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Integrated Urban Water Management Applied to Adaptation to Climate Change

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Abstract

Integrated Urban Water Management (IUWM) is the holistic management of urban water supply, sanitation, stormwater, and wastewater to achieve sustainable economic, social and environmental objectives. All parts of the urban water cycle are managed together instead of separately. IUWM can be part of the solution for cities facing singular or multiple water management stresses under present and future climates. It has particular advantages for adaptation because it can be implemented over time and space as climate and others conditions change with options preserved for future actions, it contains no-regrets and co-benefits actions, and integrates local stakeholders into the planning process. Research was conducted to qualitatively examine how IUWM can be used to manage multiple urban water stresses under present and future climates and land use conditions upon the built, natural, and social systems of Exeter, New Hampshire, a small town located in a semi-rural area of the northeastern United States. With its emphasis on holistic solutions and systems thinking, it is shown that by looking at Exeter's suite of challenges through the lens of IUWM there are opportunities for integrated strategies that may lower overall adaptation costs and also provide wide-scale multi-criteria benefits.

Highlights

- Integrated Urban Water Management (IUWM) is the holistic management of water
- It has particular advantages for climate change adaptation
- A case study illustrates its feasibility and advantages

Key Words

Climate Change, Water, Adaptation, Urban, Integrated Management, New Hampshire

1. Introduction

A major theme is emerging in urban water management – that of Integrated Urban Water Management (IUWM). As defined by Bahri (2012), IUWM is the holistic management of urban water supply, sanitation, stormwater, and wastewater to achieve sustainable economic, social and environmental objectives. In its fullest applications, it closes the loop between water supply and wastewater disposal. IUWM is also referred to as "One Water" or the Whole Water approach or Water Sensitive Urban Design (Mukheibur and Currie, 2016). Daigger (no date) and others refer to the concept as part of "Cities of the Future." All parts of the urban water cycle are managed together instead of separately (Diaz et al, 2016, Rietveld et al, 2016).

Whitler and Warner (2014) state that IUWM considers:

- " All parts of the water cycle — natural and man-made, surface and subsurface, and recognizes them as an integrated system
- The full range of demands for water, both anthropogenic and ecological requirements
- The impact of water cycle management on the overall planning and management of cities
- The full range of water supplies available over time
- The practices which can provide water fit for purpose both in quality and quantity, and reduce the demand for potable water
- The sustainability of water service provision
- The local context and stakeholder views
- The scale, engineering, and functional aspects of the water system
- The means by which transition from current practice can be achieved" (page 1).

The United Nations World Water Assessment Programme (2015) recommends IUWM as part of the solution to urban water management challenges.

IUWM is also part of Ecosystem Based Management, Integrated Flood Management (IFM), the current public health paradigm focused on the social determinants of health, and the analysis of the urban Water-Food-Energy nexus (http://ecosystems.noaa.gov/EBM101/WhatisEcosystem-BasedManagement.aspx, August 16, 2016, World Meteorological Organization, 2009, Wilson and Bond, 2007, Centers for Disease Control, 2017, United Nations Educational, Scientific, and Cultural Organization, 2012, Gondhalekar and Ramsauer, 2016)

Figure 1 summarizes the IUWM approach from the viewpoint of our case study in Exeter NH.

Figure 1. The One Water Approach for Exeter NH (adapted from Mukheibur and Currie, 2016)

Tools exist to assist in the application of IUWM such as the Watershed Management Optimization Support Tool (WMOST, Detenbeck et al, 2016) based upon the research of Zoltay et al (2010). A more planning-level tool is the US EPA's CREATE tool primarily designed to help water utilities manage the threats of climate change. It lets users select a range of green and gray options to manage various levels of risks from present and future climate. Various cities in the US are employing some of the concepts of IUWM including Philadelphia, Seattle, New York, Boston, San Francisco, Las Vegas, Aurora, and Denver (Whitler and Warner, 2014, Boston Water and Sewer Commission, 2013, New York City, 2013). Other recent examples include Singapore, Melbourne, Sydney, Windhoek, and Sao Paulo (Bahri, 2012, Mukheibur and Currie, 2016, Onyango, et al, 2014). A review of the literature indicates that there are no small size municipalities such as our case study site, Exeter New Hampshire USA, employing many IUWM techniques besides green infrastructure for stormwater management.

IUWM is a solution for cities facing singular or multiple water management stresses. As is well documented in many places (e.g. Intergovernmental Panel on Climate Change, 2014), water stresses in many cities globally will increase over time due to anthropogenic climate change causing more riverine and coastal floods, higher temperatures, changes in flow regimes, more salt water intrusion, and more intense rainfall. Climate changes will be compounded by demographic, land use, technological, and other biophysical and socio-economic changes. Thus IUWM should also be seen by urban areas as a tool to respond to or adapt to climate change (Diaz et al, 2016, Pingale et al, 2014, Jimenez et al, 2014, Romero-Lankao et al, 2014).

IUWM also has other advantages as a response tool to climate change. As summarized by Kirshen et al (2015), an urban adaptation strategy should have these general attributes.

