverts fall within. Inset includes all precipitation values, with 20 culverts remaining adequately sized even at extreme or inconceivably high precipitation. These are box culverts or small bridges, built to maintain the grade of road surfaces, and thus affording headroom much greater than required to merely convey the TP-40 design storm.

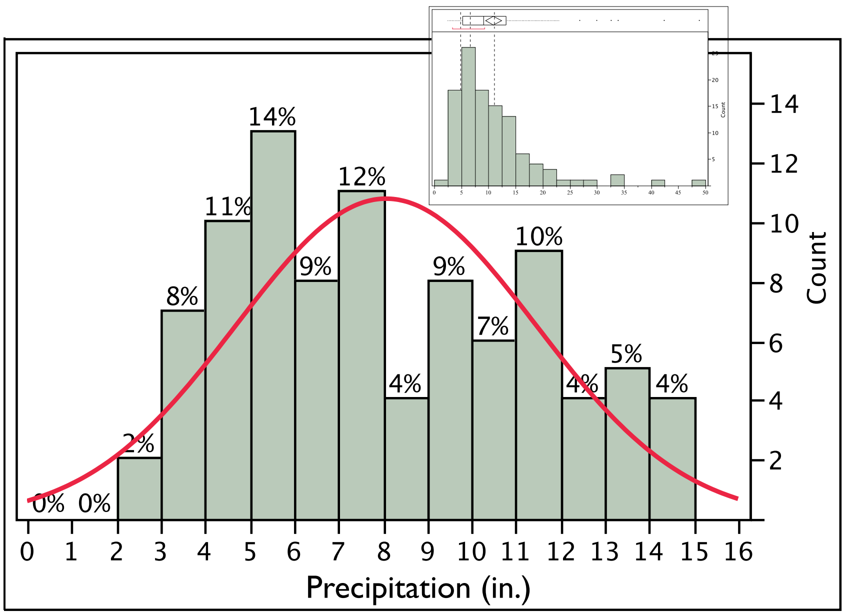


Figure 3-13. Frequency distribution of the number of culverts becoming undersized at a given precipitation (in), the maximum precipitation value that is plotted is 15". Inset shows distribution for all culverts, with precipitation-at-maximum up to 50". Dashed vertical reference lines on inset indicate GFDL A1b, A1fi ML, and A1fi+95%ci precipitation.

Discussion

The culvert design method used in this and two previous studies by the project team was the "trial sizing" process outlined in the NHDPW manual (NHDPW, 1996). This is a simple method, appropriate for planning purposes, that does not consider site-specific design considerations such as ponding and greater headwater-to-depth ratios. For watershed-wide planning purposes a simplified design method, uniformly applied to all culverts in the study site, is appropriate. This simplified design method 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.

Performing the linear regression of CAP ratio on precipitation provided more accurate determination of the specific point at which a culvert adequacy than the CAP ratio computed for the specific precipitation scenarios. Because the precipitation scenarios were discrete, rather than continuous numbers, results from the precipitation scenarios only indicated that a specific culvert became undersized between two scenarios, whereas the regression equation established the precise precipitation causing over-capacity.

LID model

Results

Table 3-7, and Figures 3-14a and 3-14b, show the impact of applying LID methods to the various zoning lot sizes and uses found in the study site. The slopes of the conventional development dashed-lines are steeper than the LID developed solid lines, indicating how LID benefits change based on lot size, i.e. impervious area. The trend in slope for LID varies by soil type, as with conventional development. LID has a generally greater benefit for higher pre-LID impervious cover rates (denser development). Commercial development results in higher rates of impervious cover than for residential development. Yellow shading in Table 3-7 indicates large, low-impervious-rate residential lot sizes, for which the LID and *CN* methods used in this study have either show little benefit or yield illogical results (see Discussion, immediately below).

Table 3-7. LID-adjusted Curve Number (CN) values, by zoning and curve number

LID Adjusted Curve Numbers based on MDE(2008)					
	percent imperviousn	HSG-A 38	HSG-B 55	HSG-C 70	HSG-D 77
Urban districts					
Commercial and business	85%	63.6	72.8	80.1	83.4
Industria	72%	63.6	72.3	79.7	83.2
Residential					
1/8 acre	65%	70.6	77.9	82.2	84.2
1/4 acre	38%	57.5	70.9	78.9	82.5
1/3 acre	30%	53.6	68.9	77.9	82.1
1/2 acre	25%	48.3	65.2	75.9	80.9
1 acre	20%	43.0	61.5	73.9	79.7
1.5 acre	16%	41.9	60.7	73.5	79.4
2 acres	12%	40.8	59.9	73.1	79.2
5 acres*	7%	39.2	58.7	72.4	78.7
10 acres	3.3%	39.1	58.7	72.4	78.7
25 acres	1.3%	38.6	58.7	72.4	78.7
50 acres	0.7%	38.4	58.7	72.4	78.7
Undevelo	0%	38	55	70	77

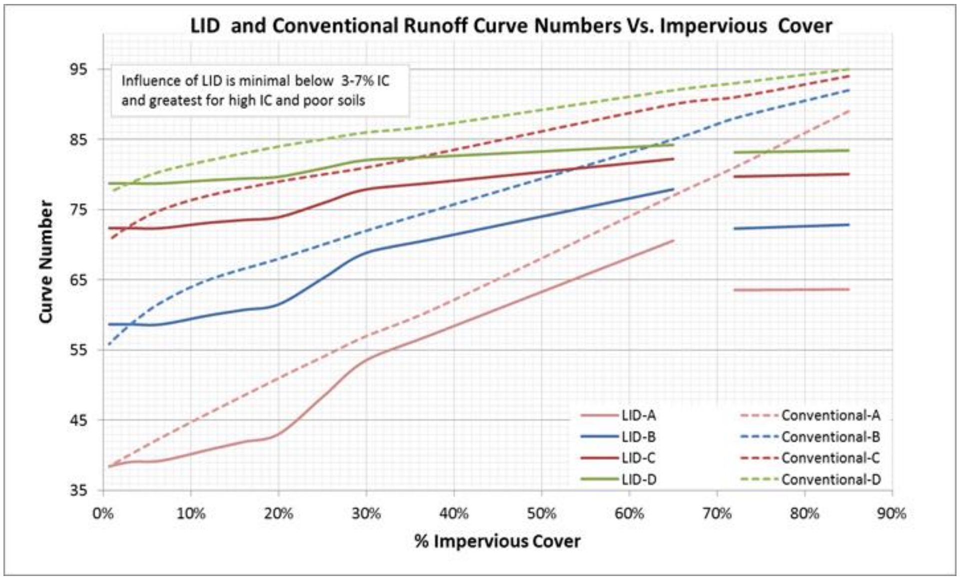
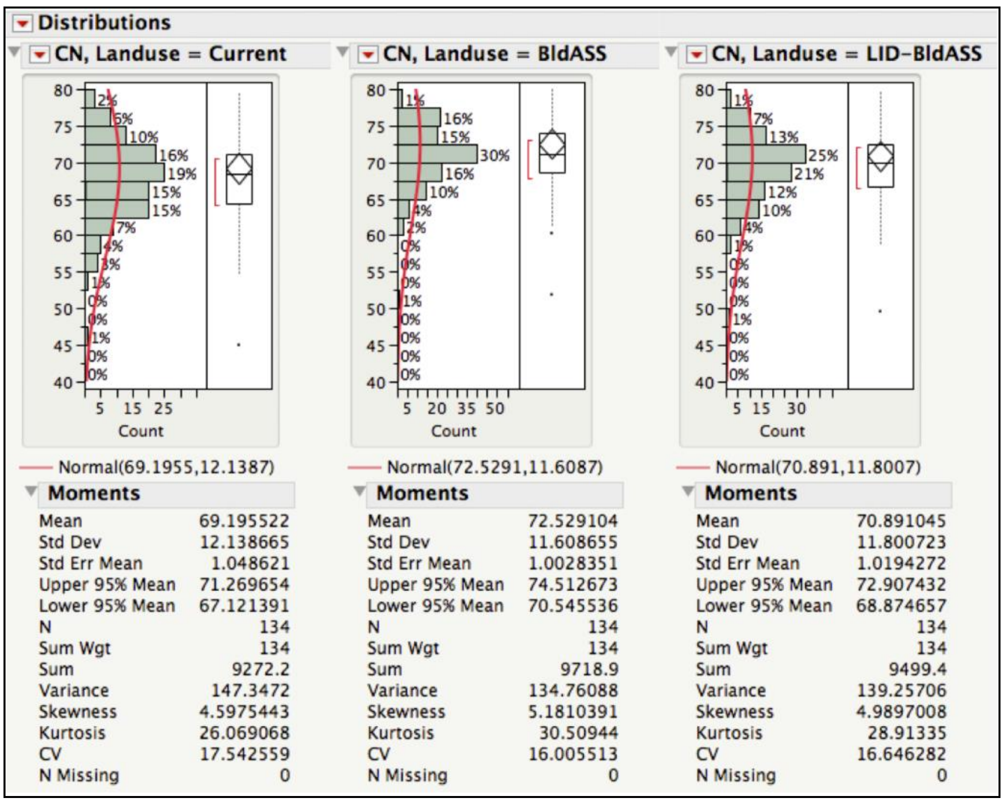


Figure 3-14a. Impacts of LID on Curve Numbers, by percentage of impervious cover, and for each of the four Hydrologic Soils Groups, A through D.



Moments	Current	BldASS	LID-BldASS
Mean	69.195522	72.529104	70.891045
Std Dev	12.138665	11.608655	11.800723
Std Err Mean	1.048621	1.0028351	1.0194272
Upper 95% Mean	71.269654	74.512673	72.907432
Lower 95% Mean	67.121391	70.545536	68.874657
N	134	134	134
Sum Wgt	134	134	134
Sum	9272.2	9718.9	9499.4
Variance	147.3472	134.76088	139.25706
Skewness	4.5975443	5.1810391	4.9897008
Kurtosis	26.069068	30.50944	28.91335
CV	17.542559	16.005513	16.646282
N Missing	0	0	0

Figure 3-14b. Impact of landuse on curve number. BldASS is an abbreviation of the scenario buildout with all steep slopes included.

Discussion

All LID development scenarios were derived from designs for actually constructed projects. Examples of construction plans for the development scenarios are depicted in

Figures 2-5 of Appendix 4.The LID model used a set of rainfall sequestering techniques that, as a whole, were likely to be politically and economically acceptable to the community. This was important because there are a limitless variety of applications of LID systems in a design context. Within this constraint the model achieved a common LID goal of sequestering, *in situ*, 1" of precipitation falling on impervious areas. The modeling assumptions of sequestering 1" precipitation onsite, and applying practical LID methods, provided realistic and economical results that increased the acceptance of LID methods by the community, and increase the likelihood that LID methods will be adopted.

Watershed-wide, the reduction in *CN* resulting from the application of LID methods can be seen in Figure 3-14b. Across all subcatchments, buildout (with steep slopes included) increases mean *CN* value by 5%, from 69.2 to 72.5, the application of LID methods reduces this increase by half, to 70.9.

The analysis showed that LID practices, by this methodology, yield no benefit beyond a two-acre density for residential development. This can be seen by cross-referencing the impervious rates from Table 3-7 to the graph in Figure 3-14a, comparing conventional and LID development curves. The Conventional and LID curves converge beginning at impervious rates of less-than about 5%. As lot sizes exceed two acres, the footprint of building and driveway are small in proportion to total lot size, and impervious areas fall below 5% of lot size (table 3-7). At this point the value and effect of LID is not observed using this methodology and, in fact, at a lot size of 25 acres (1.3% impervious), computed *CN* for LID exceeds that for conventional development. This was an artifact of the method used, a modification the Maryland Department of the Environment method (Appendix 4), and the fact that *CN* methods are not typically applied to parcels over 2 acres.

A change in slope is seen in the LID curves between about 20%-30% impervious rates (1-acre to 1/3-acre density), due to the usage of porous pavements for lot sizes greater than 1 acre. This decision was made on professional judgment based on the infrequent usage, in practice, of porous pavements for smaller size lots. However it could be applied and would have make the slope of the curve consistent. Note that the curves for commercial LID are detached because the designs applied are different in nature due to the use of rooftop infiltration and porous pavements.

The analysis showed that the greatest benefit in terms of CN reduction is obtained for poor-quality soils in high-density development, i.e. "C" and "D" soils, and lot sizes with high impervious rates such as urban residential or commercial lots. This last point is significant, in that this condition is commonly found in urban areas, where LID is least applied and most challenging. This finding is relevant for metropolitan areas contemplating the institution of methods for reducing runoff.

<u>*Cost model*</u>

Results: Construction cost

A stepwise regression was performed to determine the most significant determinants of culvert adaptation cost. The regression was limited to the buildout landuse scenario, and *Antecedent Moisture Condition II* (average). Installation cost was the dependent variable, independent variables were modeled cross-sectional area, length, material, type/shape, the ratio of modeled-to-current size, and peak flow. Significant factors were modeled cross-sectional area and length. A linear regression with these factors as independent variables yielded $r^2 = 0.827$ (Table 3-8). The impact of the two factors was significant at $p = .05$, yielding a *prob > f* of less-than 0.0001 (Table 3-9).