- Proactive adaptation strategies that are implemented over time and space as climate and others conditions change with options preserved for future actions
- Methods to incorporate the uncertainty of climate change into the analysis
- Actions that are robust enough to respond to all uncertainties and/or flexible and adjustable
- Evaluation with multiple social, economic, and environmental criteria
- No-regrets (i.e. valuable even without climate change) and co-benefits (i.e. valuable to multiple sectors) actions
- Integration of local stakeholders into the planning process

IUWM can incorporate these attributes. It can be implemented modularly over time as conditions change. For example, wastewater can be initially only treated to a level suitable for irrigation and then as water supply becomes scarcer, the treatment can be upgraded to higher level uses. Decentralized stormwater strategies such as Low Impact Development (LID), discussed subsequently in this paper, can be expanded over time as rainfall intensity increases and perhaps groundwater recharge diminishes. Hecht (2017) shows how the uncertainty of future climates can be considered in water management using a top-down scenario based approach while Ray and Brown (2016) illustrate a more bottom-up process which focuses upon the context first. The result of such uncertainty management processes may be solutions that combine both robust actions (here defined to be of sufficient scale to manage all uncertainties by, e.g., constructing an overly large floodwall) or flexible actions that can be implemented or adjusted over time as the climate changes (e.g., by building a dam of low height now but with a sufficiently large foundation that the height can be increased over time as more storage is needed). By its very nature, an IUWM plan is evaluated with multiple criteria and requires stakeholder engagement. Depending upon how it is implemented, IUWM may also provide no-regrets actions such as water conservation, floodplain restoration, and water quality improvements. The provision of co-benefits is one of the pillars of IUWM and examples abound. Recharging stormwater not only decreases urban flooding but also can replenish aquifers and increase baseflows during the low flow season. Reusing wastewater lowers stress on water supply sources while also improving water quality. Restoring floodplains decreases flood losses while enhancing ecosystems. These co-benefit features and the other aspects of IUWM make IUWM a potentially important tool for urban adaptation to changing water resources conditions under climate change.

In this paper we assess the impacts of river and coastal flooding, stormwater drainage, and the hydrologic flow regime under present and future climates and land use conditions upon the biophysical and social systems of Exeter, New Hampshire, a small town located in a semi-rural area of the northeastern United States. After the assessment, we qualitatively present options for managing these stresses using the principles of IUWM. Particular attention is given to the value of merging the biophysical with the social system analysis because the latter informs the readiness of the community to implement aspects of IUWM in Exeter. The research project was known as Climate Adaptation Planning for Exeter (CAPE).

2. Exeter, New Hampshire

The Town of Exeter is located in the northeastern US in the state of New Hampshire (Figure 2) and it has a land area of approximately 50 square kilometers. Exeter's population is approximately 14,000 (Mather, 2014). Land cover in Exeter is comprised of undeveloped, forested lands (47%), developed lands (33%), farmland (2%), and water/wetlands (18%) (Mather, 2014). The river flowing through the center of the commercial area of Exeter is named the Exeter River upstream of the falls in the river just downstream of High Street and is named the Squamscott River, which is tidal, just downstream of the falls. Great Dam was first built at the falls in the 1640s, functioned as a run-of-the-river reservoir with a spillway, and was removed in fall 2016.

As part of this research, a social vulnerability index (SVI) was constructed based on the emergency preparedness literature (Flanagan et al, 2011, Cutter et al, 2003) using 16 indicators from the American Community Survey. Social vulnerability refers to the socioeconomic and demographic factors that affect a community's capacity to prepare for and respond to hazardous events (Flanagan et al, 2011). Assessing social vulnerability is a critical component of the Centers for Disease Control and Prevention's "Building Resilience Against Climate Effects" (BRACE) framework (https://www.cdc.gov/climateandhealth/brace.htm, accessed December 15, 2016). The composite SVI reflects the number of social vulnerability indicators in a given census tract that exceed the 90th percentile for a particular state. Exeter has 3 census tracts. Although the SVI does not provide enough granularity to map out specific impacts to particular neighborhood subgroups, it delineates clusters of vulnerability that were confirmed with greater specificity through our community engagement and analysis process (Aytur et al., 2015). This is discussed in more detail in Section 3.7, Social Vulnerability Assessment.

Although Exeter has a lower composite SVI and a higher per capita income compared to New Hampshire (NH) overall ($39,800 vs. $33,608 respectively), Exeter has several social vulnerability indicators at the Census tract level that are above the 90th percentile for the state. These include the percentage of residents with a disability (19.6% in Exeter's most vulnerable Census tracts, compared to 12.8% statewide); the percentage of residents living in mobile homes (33.5% compared to 5.6% statewide); and the percentage of adults ≥65 years of age (18.6% compared to 15.2% statewide). Compared to NH overall, Exeter's vulnerable tracts also reflected a higher percentage of single parents (46.3% compared to 31.4% statewide), and a higher percentage of residents without a car (8.5% compared to 5.5% statewide).

The Exeter/Squamscott River is one of many rivers that flow into Great Bay, which is a US NOAA National Estuarine Research Reserve (Great Bay, GBNERR) that connects to the Gulf of Maine via the Piscataqua River. The Exeter/Squamscott watershed has an area of 277 square kilometers upstream of the dam, and an additional 52 square kilometers downstream of the dam. The entire watershed is less developed than Exeter, and is comprised of undeveloped, forested lands (57%), developed lands (21%), farmland (6%), and water/wetlands (16%) (Mather, 2014). The annual average flow at High Street is approximately 5.7 cubic meters per second (1997-2011, HDR/HydroQual, 2012). Large portions of the downtown commercial zone of Exeter as well as some outlying neighborhoods were developed over the past several centuries within the active floodplain. The High Street bridge also restricts flow during high flows. The narrow tidal floodplain just downstream of the former dam widens appreciably as the river becomes tidal past urbanized sections of the town. Wetlands border large portions of the rivers in Exeter.

The town's primary water supply source is the Exeter River upstream of High Street. They are capable of withdrawing water from the river and sending it straight to their treatment plant (near the Exeter Reservoir on Dearborn Brook, a tributary of the Squamscott River) or withdrawing from the river and diverting it to the Exeter Reservoir for storage. The Town, however, is lessening its dependence upon surface water because of high turbidity after storm events. They have turned to municipal wells: expanding the capacity of the Lary Lane well and reactivating the Gilman and Stadium wells. Both Gilman and Stadium wells are treated with a new groundwater treatment plant. The dam removal is not expected to significantly decrease the yields of wells in the basin (VHB, 2013). The dam removal is also expected to increase the water quality of the river by lessening the periods of low dissolved oxygen or anoxic conditions upstream of the former dam. This will result in less releases of harmful nutrients and metals into the water column. The higher flow velocities after the removal, however, might occasionally increase turbidity over present levels during high discharge events (VHB, 2013). Private supplies also take surface water upstream of the former dam or from nearby groundwater wells.