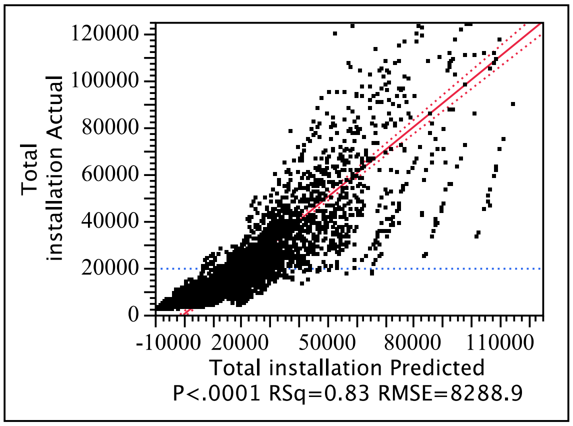


Figure 3-15. Plot of actual versus predicted total installation cost, factors modeled were cross-sectional area, and length. Records were limited to GFDL A1fi with Buildout.

Table 3-8. Summary of linear regression, Total Installation Cost.

Rsquare	0.827
RSquare Adj	0.827
Root Mean Square Error	8,288.92
Mean of Response	19,610.26
Observations (or Sum Wgts)	555

Table 3-9. Analysis of Variance for Total Installation Cost linear regression.

Source	**DF**	**Sum of Squares**	**Mean Square**	**F Ratio**
Model	2	1.8244e+11	9.122e+10	1327.646
Error	552	3.7926e+10	68706236	**Prob > F**
C. Total	554	2.2036e+11		<.0001*

The relationship between installation cost and precipitation, and the impact of LID on this relationship, is shown in Figure 3-16 and Table 3-10, for the GFDL scenarios. Note that LID benefits increase as precipitation increases: the flatter slope for LID in Figure 3-16 indicates that costs with LID are less sensitive to changes in precipitation than costs without LID.

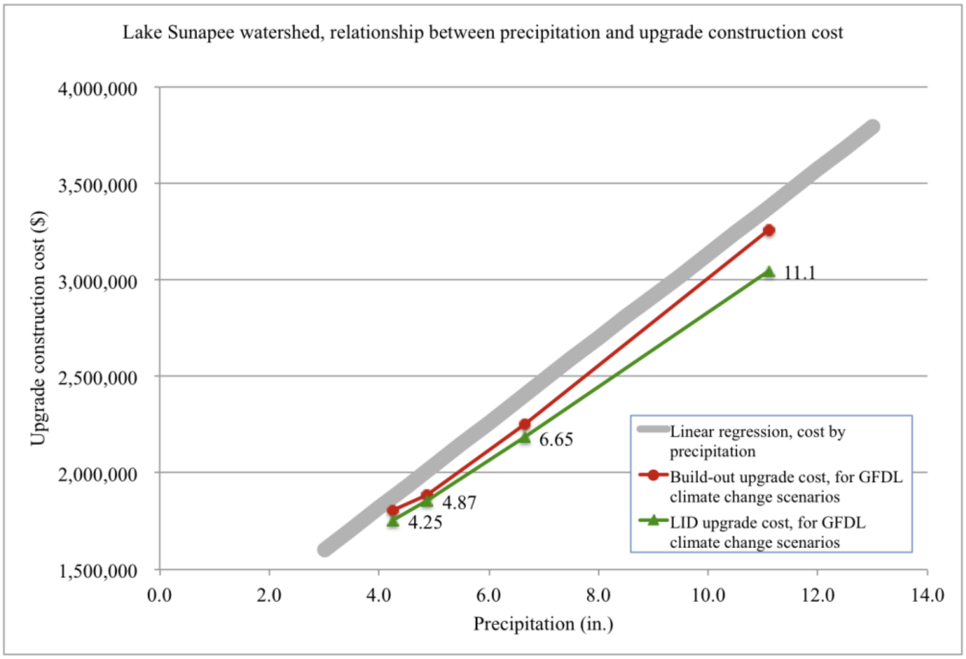


Figure 3-16. Watershed-wide upgrade cost (replacement or upgrade on a per-culvert basis, whichever is sufficient to provide adequate capacity), as a function of precipitation.

Table 3-10 Reduction in watershed-wide total construction cost, resulting from LID methods.

Impact of LID on watershed-wide culvert system construction				
		Landuse		
Climate	**Precipitation (in.)**	**Buildout**	**Buildout w/ LID**	**LID benefit**
Recent (NCDC 1971-'00)	4.06	1,760,000	1,730,000	1.7%
Moderate change (A1b)	4.87	1,950,000	1,900,000	2.6%
Heavy change (A1fi)	6.65	2,350,000	2,265,000	3.6%
Very heavy change (A1fi +95%c.i.)	11.10	3,375,000	3,200,000	5.2%

Results: Marginal cost

Marginal costs were computed as the difference in cost for a given scenario, over that required to construct a culvert capable of conveying TP-40 flow. An alternate "base" cost that could have been used was replacement cost. However, the capacity of existing culverts in the study site often varies significantly from that required to convey TP-40 precipitation. As a result the incremental upgrade cost, if computed from the replacement cost, would not be an accurate measure of adaptation cost outside of the Lake Sunapee watershed. Using TP-40 as the base cost affords a uniformity that is more transferrable to other communities for adaptation planning.

Figure 3-14 fits a linear trend to marginal costs by town. Marginal adaptation costs are more sensitive to changes in precipitation for the towns of New London and Sunapee, than for Springfield and Newbury. In Figure 3-15, the flatter slope for LID costs shows that marginal adaptation costs are less-sensitive to precipitation changes when LID methods are employed, a finding that has implications for managing uncertainty.

Note in Figures 3-14 and 3-15, and Table 3-10, that values for GFDL B1 and A1b scenarios are negative. Because the TP-40 precipitation of 5.1" is greater than the B1 and A1b *most likely* precipitation of 4.25" and 4.87", it costs less to adapt the system to the latter two scenarios than to TP-40.

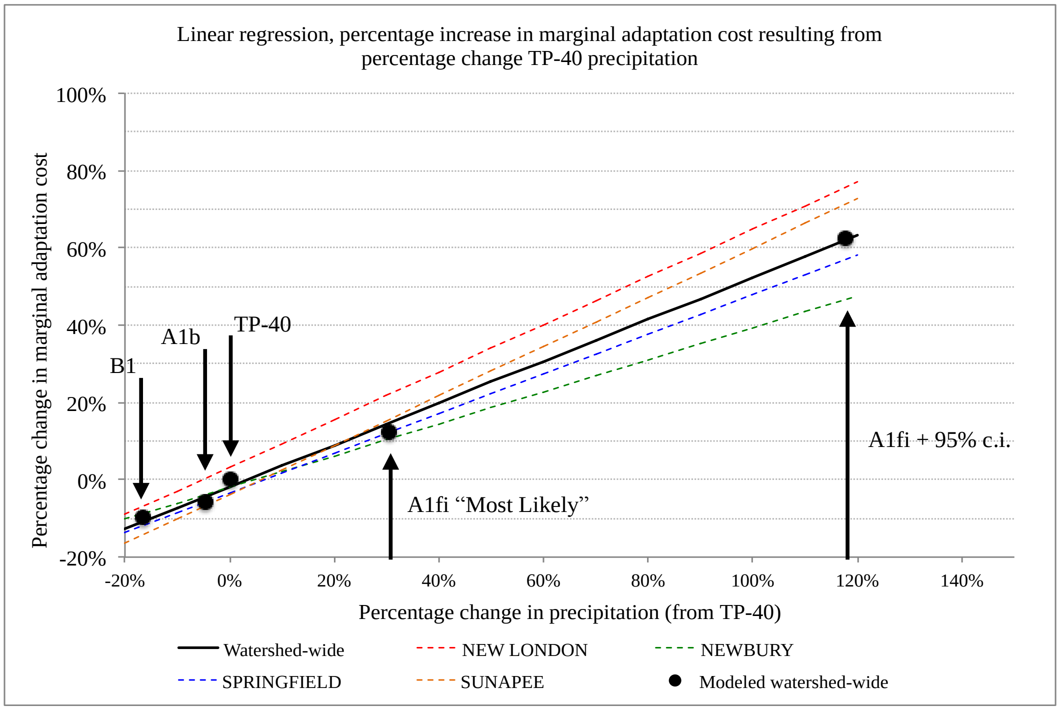


Figure 3-17. Linear regression, by town and watershed, of the percentage change in marginal adaptation cost per a given percentage change in precipitation.

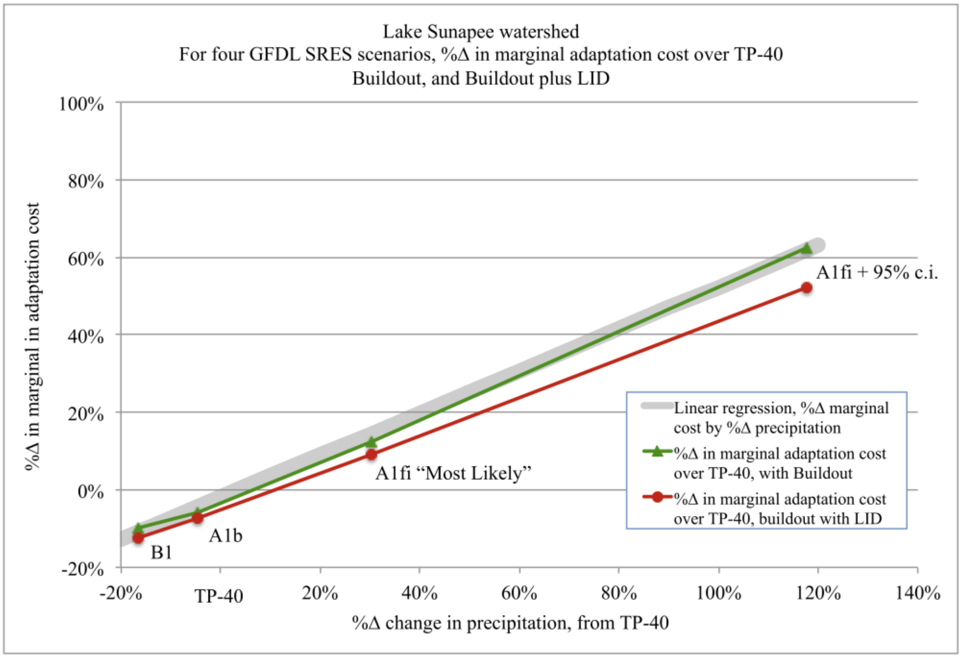


Figure 3-18. Impact of LID on the change in marginal cost resulting from a change in precipitation.

For A1fi, LID reduces the watershed-wide marginal cost by ¼, from 12% to 9% (Table 3-11, column 4: A1fi). For individual towns, New London has the largest reduction in marginal cost resulting from LID, Newbury the smallest. This variation results partially from the interaction of LID with differences in catchment hydrology and zoning between towns (see Figure 3-12). New London is zoned for the largest lot sizes among the four towns, followed by Newbury, Springfield, and Sunapee.

Table 3-11. Marginal adaptation cost, over TP-40, by town and SRES.

	TP-40 5.1	B1 4.25	A1b 4.87	A1fi 6.65	A1fi+95ci 11.1
%Δ in Precip	0%	-17%	-5%	30%	118%
Marginal cost % (increment over no-LID TP-40)					
NEW LONDON	0%	-6%	2%	23%	76%
NEWBURY	0%	-8%	-7%	11%	47%
SPRINGFIELD	0%	-13%	-6%	8%	58%
SUNAPEE	0%	-12%	-9%	10%	73%
Watershed-wide	0%	-10%	-6%	12%	63%
LID marginal cost % (increment of LID cost over no–LID TP-40)					
NEW LONDON	8%	-4%	8%	16%	50%
NEWBURY	0%	-11%	-9%	9%	41%
SPRINGFIELD	-7%	-10%	-8%	3%	51%
SUNAPEE	-11%	-18%	-13%	7%	64%
Watershed-wide	-3%	-12%	-7%	9%	52%

A simple scenario, to examine the potential financial impact of adapting the culvert system on town budgets, assumes that these towns choose to upgrade, in a single short-term project, all culverts projected to be undersized, and that this project be funded via a municipal bond. This scenario, while useful to illustrate the affordability of adaptation by examining worst-case financial impacts, would not likely be implemented: upgrading drainage components is generally accepted to be the most-expensive means of adapting stormwater systems, after mitigations such as LID, adaptive tools such as retention ponds, and capacity-increasing landuse policies were implemented. Thus only a subset of culverts in the study site likely would be upgraded.

Examining the affordability of worst-case adaptation costs facilitates moving beyond the reticence to adapt that still dominates published literature. Assuming bond specifications of a 20-year term and interest rate of 2% per annum, with repayment funded from property taxes, the impact on taxes is shown in Table 3-12. Calculations were based on actual tax rates and median home values for 2010.

Table 3-12a. Property tax impact from funding stormwater adaptation via a 20-year municipal bond at 2% interest. Increase in cents-per-$1,000 of assessed value; percentage increase per $1,000 of assessed value; and total increase in per-household property taxes, based on median residential property assessed value for 2010.

Town	TP-40	A1b	A1fi	A1fi + 95% c.i.
Marginal increase (¢ per $1,000 assessed value)				
New London	0.021	0.021	0.025	0.035
Newbury	0.058	0.056	0.066	0.087
Springfield	0.067	0.071	0.082	0.120
Sunapee	0.034	0.035	0.043	0.067
Average	0.045	0.046	0.054	0.077
Percentage increase (per $1,000 assessed value)				
New London	0.14%	0.14%	0.17%	0.24%
Newbury	0.42%	0.40%	0.48%	0.63%
Springfield	0.35%	0.37%	0.43%	0.62%
Sunapee	0.25%	0.26%	0.31%	0.49%
Average	0.29%	0.29%	0.35%	0.50%
Annual increase ($ per median assessed value ÷ 1,000)				
New London	9.29	9.22	11.09	15.83
Newbury	18.26	17.55	20.79	27.56
Springfield	14.76	15.76	18.11	26.42
Sunapee	8.97	9.25	11.24	17.57
Average	12.82	12.94	15.31	21.85

Table 3-12b. Reduction in property tax adaptation impact, from LID

LID benefit to property taxes, for adaptation funded through a municipal bond (*i* = 2% for 20 yrs)

	A1b	A1fi	A1fi + 95% c.i.
New London	–	6%	15%
Newbury	3%	1%	4%
Springfield	3%	5%	4%
Sunapee	2%	3%	6%
Average	2%	4%	7%

<u>Synthesis of technical activities</u>
Results
Summary Maps of Culvert Capacity Results

Figures 3-19 through 3-22 locate adequate and undersized culverts spatially within the watershed. These were produced to help stakeholders understand the vulnerability of their towns to climate change and population growth.

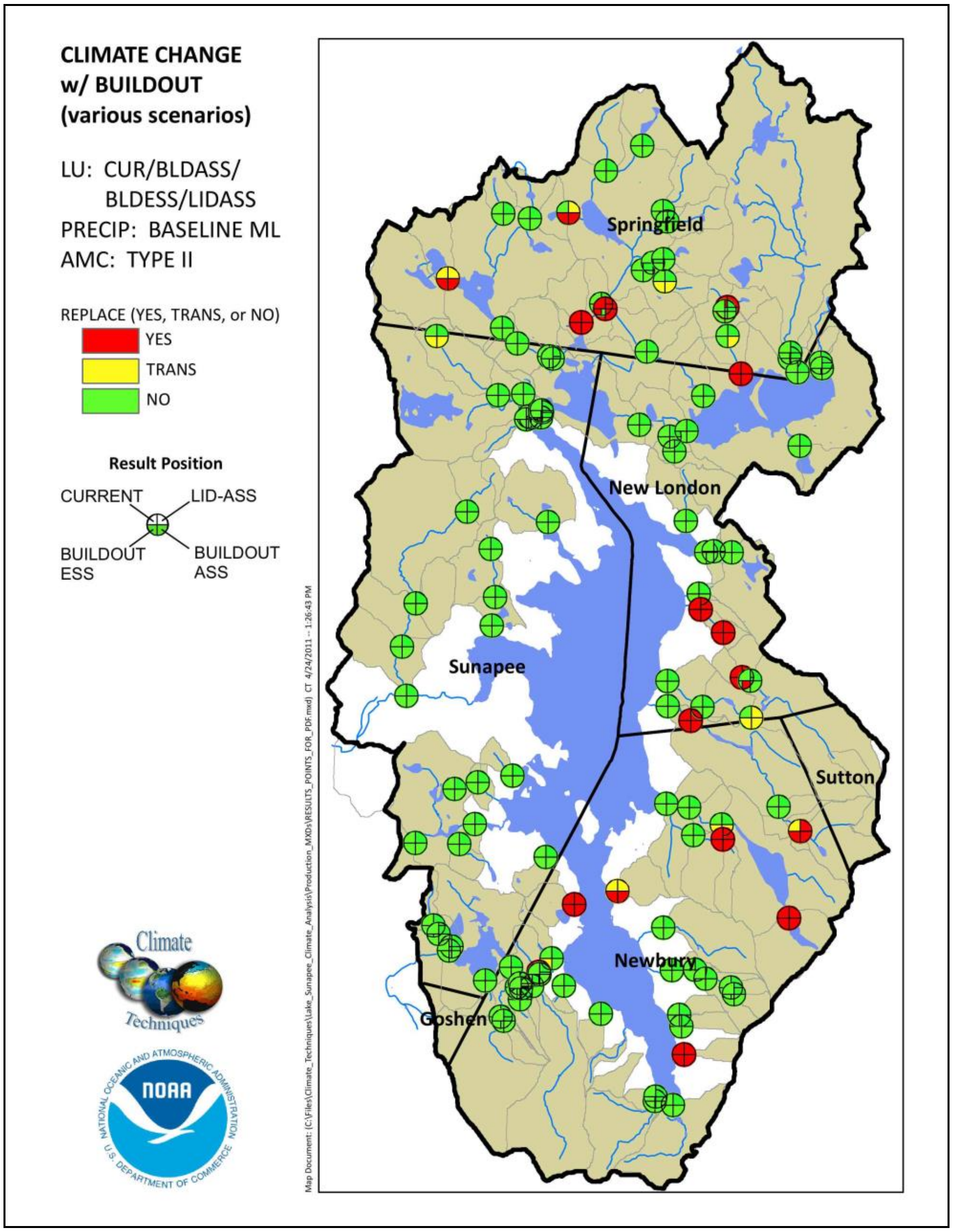


Figure 3-19. Locations of adequate and undersized culverts, recent precipitation (1971-2000).

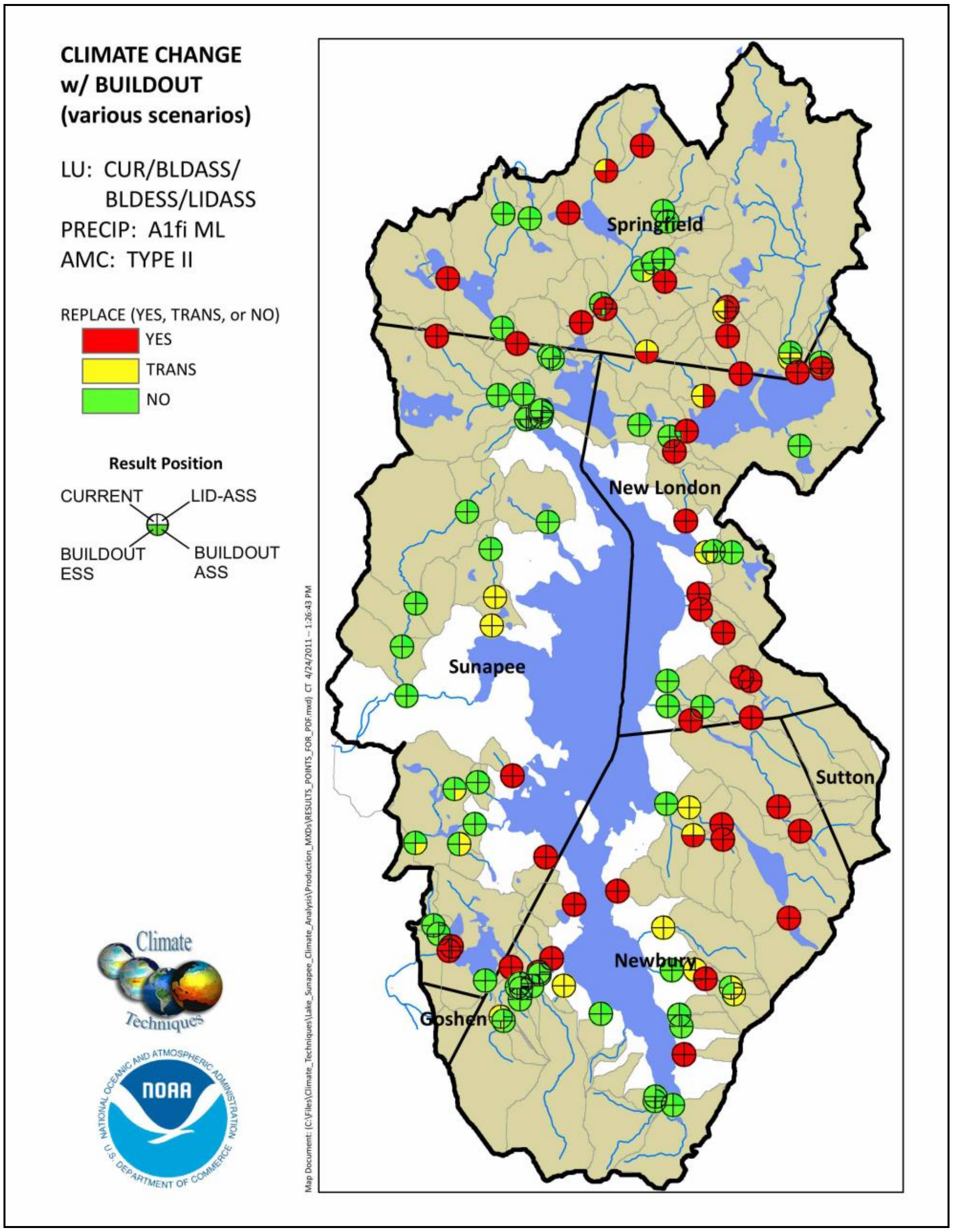


Figure 3-20. Locations of adequate and undersized culverts, A1fi "most likely" precipitation (2046-2075).

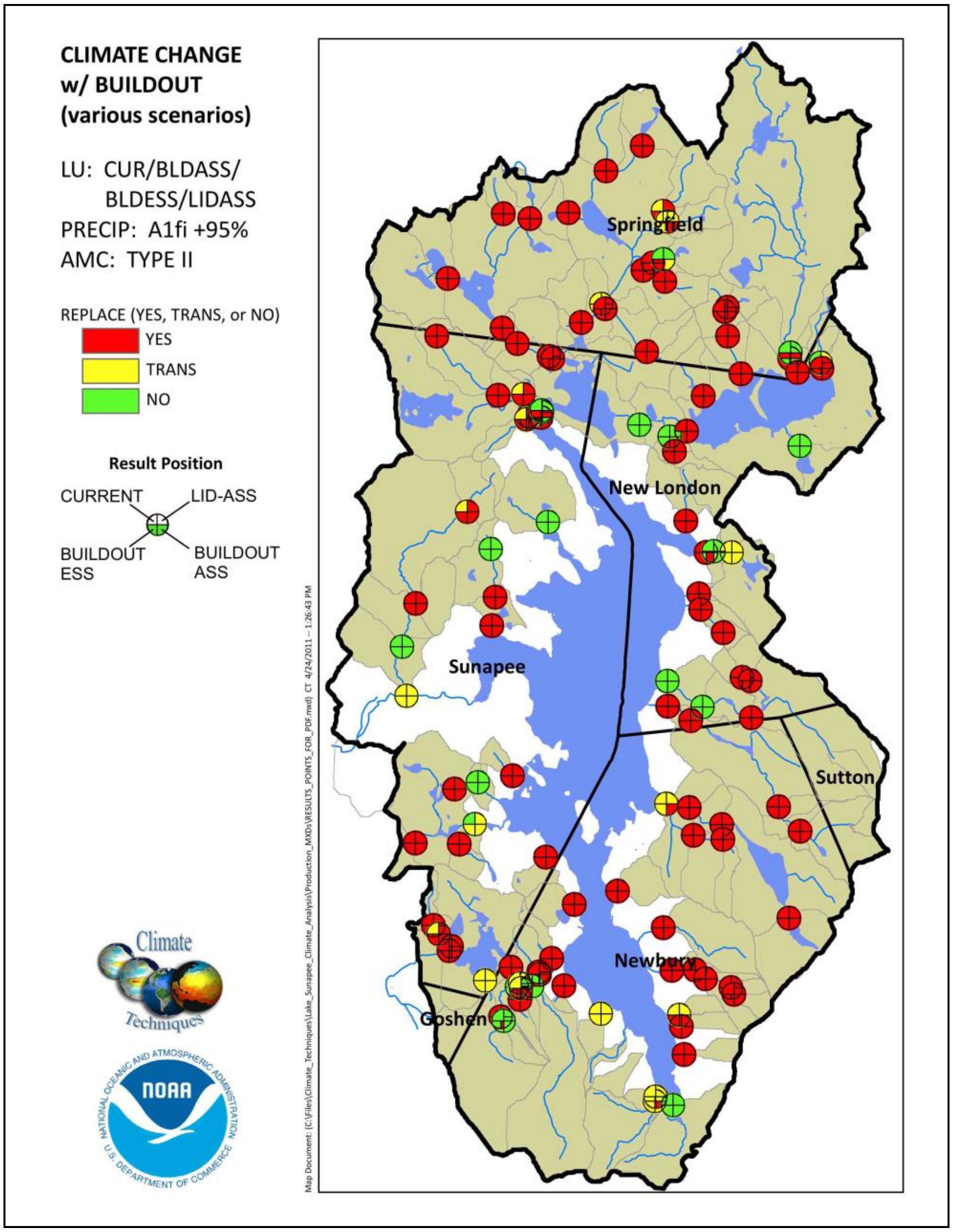


Figure 3-21. Locations of adequate and undersized culverts, extreme climate change impacts modeled as the A1fi +95% c.i. (2046-2075).