Approximately 30 percent of the land area of the town is served with sanitary sewers and nine pump stations. Exeter's central sewage treatment plant using aerated lagoons is approximately 1.6 kilometers downstream of High Street and discharges to the Squamscott River. The only other wastewater plant in the basin is downstream of Exeter in another municipality. The intermittent discharge of high levels of algae and routine discharge of elevated dissolved inorganic nitrogen from the lagoon treatment ponds influence the dissolved oxygen (DO) levels in the river downstream of the outfall, including periodic depressed DO levels under certain conditions (HDR/HydroQual 2012).

Exeter was issued a draft wastewater permit last summer that set an effluent limitation for Total Nitrogen. The wastewater treatment is presently being upgraded at a new site at higher elevation than the present site. The town has one combined sewer system overflow (CSO), which discharges into the tidal portion of the river downstream of High Street. Sanitary sewer upgrades will eliminate CSO.

The urban core of Exeter of approximately 11.7 square kilometers already has local drainage problems and will continue to experience river flood damage upstream and downstream of the former dam –in some places with a recurrence interval of 10 years.

Water quality sampling in 2012 showed widespread impairments existed at ten stretches of the Exeter River, five of which are in Exeter, because of low pH, low dissolved oxygen saturation, elevated fecal-borne bacterial contamination, excess chloride and poor benthic-macroinvertebrate communities (NH Department of Environmental Services (NHDES), 2012). The Squamscott River in Exeter had similar impairments but also included high levels of PCBs, dioxin, chlorophyll *a* and total nitrogen. Stormwater runoff has been documented as a highly significant source of bacterial, toxic and nutrient pollution to New Hampshire coastal waters, including the Exeter and Squamscott Rivers for over two decades (Jones, 2000, Jones and Langan, 1996a&b, Jones and Gaudette, 2001, Jones et al, 1999, Jones, 1998).

There are multiple sets of evidence that show the episodic occurrence of low dissolved oxygen (DO) levels at sites in the Exeter and Squamscott rivers. Both warm temperatures and extreme rainfall events can cause serious and prolonged low DO episodes. Now that the Great Dam has been removed, a decrease in low DO episodes is expected, both upstream and downstream (VHB, 2013).

The Lower Exeter/Squamscott River is a protected river as part of the NHDES Rivers Management Protection Program and the New Hampshire Resource Protection Project due in large part because of its critical value for wildlife, vegetation and natural communities, and fish resources. Alewife and blueback herring, already state listed as threatened, are under consideration to be listed as federally threatened due to declining populations (NRDC, 2011). The dam in downtown Exeter was a barrier for anadromous fish, and those herring that could ascend the fish ladder encountered low DO behind the dam (VHB, 2013), which could also reduce survival of outgoing young.

While modifications to the Exeter River ladder in 2000 had an initial positive impact on river herring passage, the numbers continued to drop since 2001. This indicates that the problem is most likely not with the ladder but with the spawning run, recruitment, water quality, dissolved oxygen levels and possibly flow regime. Herring return numbers and episodic low DO occurrences are indicative of cascading consequences for the totality of environmental and climatic conditions. Removal of the dam, however, is expected to allow more fish to pass upstream than previously and, as stated above, increase DO in the rivers.

Besides the Town of Exeter, GBNERR was an important stakeholder in the research. It was GBNERR's interest in managing stormwater, nonpoint source pollution, land use, and habitat restoration habitat in the Great Bay basin that led to this research; Exeter was seen as a pilot study of an integrated approach. As stated by Paul Stacey, GBNERR Research Coordinator, "….In short, a lot of efficiency can be built by considering multiple issues and implementation strategies simultaneously, especially since the remedy is basically the same for climate, water quality and habitat quality" (personal communication January 7, 2012).