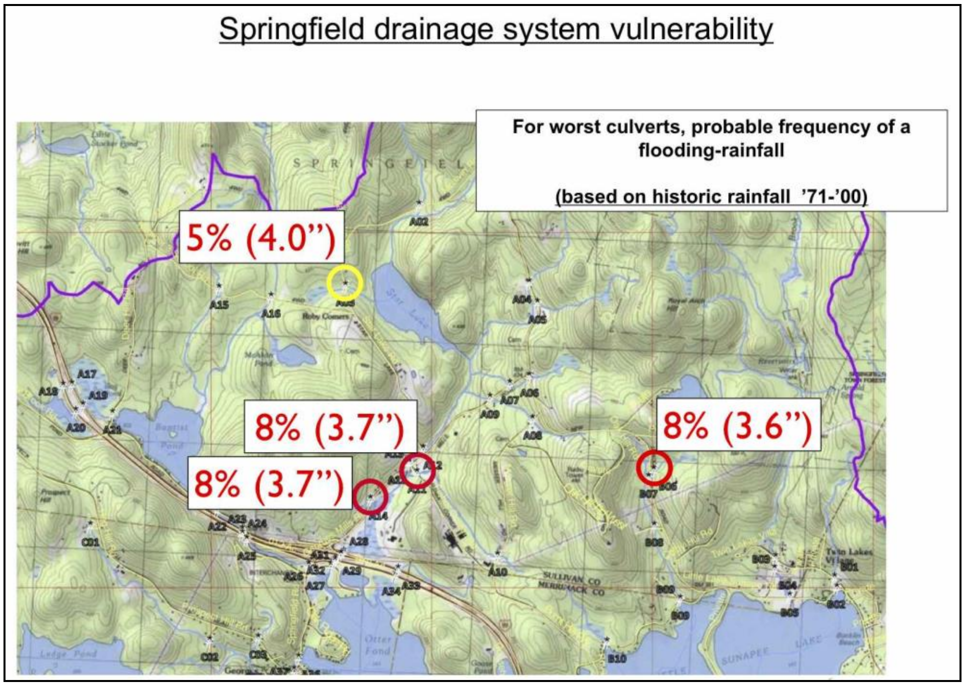


Figure 3-22a. For the recent climate (1971-2000), a sample graphic used to convey, to stakeholders and the general public, the annual risk for vulnerable culverts.

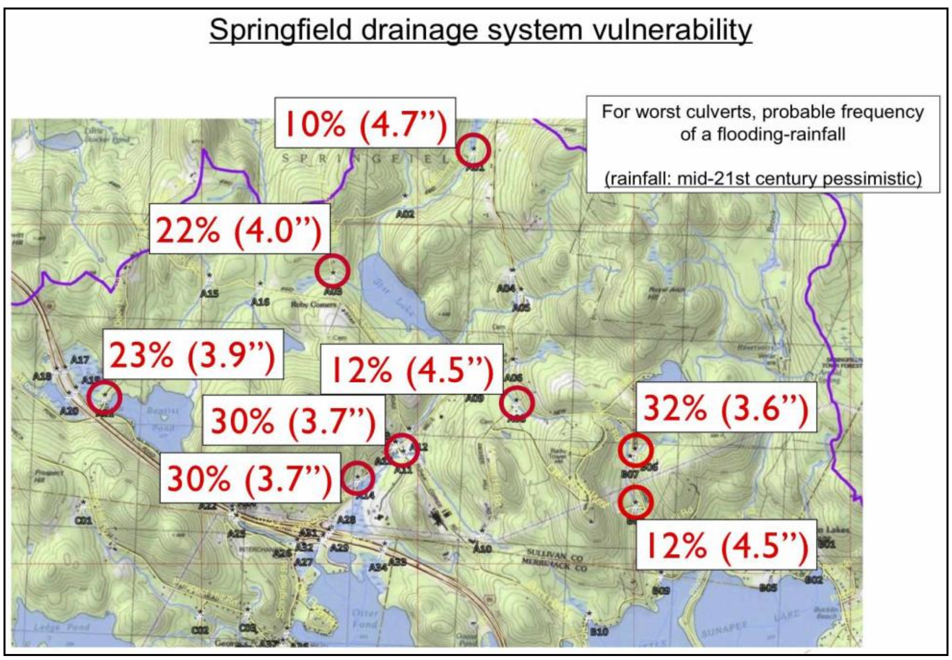


Figure 3-22b. As for Figure 3-22a, but moderate climate change (A1fi "most likely").

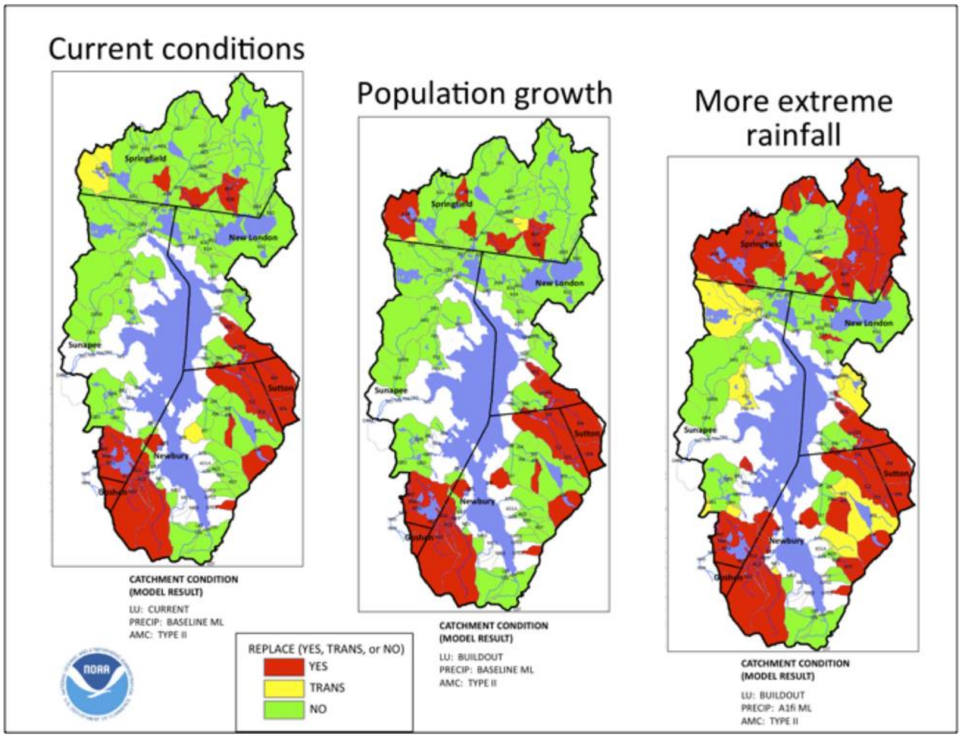


Figure 3-24. Example slide used to present results to stakeholders and the general public. Subcatchments vulnerable from undersized culverts due to climate change and population growth.

Tables 3-14 through 16 also were produced to help stakeholders understand the drainage systems and vulnerabilities in their communities, and how their town compared with the others in the watershed. Table 3-14 shows the distribution of culverts by New Hampshire's six road classifications in the study site. The class of road underwhich a culvert is sited is one facet of risk that should be considered when assessing vulnerability from undersized culverts. Major roads have lower Road Classes.

Table 3-14. Distribution of culverts by Town and Road Class.

	Road Class						
Town	**I**	**II**	**III**	**V**	**VI**	**no data**	**Total**
NEW LONDON	9	7		6			22
NEWBURY	13		2	11	2	7	35
SPRINGFIELD	1	8		7	6		22
SUNAPEE	9	1		22	1		33
	32	16	2	46	9	7	112

Table 3-16a. Comparison of undersized rates between the Town of Sunapee and other towns in the watershed.

Rate of undersized culverts:

	TP-40	-95% c.i.	Most Likely	+95% c.i.
			Recent (1971-2000)	
SUNAPEE	12%	0%	0%	15%
Other towns	33%	4%	23%	43%
			More Extreme	
SUNAPEE		0%	18%	67%
Other towns		23%	43%	71%

Table 3-16b. Comparison of undersized rates between the Town of New London and other towns in the watershed.

Rates of undersized Culverts for various rainfall events:

	TP-40	-95% c.i.	Most Likely	+95% c.i.
			Recent (1971-2000)	
New London:	23%	9%	23%	41%
Other towns:	15%	0%	9%	27%
			More Extreme	
New London:		23%	41%	55%
Other towns:		11%	28%	64%

Table 17 was produced to help towns plan a program to remediate culvert vulnerability. Culverts that are undersized for TP-40 or the GFDL climate change scenarios are listed in order of descending vulnerability, based on the precipitation at which the culvert becomes undersized. Note that, for several culverts, more extreme precipitation results in lower upgrade cost. This is an artifact of the culvert design model, arising from selection of a less-expensive but larger round culvert, over a more expensive but smaller oval culvert. This table is a simple prioritization that can be incorporated into existing asset management programs. The modified asset management program would consider other factors in determining which culverts should be upgraded during a funding cycle, including:

- More cost-effective adaptation methods than culvert up-sizing, such as LID, and changes to building codes and flood-zone exclusions;
- Adaptive adaptation methods, such as retention ponds, that mitigate climate model uncertainty;
- Remaining service life;
- Hazard from culvert failure;
- Construction cost efficiencies from upgrading nearby culverts at the same time.

Table 3-17. Schedules of undersized culverts, by town & precipitation scenario, for buildout. Prioritized by degree undersized.

		Precip. at capacity	Adaptation cost				Adaptation cost			
			Per culvert				Running total			
Town_Name	**Culvert_ID**	**(in.)**	**TP-40**	**A1b_ML**	**A1fi_ML**	**A1fi_Pos95**	**TP-40**	**A1b_ML**	**A1fi_ML**	**A1fi_Pos95**
New London	H02	2.22	9,104	9,104	7,759	12,947	9,104	9,104	7,759	12,947
	I15	2.32	34,827	34,722	51,818	83,338	43,931	43,826	59,578	96,284
	H03	3.12	7,636	10,069	8,723	9,268	51,567	53,895	68,301	105,552
	I02	3.14	7,860	6,358	8,910	8,803	59,427	60,253	77,211	114,356
	B09	3.53	10,046	8,508	9,657	16,639	69,474	68,761	86,868	130,995
	H01	4.80	5,294		5,641	7,717	74,767		92,509	138,711
	I03	4.85	11,381		13,068	20,308	86,148		105,577	159,019
	B02	5.34			6,693	7,288			112,270	166,307
	B14	5.54			12,787	11,944			125,058	178,251
	B10	6.30			8,397	10,872			133,454	189,123
	G05	7.06				29,962				219,085
	I16	9.46				20,162				239,247
Total			86,148	68,761	133,454	239,247	86,148	68,761	133,454	239,247
Newbury	GP01	3.27	8,600	8,600	6,676	8,358	180,897	146,123	273,584	486,851
	O01	3.39	5,384	6,301	6,591	7,491	186,281	152,424	280,175	494,343
	J01	3.67	9,804	9,804	15,515	24,416	196,085	162,228	295,691	518,758
	I10	3.75	13,441	17,298	15,639	19,015	209,526	179,526	311,330	537,773
	J05	3.79	7,632	7,364	9,188	11,993	217,158	186,890	320,518	549,765
	N20	3.86	34,218	15,661	26,811	61,271	251,376	202,552	347,329	611,036
	J09	3.99	5,476	5,476	6,624	8,090	256,852	208,028	353,954	619,126
	K02	4.67	7,479	8,784	7,176	12,114	264,331	216,812	361,130	631,240
	N21	4.74	6,281	5,215	7,035	6,607	270,612	222,027	368,165	637,847
	N12	4.87	19,683		24,572	26,200	290,295		392,736	664,047
	J06	6.32			13,619	19,720			406,356	683,767
	L03	6.73				106,846				790,613
	N01	6.81				14,250				804,863
	N02	6.91				164,550				969,414
	J04	7.18				27,713				997,127
	K01	7.18				33,179				1,030,306
	K06	7.21				15,623				1,045,929
	K07	7.24				21,128				1,067,057
	K04	8.25				25,613				1,092,670
	N19	8.43				25,351				1,118,021
	GP02	9.33				15,992				1,134,013
	N03	9.71				8,187				1,142,200
	N15	10.35				52,195				1,194,395
	J08	10.89				25,917				1,220,312
Total			109,398	75,904	132,771	733,461	109,398	75,904	132,771	733,461

Table 3-17 (continued). Schedules of undersized culverts, by town & precipitation scenario, for buildout. Prioritized by degree undersized.

		Precip. at capacity	Adaptation cost				Adaptation cost			
			Adaptation with Buildout				Adaptation with Buildout			
Town_Name	**Culvert_ID**	**(in.)**	**TP-40**	**A1b_ML**	**A1fi_ML**	**A1fi_Pos95**	**TP-40**	**A1b_ML**	**A1fi_ML**	**A1fi_Pos95**
Springfield	B06	3.63	4,103	5,133	4,556	5,739	403,796	303,065	543,683	1,959,511
	A14	3.68	13,812	7,926	14,988	20,734	417,608	310,990	558,671	1,980,245
	A11	3.70	14,516	10,951	16,650	20,676	432,124	321,941	575,322	2,000,921
	A21	3.92	7,595	10,014	9,513	18,418	439,719	331,955	584,835	2,019,340
	A03	3.96	3,503	3,503	3,938	4,548	443,222	335,458	588,773	2,023,888
	B08	4.47	6,022	6,022	5,904	9,928	449,244	341,480	594,677	2,033,816
	A08	4.47	6,017	6,586	6,532	9,356	455,261	348,066	601,209	2,043,172
	A01	4.68	3,509	3,565	4,651	5,580	458,770	351,631	605,861	2,048,752
	A02	5.59			2,825	4,013			608,685	2,052,765
	B07	5.82			20,651	17,578			629,336	2,070,343
	A10	5.88			8,335	7,900			637,671	2,078,243
	B05	6.10			15,741	38,338			653,412	2,116,581
	A09	7.62				21,241				2,137,822
	A16	7.94				5,879				2,143,701
	A15	8.24				3,622				2,147,323
	A22	8.28				66,302				2,213,625
	A07	9.41				22,160				2,235,785
	A04	9.97				14,898				2,250,683
	A05	10.88				13,180				2,263,863
Total			59,077	53,699	114,285	310,091	59,077	53,699	114,285	310,091
Sunapee	N09	4.46	9,791	9,791	14,096	11,783	527,637	415,121	781,792	2,585,737
	C01	4.55	3,807	4,301	3,380	5,037	531,445	419,422	785,172	2,590,774
	P01	4.58	13,607	11,598	14,827	15,397	545,052	431,021	799,999	2,606,171
	S01	4.91	5,876		4,639	5,774	550,927		804,638	2,611,945
	A25	5.42			55,373	96,682			860,011	2,708,627
	N10	6.15			7,374	13,923			867,385	2,722,550
	F03	6.68				48,112				2,770,662
	Q03	6.75				8,909				2,779,571
	F02	6.82				40,396				2,819,967
	C05	6.88				35,165				2,855,132
	Q01	7.32				10,053				2,865,185
	Q02	7.47				9,999				2,875,184
	C03	8.41				10,060				2,885,244
	A27	8.47				69,618				2,954,862
	D03B	8.49				17,754				2,972,616
	A26	8.77				142,140				3,114,755
	N07	8.81				9,579				3,124,335
	C02	8.88				13,968				3,138,303
	N08	8.92				7,153				3,145,456
	C04	9.18				7,172				3,152,627
	A39	9.54				53,692				3,206,319
	D02	10.62				29,332				3,235,651
Total			33,081	25,690	99,688	661,697	33,081	25,690	99,688	661,697

Tables 3-18a-b provide watershed-wide total *peak flow* for combinations of precipitation, landuse, and *Antecedent Moisture Condition (AMC)*. Table 3-18a shows that the impact of *AMC III*, saturated soil, is greater than that from either population growth or climate change. This is important because recent extreme/record storms have occurred when soils were either saturated, or mimicked saturated soils by being frozen. Table 3-18b shows that adapting the stormwater system to accommodate *peak flow* resulting from the estimated A1fi +95% confidence limit with population growth on average soil moisture, also accommodates *peak flow* resulting from the *most likely* A1fi estimate on saturated soil and with population growth.

Tables 3-18a-b. (a) Impact of AMC III on peak flow, vs. buildout and climate change

		Current	Current	Buildout Ass	Buildout Ass	LID Ass	LID Ass
		AMC II	AMC III	AMC II	AMC III	AMC II	AMC III
SRES	P	∑ Qp	∑ Qp	∑ Qp	∑ Qp	∑ Qp	∑ Qp
TP-40	5.10	11,367	28,162	13,761	31,630	12,507	29,864
A1b *ML*	4.87	10,434	26,377	12,682	29,696	11,498	28,004
A1fi *ML*	6.65	18,101	40,457	21,439	44,895	19,710	42,639
A1fi +95ci	11.10	39,888	77,061	45,784	84,116	42,744	80,542

Tables 3-18a-b. (b) Best adaptation to mitigate impacts from AMC III

		Current	Current	Buildout Ass	Buildout Ass	LID Ass	LID Ass
		AMC II	AMC III	AMC II	AMC III	AMC II	AMC III
SRES	P	∑ Qp	∑ Qp	∑ Qp	∑ Qp	∑ Qp	∑ Qp
TP-40	5.10	11,367	28,162	13,761	31,630	12,507	29,864
A1b *ML*	4.87	10,434	26,377	12,682	29,696	11,498	28,004
A1fi *ML*	6.65	18,101	40,457	21,439	44,895	19,710	42,639
A1fi +95ci	11.10	39,888	77,061	45,784	84,116	42,744	80,542

<u>*Outreach*</u>

Figures 3-23a-e show stakeholders' opinions of various measures used to evaluate the success of the Outreach program.

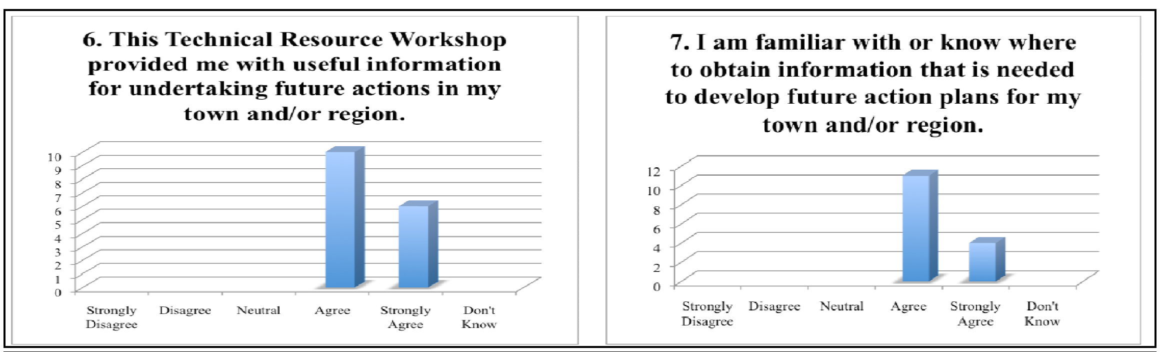


Figure 3-23a. results of Outreach program

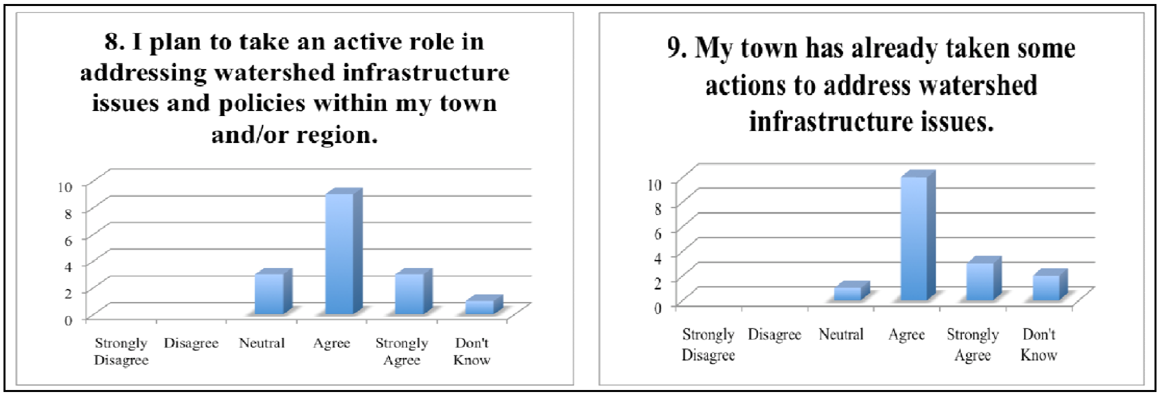


Figure 3-23b. results of Outreach program

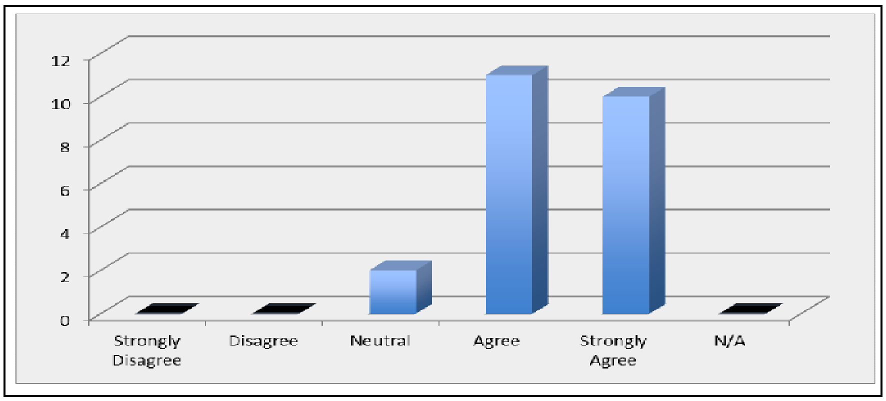


Figure 3-23c. Response to Forum Question 6: "People participating in this project will be more likely to cooperate and/or collaborate across towns."

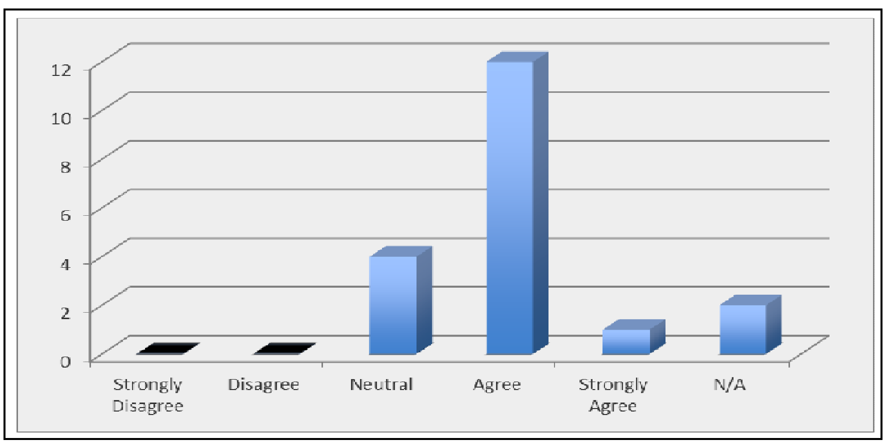


Figure 3-23d. Response to Forum Question 13: "My town is likely to implement some solutions or strategies that are a result of this project."

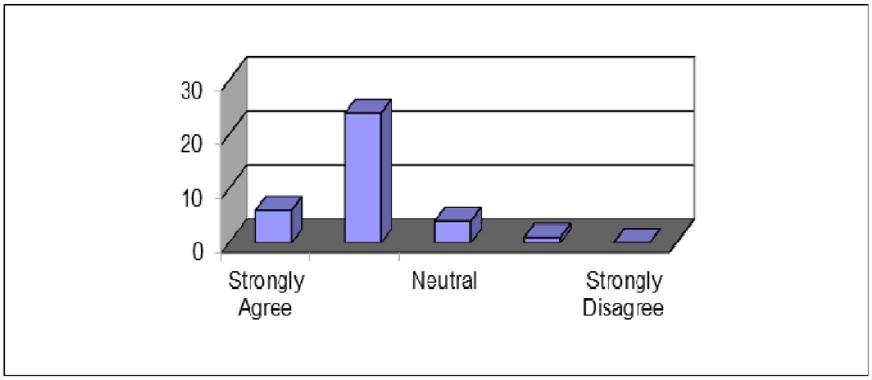


Figure 3-23d. Response to Town Workshops Question 2: "As a result of this workshop, I anticipate that my town will likely proceed to plan and develop priority actions to mitigate flooding and other adverse impacts from storm water."

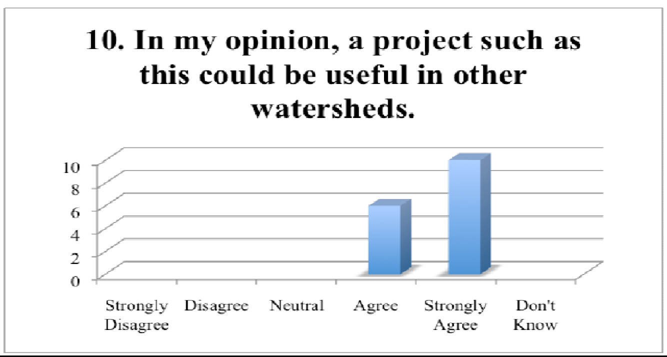


Figure 3-23e. Transferability of results

Advisory Committee Input

In addition to the surveys at these meetings, the team utilized the Advisory Committee to help assess progress towards meeting the project's stated goals. There were two formal Advisory Committee meetings that focused on assessment. One was in October 2010 and the second was in June 2011. During the first formal meeting, the Advisory Committee addressed the following questions raised by the project management team. Questions 1, 2 and 4 received a numerical score ranging from 1 to 5 with the scale: Not Achieved = 1 and Well Achieved = 5. Also, positive statements as well as proposed changes/improvements related to each question were solicited and recorded. A general discussion was held around question five.