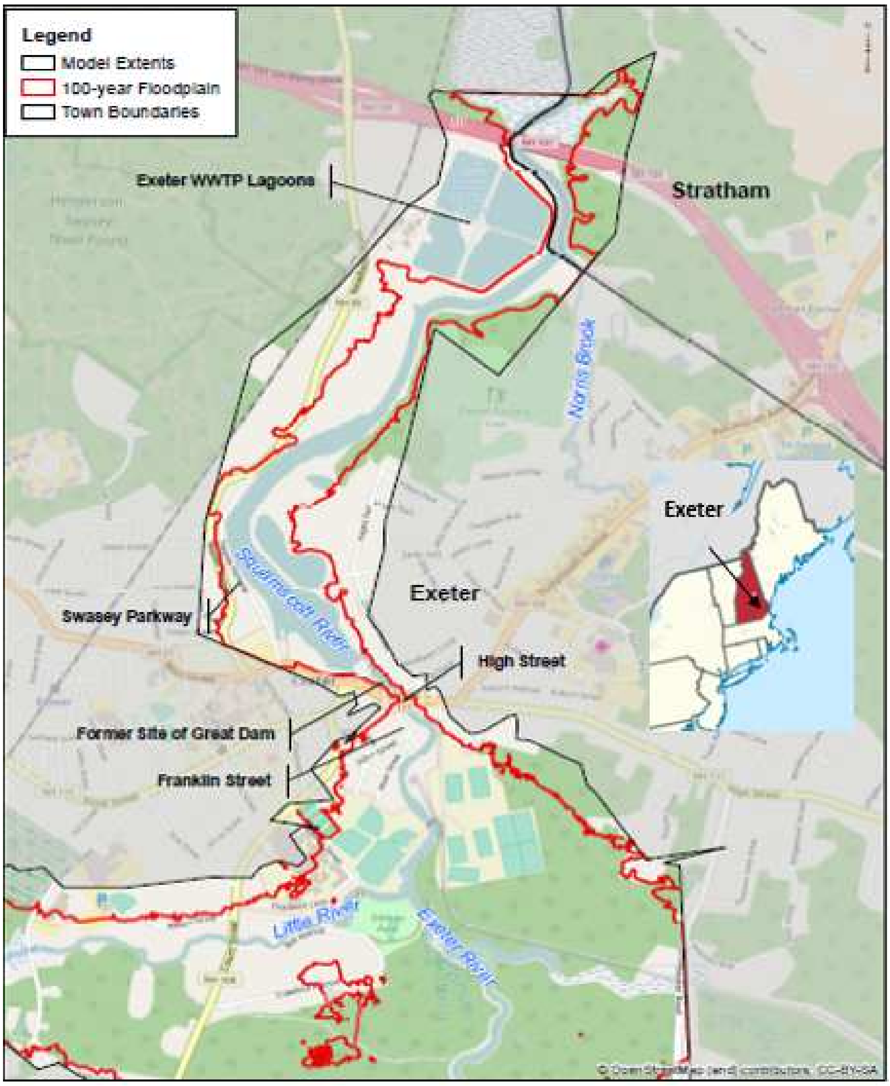

Figure 2. Exeter, New Hampshire USA. See legend in upper lefthand side.

3. Vulnerability Assessment

A vulnerability assessment includes an analysis of the exposure of the site to present and future climate change and SLR threats (e.g., increases in extreme precipitation), determining the sensitivity of the site to the threats (e.g., impacts of increase in extreme precipitation on drainage flooding), and then the adaptive capacity (e.g., ability of system to adjust, IPCC, 2001). In most cases, sensitivity was measured here by changes compared to present conditions. In addition, flooding sensitivity also measured by costs, miles of roads flooded and other metrics. Institutional adaptive capacity was only considered in this preliminary analysis stage via Social Network Analysis (Section 4.1).

We used four numerical simulation models and two conceptual models to understand the interactions as shown in Figure 3. As appropriate, the models used the output of one as input conditions to another and all models were also driven by climate and land use conditions. A partial description of the public engagement process that accompanied the model application is in Aytur et al (2015) where the aims were to develop a collaborative planning process with many types of stakeholders, improve understanding of the local social vulnerabilities in the area and the social costs of not taking action, and build public and political support for the project's desired outcomes. The findings of the vulnerability assessment are summarized here to provide context for the application of IUWM to adaptation; full details are available in Kirshen et al (2015).

All planning was done within the context of the below set of Guiding Principles.

1. **Recognizes that preparing for weather events and protecting our quality of life is the responsibility of all community members.** We all have a stake in preparing our community for weather events and protecting our quality of life. There is a role that each of us can play; we are all stakeholders

2. **Places the highest value on community involvement.** We will ensure an equitable voice for community members in the discussion and the decision-making process surrounding the creation of a climate adaptation plan for Exeter. Mutual trust, respect, equity, and empowerment are the core tenets of this process.

3. **Honors what works within the community and values local assets**. We pledge to look first to the community for solutions, and to focus on including community input in the development of recommendations for the climate adaptation plan.

4. **Employs a transparent process based on community values.** We will implement the process by being inclusive and representative of the community of Exeter, maintaining an open process based on understanding each others' values, and promoting community ownership of these recommendations.

5. **Believes that communities can prepare for weather events and become stronger and more resilient.** Fortunately, similar strategies can be used to simultaneously protect quality of life, public health, and our social, environmental, and economic assets. Exeter can be a front-runner in working together to protect what we care about most.

6. **Acknowledges the underlying contributing factors of weather events.** We understand that key factors – such as storm water management, nonpoint source pollution, land use, habitat change and restoration – must be openly discussed in order to begin preparing our community for the future.

7. **Commits to being positive, proactive and data driven.** We pledge to define priorities based on community strengths and opportunities for improvement, based on the best available science, and align community resources to maximize efforts and promote partnerships.

8. **Acknowledges that preparing for weather events and building community readiness is a long-term effort.** We discuss short-term challenges, but not lose sight of the importance of a long-term vision as we plan for our future.

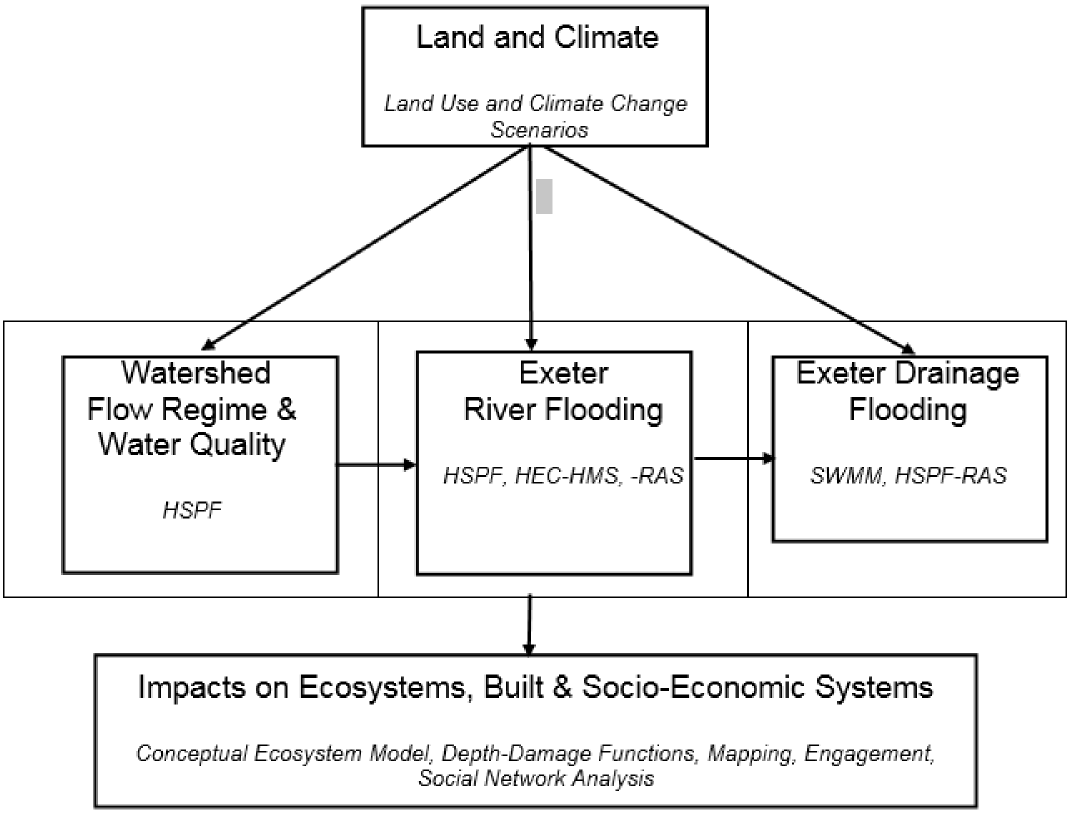

Figure 3. Water Resources Analysis Tools, Exeter NH

3.1 Land Use Change

The first step in the analysis was to estimate the future land use in the entire watershed draining into the Exeter/Squamscott River. The analysis is described in detail in Kirshen et al (2015). Past trends in residential, and industrial/commercial land use since 1964 were analyzed from aerial imagery and then projected forward to 2030, 2050, and 2070. Road expansion was correlated to these land use trends. The changes in land uses and road extent were then allocated to subareas based upon undeveloped land zoned for development and the attractiveness of that land based upon development potential factors such as slope, distance to roads, and proximity to developed land. Generally, by 2070, in the upper watershed total developed land is projected to increase by 3 to 4 times the present developed land and in the lower watershed, where Exeter is located, developed land area is expected to double. Most of the area, however, remains forested (approximately 60 % now, 50 % in 2070.). We did not directly conduct sensitivity analysis on the results of the land use change. We did, however, investigate how the use of more green stormwater and runoff infrastructure (Low Impact Development, LID) in the basin as it developed over time compared to conventional development patterns would impact peak flood flows; this is discussed in Section 4.2.

3.2 Water Quality and Hydrologic Analysis

The HSPF hydrologic and water quality model (http://www2.epa.gov/exposure-assessment-models/hspf, accessed October 19, 2016) was first calibrated and verified for present conditions, and then driven by the present climate and climate change scenarios for 2040 and 2070 to estimate changes in the annual flow regime and annual water quality loads given the climate and land use changes. For the respective calibration and verification periods of 1996 to 2006 and 2006 to 2014, hourly precipitation (P) and temperature (T) values were used from Epping meteorological station. PET was calculated by the Hamon method (described in http://naldc.nal.usda.gov/download/7287/PDF). The hourly values of cloud cover, dewpoint temperature, solar radiation, and wind were taken from Durham NH meteorological station. During calibration, model parameters were adjusted to achieve the best fit. During verification, model parameters were not adjusted. The results for the verification at Haigh Road USGS gauge on the Exeter River which is the gage closest to Exeter in the basin is in Figure 4. As can be seen, the model strongly captures high and low daily flows.

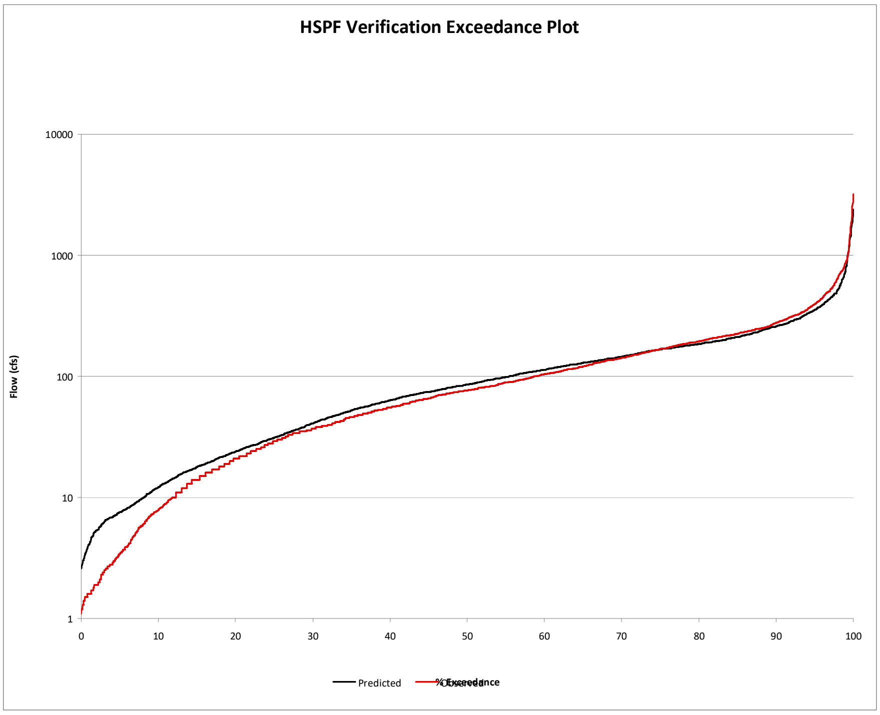

Figure 4. HSPF Flow Verification at Haigh Road

The simulations were done on an hourly time step for 30 years with historic data to represent the present and then downscaled values to represent conditions in 2040, and 2070. The downscaled values were from the outputs of 8 General Circulation Models (GCM) for the RCP 4.5 and RCP 8.5 emission scenarios. Six climate change scenarios from the downscaled dataset that represented the broadest ranges of P and T were chosen to simulate climate change impacts. The 2040 period was represented by values from 2015 to 2055, the 2070 period with values from 2055 to 2085.