1. Did the process raise the level of awareness, knowledge, and understanding of future risks by multiple stakeholders? (Advisory Committee rating: 4+)
2. Was the engagement process effective? (Advisory Committee rating: 5-)
3. Did the process increase the readiness of stakeholder and decision makers to make policy changes and/or take action? (Not rated)
4. Has the process increased a willingness to cooperate and collaborate across intra- and inter-local government stakeholder groups so far? (Advisory Committee rating: 4)
5. What can we do to improve the project's likelihood of success? (Discussed)

Overall results from the first meeting indicated a successful first year of raising awareness including future risks. The engagement process was also perceived as effective with mention that key members from each town in the region were now involved in the process. They also stated that the readiness to cooperate across political boundaries had improved since the project was “getting people from multiple towns to sit at one table to discuss these issues.” The key recommendation for enhancing the project was to focus on more public outreach and education, and a request for more concrete information (at this stage the data was still being gathered and analyzed). The project management team responded to these requests by holding four Town Workshops in January-March of 2011 to provide individualized data for each town, and also by publishing two more newsletters to help inform the public about the project. Please see Appendix 12 for detailed results.

Communication of results of technical activities

Dissemination and discussion of the technical analyses were part of every meeting after data gathering and analysis was complete. This information also was disseminated in three (rather than the required two) citizen-friendly newsletters, which was named the “Sunapee News-Stream.” Two of these were in print form, and the final was electronic. Three regional Forums for stakeholders were held (although only one was stated in the grant agreement). The first Forum served as a kick- off event and set up the three Task Forces. The second Forum brought stakeholders up to date on progress, set up the Advisory Committee, and Town Workshops (referred to in the deliverables as “Cluster Workshops”). The third served to deepen technical knowledge, provide financial data, and to coalesce previously generated ideas into a concrete action plans. Follow-up assistance was provided as needed. The only deliverable that was not fully attained was the incorporation of climate change adaptation into a master planning document. Unfortunately, though much groundwork was laid, there was not enough time to attain that deliverable within the given time span and scope of the project. However, indicators (see below) are consistent with this objective being attained in the near future. The Advisory Committee has taken up leadership for future action. The commitment and active involvement in the project will help insure the eventual attainment of climate change adaptation measures in the Lake Sunapee region.

Table. 3-15. Indicators of stakeholder engagement and readiness for action, in the arenas of improving community infrastructure, enhancing land use regulations, and adopting innovative land use practices. Items in italics indicate anticipated actions, which were primarily outside the scope of the timeframe of this project.

Indicator of Readiness/ Action Taken	**Goal: Improve Community Infra-structure**	**Goal: Enhance Land Use Regulations**	**Goal: Adopt Innovative Land Use Practices**
Attendance at Stakeholder Forums	Yes: Readiness	Yes: Readiness	Yes: Readiness
Task Force 1 Participation: Development and Zoning	Yes: Readiness	Yes: Readiness	Maybe: Readiness
Task Force 2 Participation: Reducing Impact: Water Retention and Impervious Surfaces	Yes: Readiness	Maybe: Readiness	Yes: Readiness
Task Force 3 Participation: Local Government and Infrastructure	Yes: Readiness	Yes: Readiness	Maybe: Readiness
Town Workshop Participation	Yes: Readiness	Yes: Readiness	Yes: Readiness
Advisory Committee Membership	Yes: Readiness	Yes: Readiness	Yes: Readiness

Soliciting more information from sources: AUNE, consultants, state board, etc.	Yes: Action	Yes: Action	Yes: Action
Planning and conducting more town workshops on related subjects	*Yes: Action*	*Yes: Action*	*Yes: Action*
Planning and conducting cross-town/regional workshops on related subjects	*Yes: Action*	*Yes: Action*	*Yes: Action*
Publicize planned actions	*Yes: Action*	*Yes: Action*	*Yes: Action*
Storm water issues discussed at planning board	*Yes: Action*	*Yes: Action*	*Yes: Action*
Replacing infrastructure	*Yes: Action*	*Maybe: depends on regulations*	*Maybe: depends on type of infrastructure*
Implementing LID	*Yes: Action*	*Maybe: could be concurrent*	*Yes: Action*
Changing regulations	*Yes: Action*	*Yes: Action*	*Yes: Action*

Validation

Precipitation model

A common method of validating downscaled climate model output is to test the model's skill at reproducing results for a known historical period. For the present study, the historical record at the Mt. Sunapee NCDC station dates only to the early-1950s, too short a period to contain two sets of thirty-year records: an early set to serve as the predictor, and a later set to serve as the predictand. However, such a validation was performed for two previous studies that applied the same downscaling method (Stack et al., 2006; Stack et al., 2010), and results from these tests reflect the skill of the method for the present study.

Figure 3-24 displays the results of using the modified delta method for two runs of the Climate of the 20th Century scenario, for the GFDL CM2.1, to project the 24-hour 25-year precipitation for a known historical period. The predictor time period was 1926-1955, and the predictand time period was 1971-2000. Differences between the two validation runs of the downscaling method, and the same intensity/return-period event computed from the historical NCDC data record, were 1% and 3%.

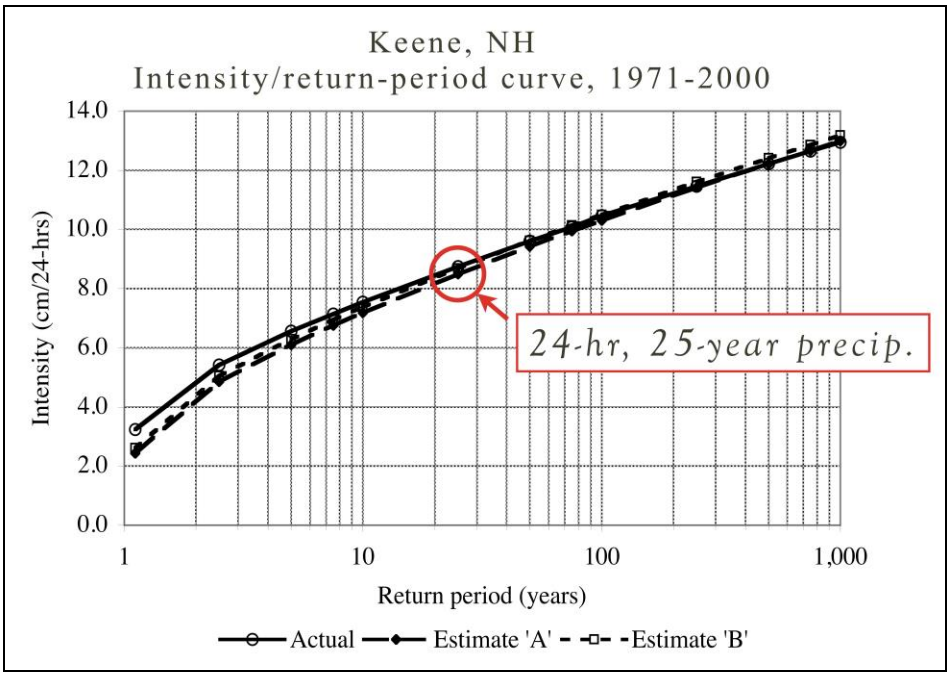


Figure 3-24. Results of validation for the modified delta downscaling method from a previous study by the project team (Stack et al., 2006).

This validation technique was also used to test the skill of the same downscaling method, for a subsequent study (Stack et al., 2010). The 24-hour, 25-year event was computed for thirty years of historical precipitation records from two time periods, for a set of homologous climate stations that included the study site (Table 3-18). The predictor period was again 1926-1955, and the predictand period was 1971-2000. The set of homologous stations was selected from a population of northeast United States and Quebec, Canada 152 stations with records dating to 1926, using the method of L-moments developed by Hosking and Wallis (1997) for regional analysis. Climate model output for six gridpoints of the GFDL CM2.1, for a single model run, was extracted for the same two thirty-year periods as for the historical stations. The percentages of change in the 25-year event were computed for the GCM gridpoints, transferred to the homologous stations using the modified delta method, applied to the predictor period for the historical stations, and compared with the predictand period. Results are shown in Table 3-18, the mean error was -0.3%, although errors for individual stations spanned a 39.4% range from -20.0% to 19.4%. The error for the study site was -19.4%. All errors were within the 95% confidence interval for the *point process* estimate of the design storm.

Table 3-18. Skill at projecting design storm change for a known historical record.

Station site	Station ID	Longitude	Latitude	Elevation (m)	%Δ in 25-year event: Estimated via downscaling	%Δ in 25-year event: Computed from historical records	Error
Boston	190770	-71.02	42.37	6	-14.1%	-13.5%	0.6%
Lawrence	194105	-71.17	42.70	18	-30.1%	-23.1%	7.0%
Concord	271683	-71.50	43.20	106	-24.3%	-18.4%	5.9%
Durham, NH (study site)	272174	-70.95	43.15	24	-3.7%	-23.0%	-19.4%
Hanover	273850	-72.28	43.70	184	5.6%	-13.0%	-18.6%
Keene	274399	-72.32	42.95	155	-34.6%	-15.4%	19.3%
New York	305801	-73.97	40.78	40	3.9%	-16.1%	-20.0%
Setauket	307633	-73.10	40.97	12	-24.7%	-18.8%	5.9%
Whitehall	309389	-73.40	43.55	36	10.1%	-5.6%	-15.7%
Kingston	374266	-71.53	41.48	31	-38.8%	-30.7%	8.2%
Brome (Quebec, Ca)	7020840	-72.34	45.11	206	-20.8%	-6.4%	14.5%
Drummondville (Quebec, Ca)	7022160	-72.29	45.53	82	-18.1%	-9.6%	8.5%
Mean error							-0.3%
Maximum error (absolute value)							20.0%

Downscaled results shown in Tables 3-19b for the present study site are lower, for all GCM/SRES combinations, than results shown in Table 3-19a for the Oyster River watershed on the coast of New Hampshire (Stack et al., 2010). Insofar as the values were computed for the identical historical periods, using the identical *point process* method for *peaks over threshold* (column three in Tables 3-19a, b), the difference may result from variations in microclimate between the two sites, as would be expected between a coastal and an inland watershed.

Table 3-19a. Design storm estimates for Durham, NH (Stack et al., 2010)

	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%

Table 3-19b. Design storm estimates for Mt. Sunapee, NH (present study)

	24-hour 25-year precipitation (in.)				Percentage change from TP-40		
	TP-40	1971-2000 baseline (observed)	2046-2075 A1b	2046-2075 A1fi	1971-2000 baseline (observed)	2046-2075 A1b	2046-2075 A1fi
+95%c.i.		6.65	8.00	11.10	30%	57%	118%
Most Likely	5.1	4.06	4.87	6.65	-20%	-5%	30%
-95%c.i.		2.70	3.23	4.34	-47%	-37%	-15%

Fieldwork

For the fieldwork program, quality control was achieved by auditing, for accuracy, information on a judgmentally-selected sample of completed data collection forms. A team different than the one originally collecting data for a culvert went to the culvert site and re-measured culvert and surrounding site specifications. Error rates for each team were determined, and used for remedial action that ranged from feedback and additional training, to re-organizing the people on teams with excessive error rates.

Runoff model

The runoff model was validated by comparing results from the present study with previous research, for the sensitivity of *peak flow* to changes in *curve number* and precipitation. Figure 6 in Hawkins et al. (2006) was derived from a single urbanized 110 acre watershed in Tucson, Arizona. Black lines show sensitivity of *peak flow* to various factors. Colored lines are averages across all subcatchments of the current study, the red line is percentage change in *curve number*, the blue line is percentage change in precipitation. Results from the present study match very closely with those reported in Hawkins et al. (2006).

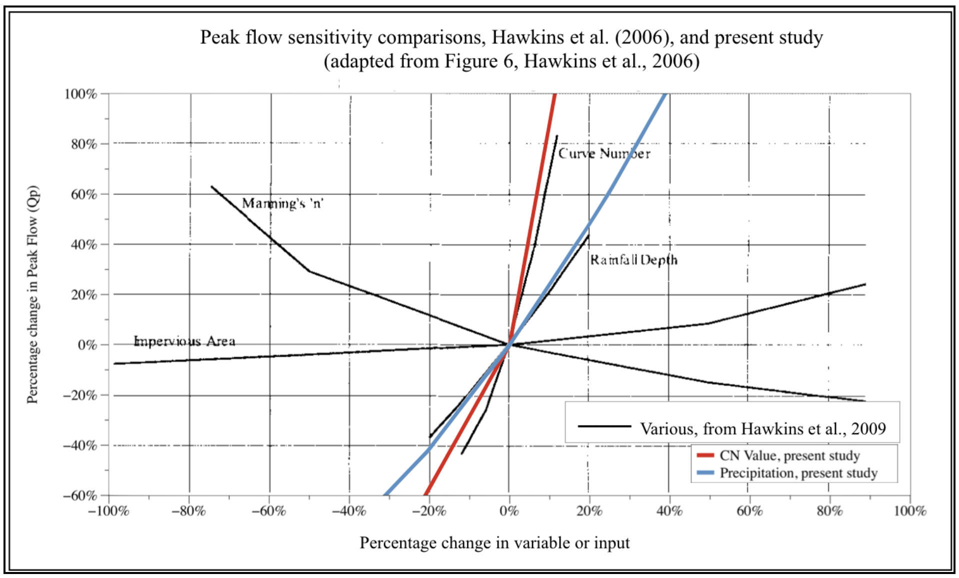


Figure 3-25. Validation of models. Sensitivity of peak flow, Q_p, to changes in Curve Number, Precipitation, and other factors. Results from this study compared with previous research. Adapted from Figure 6., Hawkins et al., 2006).