It was found in 2040 that, depending upon the GCM and scenario, there is not much difference in mean annual flows compared to the present. The peak flow, however, may occur in winter in the future instead of the present spring period. Low summer weekly average flows may decrease or stay approximately the same as present for all the scenarios. It was found that the 7 day-average low flow that is less than or equal to all 7 day average flows 10 percent of the time (7Q10), which is important to maintain water quality, could significantly decrease or stay approximately the same in 2040. The variability of the flows throughout the year may increase or decrease compared to present. Similar results were found for the flow regime in 2070 except the differences were larger. The water quality findings are discussed in the Section 3.6, Ecosystems.

3.3 River Flooding

Using a design storm approach instead of the continuous simulation approach for water quality and hydrologic modeling, the event based hydrologic model HEC-HMS (http://www.hec.usace.army.mil/software/hec-hms/, accessed October 19, 2016) was used to estimate runoff upstream and downstream of the former dam under various climate change and land use conditions. The hydraulic/open-channel river model HEC-RAS (http://www.hec.usace.army.mil/software/hec-ras/, accessed October 19, 2016) was then used to estimate the areas and depths of river flooding given these inflows and downstream estuary elevations. Calibration and verification of the models are described in Walker (2014) and some of its applications are in Mather (2014). Estimates of the present 100 year, 25 year, and 10 year, 24 hour precipitation for this area were taken from the Northeast Regional Climate Center using nearby Epping NH. Scenarios of future fractional changes in the magnitude of the events were taken from estimates developed by Boston Water and Sewer Commission (2015) for Boston MA, a city with a comparable climate approximately 100 kilometers south of Exeter, for similar emission scenarios. For example, BWSC showed an increase of 27 percent in the 10 year storm from the present to 2100. One precipitation and SLR scenario was used for 2040 conditions because all scenarios were relatively similar, but high and low climate change and SLR scenarios were used for 2070 conditions. Scenarios were developed for when river flooding occurred at high tide (Mean Higher High Water, MHHW) and also when flooding occurred during the 100 year storm surge.

24 combinations of the scenario conditions for climate change, Great Dam-in and Great Dam-out, and estuary tide and flood conditions were simulated. Dam-in conditions were only run for the present climate so stakeholders could compare conditions without the dam with conditions they were familiar with. Dam-out conditions, the present situation in Exeter, were run for all time

periods. Here we focus upon the results for the present case of the 100 year river flood and storm surge with dam-out and the future scenario in 2070 of high climate change, 100 year river flood and storm surge, and dam-out. Some of the flood heights are severe. For example, in a section of Franklin Street upstream of High Street in the urbanized part of Exeter, present flood depths are 0.9 to 1.8 meters (m). Under the 2070 high climate change scenario, the depth ranges from 1.8 to 2.7 m. Similar impacts also extend upstream and downstream. For example in a manufactured home park upstream, the same ranges in flood depths were found. Downstream along Swasey Parkway, a popular and scenic roadway, flood depths vary from 0 to 0.9 m under the present climate with a 100 Year surge flooding parts of the Parkway. Under 2070 climate conditions, flood depths increase to 0.9 to 1.8 m. In most locations, the major differences between the scenarios is greater flood depths, not a larger floodplain.

Estimated damages to buildings and contents were derived using depth-damage curves from US Army Corps of Engineers (2003) and appraised values of buildings for various scenarios possible with 100 Year flooding and storm surge conditions and are shown in Figure 5.