4. <u>Discussion: Synthesis of findings</u>

Aims and activities committed to in the funding proposal were achieved by applying a multi-disciplinary team to:

- Conduct a program of fieldwork to gather detailed specifications on the one hundred twelve culverts within the study site. Although fieldwork received little visibility in the proposal, it was significant due to its size and complexity, and for being the foundation for all subsequent technical activities. Over six hundred hours of volunteer and investigator time were incurred for this work. Investigators trained and supervised the three teams of two people each; planned, scheduled, and participated in fieldwork; designed the fieldwork form; input collected data; and audited data to assure accuracy and reliability.

- Develop a novel method for building-out the study site to incorporate projected population growth into long-term drainage system planning. This method altered GIS polygon-level curve number values based on changes to impervious rates derived from current zoning standards, to estimate changes to runoff from anticipated mid-21st century population levels;
- Derive a novel method for specifying an achievable set of Low Impact Development methods. The method assumed that one inch of precipitation falling on impervious, and near-impervious, surfaces, be sequestered on-site. This was modeled by drafting building site construction plans, based on current zoning standards and published effectiveness rates for each LID technique applied;
- Project future precipitation for 25-year, 24-hr design storm specified by current New Hampshire culvert design guidelines, using a *point process* model of *peaks-over-threshold*. This activity used a range of GCMs and emissions scenarios, downscaled coupled-climate model data using a modified *delta method*, and utilized downscaled data applied in previous published studies by other research teams;
- Apply standard national construction cost estimator data, and site-specific conditions, to estimate the cost of adapting each culvert for the various landuse and climate change scenarios;
- Promote the implementation of stormwater adaptation through an Outreach program designed to translate knowledge generated in the technical activities into action. This program engage stakeholder groups to assume ownership of stormwater-related problem analysis, solution development, and decision-making (Wilson, 2010);
- Provide knowledge tools to facilitate adaptation planning and implementation.

The study team also committed to the research aim of examining several unresolved issues in the stormwater adaptation literature pertaining to uncertainty:

- Conclude on the significance and manageability, for stormwater adaptation, of climate model uncertainty;
- Identify factors influencing the rate by which the stormwater system becomes undersized, and factors influencing associated adaptation costs for maintaining historical risk levels;

Synthesis of findings

This study fills important gaps in research literature by assessing the impact of uncertainty, inherent in long-term climate projections, on required stormwater system capacity and resulting construction cost. This is necessary because, as recognition widens that no significant decreases in uncertainty is expected in the foreseeable future, and as impacts from climate change increasingly manifest, communities need to understand the significance of uncertainty, and the size and affordability of safety factors that accommodate uncertainty. By studying the relationship between climate change, current and required stormwater system capacity, and costs, this study provides important knowledge resources and directly contributes to goals four and five of the U.S. Climate Change Science Program (Beller-Simms et al., 2008):

4. Understand the sensitivity and adaptability of…human systems to climate and related global changes;

5. Explore the uses and identify the limits of evolving knowledge to manage risks and opportunities related to climate variability and change.

Findings show that: both required capacity and construction cost can be determined for a given combination of climate model, emissions trajectory, and landuse; both required capacity and construction cost are insensitive to changes in precipitation intensity, and thus insensitive to uncertainty; a significant percentage of culverts remain adequately sized even for extremely pessimistic climate change impacts; on a by-town or watershed-wide basis, the incremental cost of designing for pessimistic climate change impacts does not result in a prohibitive impact on town budgets or property taxes; application of LID methods provides a significant reduction in adaptation costs, lowers the impact of uncertainty, and is more beneficial for more pessimistic climate change scenarios; and a program of education and outreach can significantly increase a community's motivation to protect itself from more extreme climate impacts. This motivation has persisted past the completion of the project, and over the near- and mid-term can be expected to significantly reduce the community's exposure to losses from flooding.

The ability to quantify required capacity and related construction costs for specific climate change scenarios, the insensitivity of capacity and costs to uncertainty, and the percentage of culverts that never require upsizing, limit the impact of uncertainty inherent in climate change projections. By constructing systems to more extreme scenarios and to the upper limit of confidence intervals, a safety factor is incorporated to adaptation programs that buffers uncertainty. Moreover, the insensitivity of construction cost to increased precipitation intensity provides incentive to incorporate even a very large safety factor. Thus, the ability to manage uncertainty, combined with the affordable impact of adaptation on town budgets and property tax rates, support a conclusion that adaptation is viable under current levels of uncertainty about future climate impacts severity.

Significance of uncertainty in the context of adaptation

The ability to develop specific capacities and costs for a given scenario derive from the use of standard civil engineering design methods, and standard construction cost compilations, applied on a culvert-by-culvert, and scenario-by-scenario basis. The combination of the number of culverts, and the number of landuse/AMC/climate-change scenarios modeled, resulted in a dataset of over 34,000 records from which to establish the relationship between culvert capacity and cost, and precipitation and landuse. The use of widely-established methods, and the size of this dataset, provide capacity and cost estimates that have a high degree of reliability, and limit uncertainty to that which is inherent in long-term climate forecasts.

As shown in Table 4-1, *peak flow*, and thus culvert capacity, is more sensitive to changes in *curve number*, i.e. hydrological characteristics, than to changes in precipitation. Therefore a given percentage of uncertainty from hydrological factors has a greater impact on culvert capacity, and thus adaptation planning, than an equal percentage of uncertainty in precipitation forecasts. From Table 4-1a, average watershed-wide *peak flow* changes by 2.1% for every 1% change in precipitation, by 3.1% for every 1% change in *CN* resulting from landuse change, and by 8.6% for every 1% change in *CN* resulting from change in *antecedent moisture condition*.

This study examined the effect of a high degree of uncertainty in the climate-changed precipitation estimate, by selecting as a precipitation scenario the A1fi +95% confidence limit, which is equivalent to a 1-in-750 year event under A1fi and a 1-in-2,500 year event under TP-40 (Table 3-3b), and is 67% greater than the A1fi *most likely* estimator (Table 4-1b). *Peak flow* increases by 1.8% for every 1% increase in precipitation from the A1fi to the A1fi +95% confidence limit. Because this sensitivity is so much less than that for *antecedent moisture condition*, and given that the extreme or record events of recent years in central New Hampshire occurred on frozen or saturated soils, the professional community should be more concerned with uncertainty in designing for these events, than uncertainty in designing for climate change.

Tables 4-1a,b. Sensitivity of peak flow to precipitation, landuse, and AMC

Table 4-1a. Sensitivity of peak flow to precipitation, landuse, and AMC

	Precip.				Average CN		Average Peak Flow		Ratio of %Δ*Qp* to:	
P_Scenario	**inches**	**%Δ**	**Landuse**	**AMC**	**CN**	**%Δ**	**gps**	**%Δ**	**%ΔP**	**%Δ*CN***
TP-40	5.1		Current	II			73.6			
TP-40 *2	10.2	100%	Current	II			231.1	214%	2.1	
TP-40			Current	II	64.2		73.6			
TP-40			Buildout	II	68.5	7%	88.9	21%		3.1
TP-40			Current	II	64.2		73.6			
TP-40			Current	III	75.2	17%	182.8	148%		8.6

Table 4-1b. Sensitivity of peak flow to a large uncertainty range (A1fi most likely to A1fi +95% c.i.)

	Precip.				Average Peak Flow		Ratio of %Δ*Qp* to:
P_Scenario	**inches**	**%Δ**	**Landuse**	**AMC**	**gps**	**%Δ**	**%ΔP**
A1fi ML	6.65		Current	II	118.0		
A1fi +95% c.i.	11.10	67%	Current	II	261.3	121%	1.8

The insensitivity of construction costs to increases in precipitation is seen in Table 3-11, by comparing the percentage increase in precipitation for a given climate change scenario, with the percentage increase in marginal cost. For example, the GFDL A1fi *"most likely"* precipitation is projected to be 30% greater than that specified by TP-40, yet the resulting watershed-wide marginal cost is only 12% greater than the cost of constructing to the TP-40 specification.

That not all culverts require upgrading, even under an extreme climate change scenario, increases the manageability of uncertainty by making the incorporation of a safety factor more affordable. From Figure 3-11 it can be seen that about 65% of culverts remain adequately-sized under the *"most likely"* A1fi scenario. Even at the upper 95%

confidence limit for this scenario, a precipitation amount 175% greater than the recent historical event, 30% of culverts remain adequately sized.

In published literature, "soft" adaptations such as general resilience and capacity building remain the standard prescription for potential civil infrastructure vulnerability, due to uncertainty in GCM output (e.g. Rosenberg, 2010). Yet "soft" adaptations are likely insufficient by themselves, requiring eventual supplement from "hard" adaptation methods (White House Climate Change Adaptation Task Force, 2010; Miller et al., 2010), presumably when anticipated reductions in uncertainty occur.

Implicit in the standard conclusion to delay hard adaptation are the following assumptions, portrayed in Figure 4-1:

- The cost of uncertainty will significantly decline within the planning horizon;
- The cost of damages are not yet significant enough to require "hard" adaptation, but will increase as climate change impacts increasingly manifest;
- The costs of uncertainty and damages will reach equilibrium, after which it will make economic sense to perform "hard" adaptations;
- We have not yet reached this equilibrium.

The belief that the cost of uncertainty currently exceeds the cost of damages is problematic, however:

- No significant reduction in climate change-related uncertainty is expected in the foreseeable future (Smith, 2008);
- Significant damages and loss of life from overwhelmed stormwater systems are already occurring, resulting in a penalty from inaction. Since 2005, central New Hampshire has annually experienced an extreme storm with an intensity/duration at or above the historically 1-in-75 year return period. In the study site alone this has caused hundreds of thousands of dollars in damages;
- Present systems may not be as adequate as we assume, even for current conditions. Both Waters et al (2003), and our studies, have found that existing systems are already undersized (Figure 4-2), and a consistent finding of our studies has been that a significant percentage of existing culverts have impaired capacity to convey stormwater, due to damage, sediment, or obstructions.

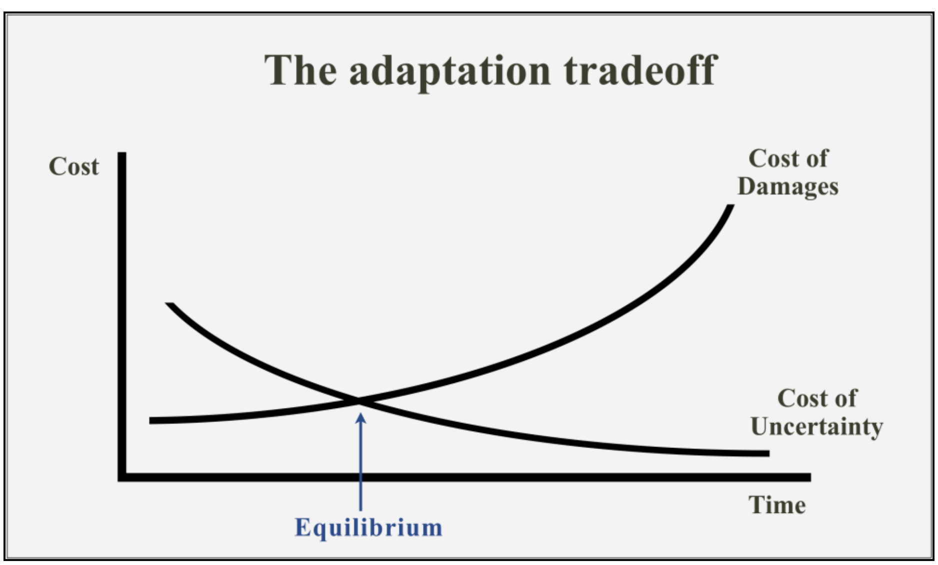


Figure 4-1. Cost curves for uncertainty and damage.

Percentage of stormwater system components already undersized

• Newbury, NH, 2010:	14%	*(present study)*
• New London, NH, 2010:	23%	*(present study)*
• Springfield, NH, 2010:	14%	*(present study)*
• Sunapee, NH, 2010:	0%	*(present study)*
• Durham, NH, 2009:	9%	*(Stack et al., 2010)*
• Keene, NH, 2005:	26%	*(Stack et al., 2006)*
• Ottawa, Canada, 2001:	21%	*(Waters et al., 2003)*

Figure 4-2. Stormwater management systems are already vulnerable, based on recent climate records.

Non-stationarity in long-term forecasts as a change from past and current conditions, and as an obstacle to adaptation

In contrast to the stability of previous and current conditions, and the precision of historical design standards such as *TP-40*, non-stationarity resulting from increasingly manifesting climate change is considered an obstacle to adaptation. However, the assumption that past and current climates have been stationary, and design standards precise, is inaccurate. For example, as shown in Figure 4-3, isoplubial contours for the 24-hour, 25-year event, as published in 1961 for *TP-40* (Hershfield, 1961) generally are an inch greater than similar contours published twenty-five years earlier by Yarnell (Yarnell, 1935).

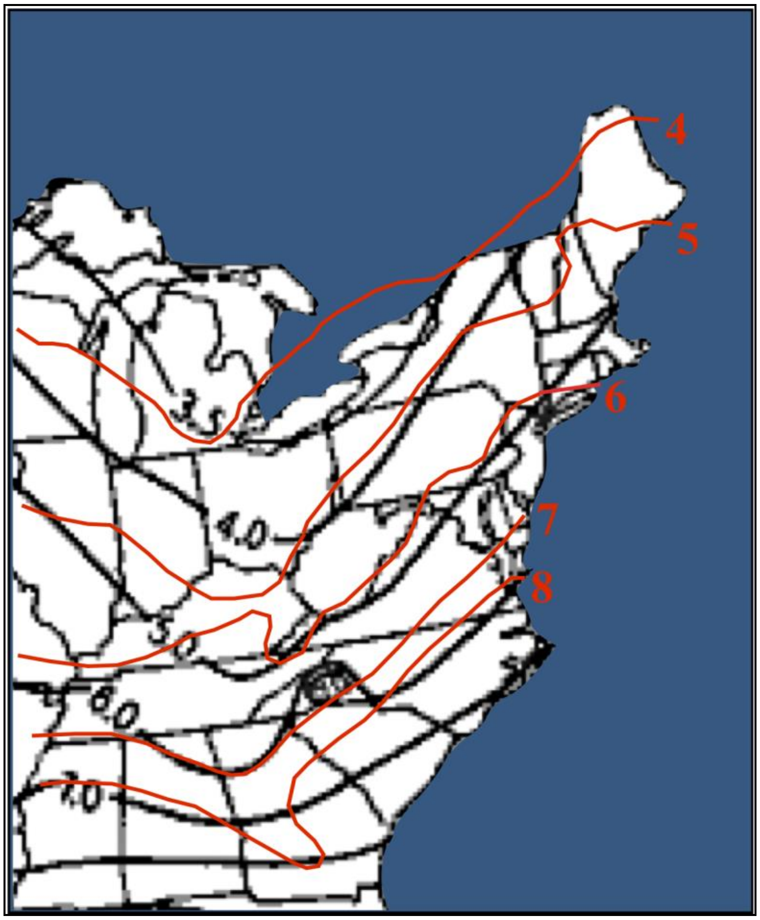


Figure 4-3. For the 24-hr 25-yr event, isoplubial lines from Yarnell (1935), overlaid with red isoplubial lines from TP-40 (Hirshfield, 1961).

The assumption that *TP-40* itself was accurate and precise is fallacious (Wilson, 2008). Standard intensity-duration-frequency modeling of rainfall asserts that a minimum thirty year record is required to accurately estimate lower frequency events such as the twenty-five year storm. However, *TP-40* utilized historical datasets that, on average, were only fifteen years. In addition, *TP-40* provided only point estimates for precipitation levels, omitting confidence intervals and thus portraying a false degree of precision. As a result of concerns about *TP-40*, there was controversy about whether to release it for publication.

Finally, the development of climate change-cognizant design specifications is possible under conditions of non-stationarity. This is achieved by estimating the design storm precipitation for a period in the future corresponding to the expiration of the service life for a stormwater component. For example, states in western Germany have developed a table of design multipliers for specific service lives (Figure 9 in Hennegriff et al., 2006).

Proposed rules-of-thumb for stormwater adaptation in central New Hampshire

Figure 3-11 shows the percentage of undersized culverts for a given increase in precipitation, for the specific scenarios applied in this study. This information can be used to determine the pipe size required to achieve a given percentage of adequately-sized culverts for a given storm intensity, and this can be expressed as a multiplier of the pipe size required for *TP-40* adequacy. Table 4-2a shows the percentage of adequately-sized culverts achieved, for a given climate-change scenario, by culverts that are arbitrary multiples of ones designed to *TP-40*. For example, 90% of culverts designed with a cross-sectional area that is 1.5 times greater than that specified for *TP-40* will be adequately sized for the estimated *most likely* storm under the mid-21st century A1fi trajectory.

Table 4-2b shows the culvert diameter to which an existing pipe must be increased, in order to achieve a specified multiplier.

Table 4-2a, b. (a) Rule-of-thumb multiplier of cross-sectional area to achieve culverts adequately-sized for a given climate-changed precipitation scenario. (b) For a given initial pipe diameter, the required pipe diameter to achieve a given multiplier.

a. Percentage of adequately-sized pipes achieved by a given cross-sectional area multiplier

	Cross-sectional area multiplier of pipe designed for TP-40			
	1.0	**1.5**	**2.5**	**3.0**
A1b	95%			
A1fi		90%		
A1fi +95%ci			50%	90%

b. For given TP-40 sized pipe diameter, required diameter upgrade to achieve multiplier

	Cross-sectional area multiplier		
TP-40 pipe diameter (ft)	**1.5**	**2.5**	**3.0**
2.0	2.5	3.2	3.5
3.0	3.75	4.75	5.25
4.0	5	6.4	7
5.0	6.25	8	8.75

Outreach program

(also see Appendix 6. Report on the Outreach program)

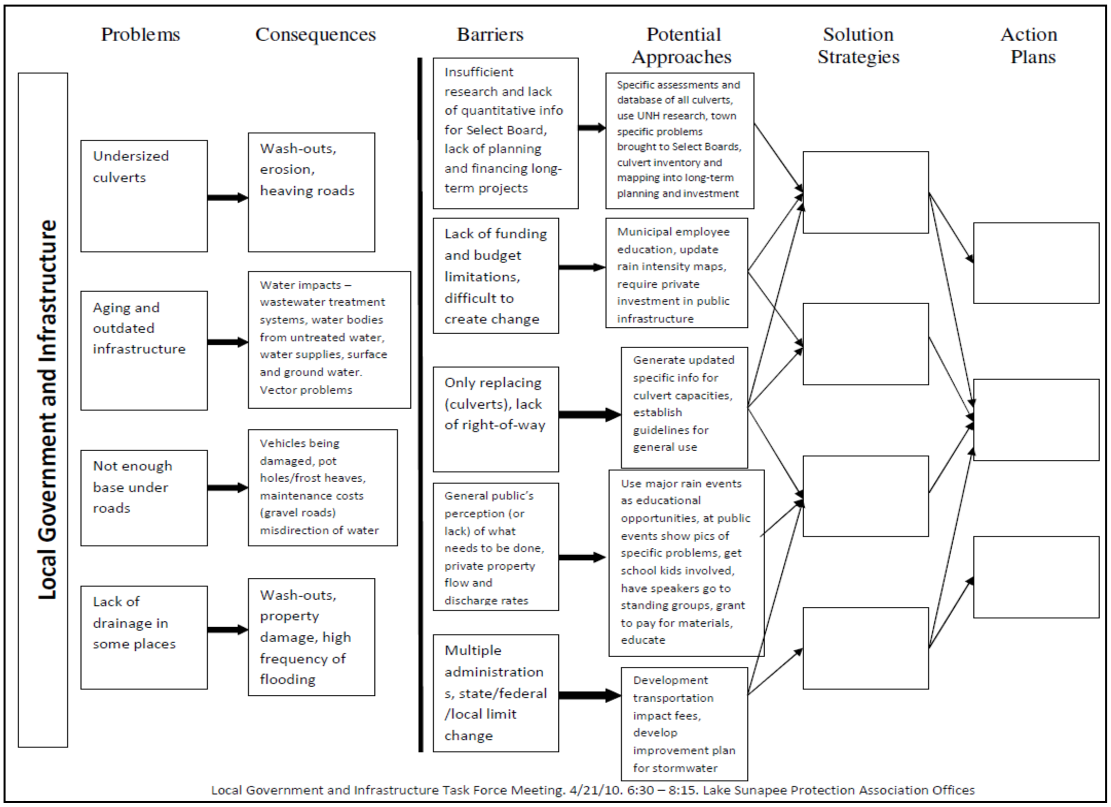
Surveys and discussion conducted at project-close indicated that there was strong agreement that collaboration within and across towns would be key to successfully addressing storm water issues. Most people at the Forum felt that their town was aware of storm water issues. They also confirmed that they were better prepared and able to participate in assessing potential approaches as a result of this project. Participants expressed that even although inter-town cooperation is not always common, people involved in this project were more likely to cooperate across town boundaries.

It seemed clear to the project team that local leaders of the four towns in the Lake Sunapee region are ready and willing to take action on stormwater infrastructure problems in their area. As indicated in the surveys, the meetings were perceived as productive, and the participants felt actively engaged from the outset. The results of the brainstorming process regarding barriers to action and proposed solutions (Figure 4-3) were all citizen-generated, which in turn may have contributed to the willingness of the Advisory Committee and others to take over the project organization and leadership as the towns move forward in implementing their action plans.

An additional important result of this deliberately inclusive process has been the increased potential for meaningful collaboration between towns. As was pointed out at the final Forum, towns and organizations working together are more likely to receive

Figure 4-3. Action map from the Local Government and Infrastructure working group, one of three established by the Advisory Forum. See Appendix 6 for completed action maps for all three groups.

funding from grant sources; additionally, the possibility of sharing mutually-needed



resources between towns may reduce the potential cost to each town.

One of the most important results of this project is that citizens and towns in the Lake Sunapee watershed are now far more prepared to face some of the potential impacts of climate change (specifically, predicted increasingly-severe storms) than they were before this project began. This region now has the opportunity to be proactive rather than reactive, thereby vastly reducing potential damage to life and property had this project not been undertaken. The public is far more knowledgeable and informed about such subjects as watershed infrastructure, the effects of build- out on the landscape, and other related subjects than they were two years ago, and thus will be able to make informed and well-thought-out decisions in regards to their towns' futures.

This project was able to raise the capacity of these communities to address climate change adaptation at the local level, and their commitment to continue this work after the close of this project. Specifically, they are committed to moving ahead on implementation of priorities developed during this project under the dual leadership of the regional planning commission (UVLSRPC) and the Lake Sunapee Protective Association.

Needs identified by this study

By performing a local scale study of adaptation, this project identified important policy issues that need to be resolved in order for stormwater adaptation to be widely implemented. Over the course of this and previous studies, a consistent and significant limitation expressed by civil engineers has been their inability to design for climate change as a result of liability issues stemming from the lack of climate-cognizant design specifications that have been given the imprimatur of state and federal governments.

The civil engineering community should determine how large a safety factor is required for professionals to be comfortable designing climate change-cognizant systems, as well as the requirements for returning to a safety-factor-based design, which has generally been supplanted by a risk-based approach (Webb and White, 2010). A very large safety factor was tested in this study by selecting, for the upper-bound of precipitation estimates used in modeling, the +95% confidence limit for the A1fi scenario. This event is equivalent to a 1-in-2,500 year event under TP-40, and a 1-in-750 year event under the A1fi scenario.

The role and extent of safety factors is one of several decisions to inform a single set of climate change-cognizant isoplubial curves, akin to TP-40, that must be developed as *de facto* design standards. This set must be formally adopted by federal and state agencies, in order to meet the liability concerns that limit action in the engineering profession. Although multiple climate models and sets of ensemble model output should be maintained for research purposes, a single set of precipitation design storms should be designated as the approved standard, serving a similar role as *TP-40*, *Atlas 14*, and similar publications have performed in the past. The standardization of a set of precipitation specifications makes climate change-cognizant design feasible on a wide-spread basis, in contrast to the significant expertise and financial resources that currently must be mobilized to downscale precipitation estimates on a study-by-study basis.

The Outreach program applied in this project was crucial for instilling awareness in the community of the current need to adapt, and of the robustness of the estimates provided for required culvert capacities. Our proposed aim of achieving the commencement of a program of adaptation, encountered significant unanticipated obstacles resulting from the lack of attention to long-term stormwater management within the study site, the lack of understanding of how even recent extreme and record storms tangibly impact specific culverts and subcatchments, and the lack of coordination among the four towns with stormwater systems within the study site. The Outreach program identified these obstacles during the initial stakeholder survey and meetings, developed and implemented a successful program to reduce the community's lack of awareness and inertia, and as a result has placed the community in an excellent position to plan and implement an adaptation program.

Subsequent to the completion of this study, the Lake Sunapee Protective Association…

Conclusion

Foundational premises of this project were that: information and methods are available today to support adequately-reliable infrastructure adaptation; the resolution of certain key issues in infrastructure adaptation will be attained most efficiently through learning-by-doing; and these issues can be studied concurrently with providing actionable adaptation guidance to communities.

Findings of this study have broad application nationally and internationally, as communities transition civil infrastructures to accommodate already-occurring and projected change, in order to maintain historically accepted risk-levels. Together, these findings posit a solution to arguably today's most significant challenge in civil infrastructure adaptation: translating the extensive corpus of adaptation policy theory and regional-scale impacts analyses into local-scale action. Though focusing on stormwater management systems, the principles and methods developed provide a template for other local, regional, and national infrastructure systems. The conviction that knowledge and methods available today are sufficiently reliable to support local-scale action, places this project at the fore of adaptation work world-wide. These findings significantly improve national and international capacities to respond to climate variability and change.

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