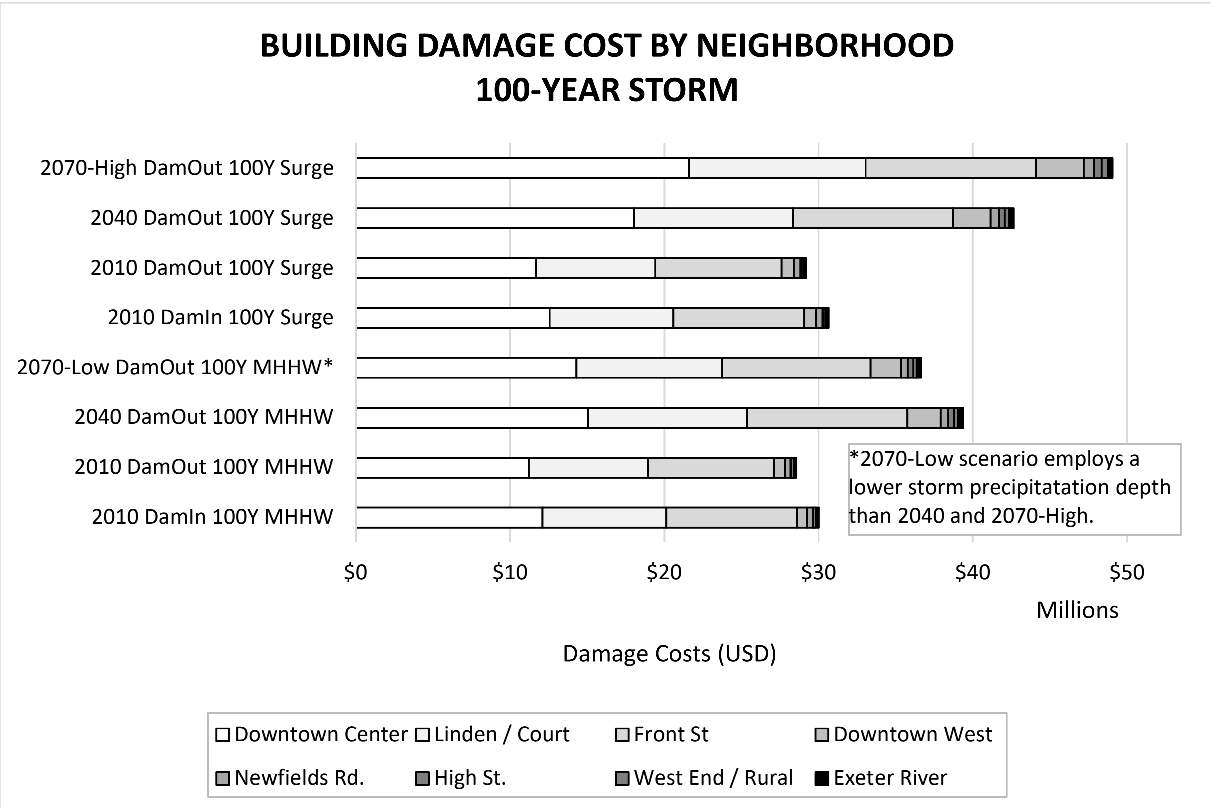

Figure 5. Estimated Damages to Buildings and Contents under Various Scenarios of 100 Year River Flooding. 2070-High Refers to Relatively Large Increase in Precipitation in 2070, 2070-Low Refers to Relatively Low Increase in Precipitation 2070. DamIn is Great Dam (now removed) in place, DamOut is it removed. MHHW is Squamscott Downstream Boundary Condition, Surge is Downstream Boundary Condition being at 100Year Elevation. See Text for Description and Relevance of Neighborhoods.

As expected most of the damage is in the more urbanized parts of Exeter. The influence of the Squamscott River having 100 Year surge conditions compared to being at MHHW is not significant through 2040. In 2070, however, depending upon the changes in precipitation, SLR, and whether the precipitation storm strikes at MHHW or during a storm surge, damages with Great Dam removed (as is now the case) can vary from approximately $35 million to $50 million, increases of 16 % to 66 % compared to the present damages of approximately $30 million with the dam in place.

Included in these buildings are important public and private assets such as the senior center, an electrical substation, the town library, and the local YMCA (a non-profit community center) that are flooded under present 100 flood and surge conditions with the dam out. Under the high scenario in 2070, the Public Safety/Fire/Policy building, the Recreational Building, and some Senior Housing are added to the flood list.

An analysis of length and number of flooded roads in Exeter found that the values do not significantly vary between the present 100 year river flood with the dam removed at MHHW to the 100 year flood in 2070 under the high precipitation and SLR scenarios and the 100 year storm surge – always approximately 11 kilometers total length and 35 roads. This is because many of the roads are in river valleys. The depth of flooding, however, does vary; in 2010, approximately 50 % of the roads are flooded to greater than 1.5 meters, in the 2070 scenario, most roads are flooded to greater than 1.5 meters. Similarly, it was found that the number of water supply and sewer structures such as pump stations and wells and land areas of recreational facilities did not vary significantly with the year or climate scenario for 100 year conditions.

3.4 Drainage

The impacts of climate change on the stormwater drainage in the portions of Exeter with formal drainage networks was modeled with the SWMM model (http://www2.epa.gov/water-research/storm-water-management-model-swmm, accessed October 19, 2016). The 25 year, 24 hour storm rainfall was used; the design frequency presently used in Exeter. The same climate and SLR scenarios as used in the flood analysis were used here. The flows in the receiving waters were taken from the HEC-HMS river flood analysis for the same storm conditions and their backwater effects were modeled in SWMM as were the downstream tidal conditions in the Squamscott River. To be conservative, it was assumed the maximum elevations in the receiving waters (i.e., the tailwater conditions) persisted during the entire 24 hour flood event.

The drainage system is presently underperforming in many areas. When backwater effects in the Exeter, Squamscott and Little Rivers are included as well as climate change and SLR, few additional surcharging conduits or flooded manholes are added; however the number of hours of surcharging and flooding do increase as the system takes longer to drain to receiving waters. The largest changes are near the outfalls on the Squamscott and Exeter Rivers. Other parts of the drainage system show similar impacts, particularly in the lower elevation sections.

Buildout has little effect on the stormwater runoff volume being generated in these sewersheds. The areas drained by these storm sewer systems are already highly developed and highly impervious, and do not contain much developable land. As a result, new development within these catchments has little effect on the stormwater runoff behavior compared to the present.

3.5 Wetlands

Although tidal marshes are highly valued today, past decisions in Exeter have filled marshes to create the wastewater treatment plant, Powderhouse Pond and Swasey Parkway. All of these marsh impacts have been made to provide another service to the town, replacing marsh values with sewage and stormwater treatment areas and a well-used recreational area. Fortunately, over 0.40 square kilometers of tidal marsh remain to provide a variety of benefits to Exeter as given in Table 1.

Categories	Values of Tidal Marshes	Values of Non-Tidal Marshes
Habitat and Biodiversity	Plant growth to support food webs	Plant growth to support food webs
	Secondary production	Secondary production
	Plant structure to provide habitat	Plant structure to provide habitat
	Support of biodiversity	Support of biodiversity
Coastal Protection	Reduce wave height and damage	
	Reduce severity of flooding	Reduce severity of flooding
	Protection from erosion	
Water Quality	Removal of sediments and excess nutrients	Modulate sediment flux, cycle nutrients
Quality of Life	Aesthetic, Recreational & Educational values	Aesthetic, Recreational & Educational values
Climate Change Mitigation	Builds in elevation with sea level rise	
	Long term carbon storage	Stores C, but releases CH_4

Table 1. Tidal Marsh Services in Exeter

The hydraulic floodplain analysis shows that dam removal will result in slightly lower water levels within the river and floodplain upstream of the Great Dam. Lower water levels will open up possible habitat for invasive plants like purple loosestrife and common reed, but new invaders from the south may arrive with increasing temperatures and exotic invaders are likely to adapt to changing climate (Richards et al. 2006) unless efforts are taken to control new infestations of invasive plants and animals. Removing the dam will eliminate a reduced-flow entrainment area that will result in more direct transport of upstream dissolved and particle-associated pollutants downstream directly to the tidal river. In addition, the greater pulsing of flows may result in greater productivity for wildlife above the dam once it is removed because the pulsing has such benefits as helping to cycle nutrients (and denitrify biologically active nitrogen), and expanding critical habitat for a variety of mobile animals (fish, birds, reptiles) (Tockner et al, 2000).

Working in New Haven, Connecticut, Bjerklie et. al. (2012) found large portions of the City would experience increased water tables similar to a 0.9 meter increase in sea level, especially if modeled with an increase in recharge of 12% over current rates. Ground water levels across most of Exeter are also likely to rise with an increase in sea level. Even with a modest increase of 0.6 meters of sea level rise by 2070, groundwater levels across the lower portions of town (presently 6 meters above mean high water) are likely to experience significantly higher water tables (0.31-0.6 meters). Besides flooding more basements, the higher water levels will likely lead to wetland expansion, especially where slopes are slight. For example, if slopes surrounding an existing wetland are 1%, a 30 cm increase in water table will expand the wetland edge 30 meters into surrounding uplands.

Since storms are short-lived and the tidal Squamscott River is protected from wind-driven waves, storm surges are much more of a human safety risk than a threat to tidal wetlands. Also, the increased flooding from increased sea level would not pose a problem for marsh survival if marshes can build in elevation at a rate similar to sea level rise (Cahoon and Guntenspergen, 2010). Our scenarios of SLR result in rapid increases, and these rates are likely to exceed the ability of the marshes to build (Kirwan et al, 2010), resulting in the erosion and drowning of low marshes and the conversion of high marsh to low marsh.

As sea levels rise, another process will replace some of the wetlands through a conversion of low-lying uplands into tidal wetlands – a process termed marsh migration. Of course if the natural land slopes steeply or there are artificial barriers, the marshes cannot migrate. Rising temperatures, found for all our emission scenarios, may also interfere with marsh building processes and reduce the ability of the marsh to store organic matter (Kirwan and Blum, 2011).

Unfortunately, past decisions to fill sections of marsh have reduced marsh area and resulted in steep shorelines. Human made barriers that prevent marsh migration landward under sea level rise is known as coastal squeeze as the marsh is squeezed out of existence (Torio and Chmura, 2013). Tidal marshes in Exeter are vulnerable to coastal squeeze along the barriers of Swasey Parkway, a section of Water Street running north just past the parkway, along the wastewater treatment lagoons, and the berm surrounding Powderhouse Pond.

3.6 Ecosystems

Qualitative analysis of ecosystem changes and impacts is based on existing and HSPF model generated data, conceptual ecosystem models and published literature. With all climate change scenarios pointing towards steady and significant increases in both minimum and maximum annual air temperatures and most of them for annual precipitation, these factors can be assessed in terms of potential ecosystem effects. Since the HSPF model results from this study for water quality parameters show few consistent increases in total nitrogen and phosphorus loading, we assume these factors will not be significantly different in the future. HSPF scenario modeling does indicate a consistent increase in total suspended solids (TSS) compared to current conditions during spring and late summer (July-September).

The ongoing and projected increased water temperatures and accompanying increased ecosystem metabolism will decrease DO in the rivers and cause stress to fish and other aerobic organisms, with the potential for species shifts where this becomes a chronic condition. Increased levels of CO_2 and acidification will also result from the increased ecosystem metabolism via increased organic matter decomposition, which will also negatively impact ecosystem carbon storage. Chronic loading of toxic contaminants loading will have continued negative impacts on fish and other wildlife (e.g., water fowl) as many tend to bioaccumulate and thus increase the duration of exposure and toxic effects on animals.

Increased TSS loading will interfere with spawning habitat for fish and downstream shellfish, and impact submerged macrophytes via reduced light penetration. Suspended solids are also vectors for nutrients, toxic chemicals and microbial pathogens, so increases in TSS may also underlie future increases in overall ecosystem toxicity and diseases. If there is increased pollution from human sewage sources, there is the potential for increased human disease from exposure to contaminated surface waters.

From a human health perspective, water-borne illness and disease (exposure via recreational activities, drinking water contamination, and fish consumption) incidence is on the rise in the Northeast due to increasing levels of infectious bacteria and toxic chemicals caused by pollution and climate change factors affecting the region's surface waters. For example, vibriosis incidence in the Northeast has risen over the past decade and even more sharply since 2010 (Jones 2011; Newton et al, 2014; Urquhardt et al. 2016). In addition, historical sources of toxic chemicals are still detectable in the Squamscott River, where sediment levels of PAHs are elevated relative to other sites in the Great Bay estuary (http://www.epa.gov/emap/nca/html/regions/ne0006/index.html, accessed November 11, 2016) due to seepage from a historical gasification coal tar site next to the river. At a series of 6 sites tested as part of the dam removal study, some potentially harmful chemical contaminants were detected in sediments but not at levels that would raise serious issues when sediments were mobilized during the dam removal (VHB 2013). Thus, the current water and sediment quality information suggest that there are concerns about microbial contamination from fecal pollution sources, vector-borne diseases that may continue to increase in the area, and the possible emergence of tropical diseases as climate changes. In addition, increased water temperature and extended time periods of warmer weather have a high probability of causing emergence of more human pathogens and biotoxin production that will increase the incidence of human illness caused by water contact/wound infections, fish/shellfish consumption and zoonotic infections.

3.7 Social Vulnerability

According to a framework developed by Saldana et al. (2012), understanding social vulnerability is an important first step towards building community capacity for the implementation of initiatives such as IUWM. Although our study in Exeter slightly pre-dated the statewide dissemination of BRACE (see Section 2), we followed a very similar process based on the tenets of adaptive governance which provided a locally-scaled prototype for completing this first step.). Overall, the social vulnerability assessment was conducted by triangulating several methods including Social Network Analysis (quantitative, Section 4.1), social vulnerability indicators (quantitative, Section 2), and surveys, focus groups, and interviews with stakeholders (qualitative, this section and Section 4.1). This process met the standards for best practices for social vulnerability assessment and Health Impact Assessment (HIA, Bhatia, 2011)

Conversations with the community were held either through large public meetings or focused meetings with communities of either a particular location or interest group. Workshops were held with the staff of many the town agencies, particularly public works, planning, and emergency services. Several times each year we met with the town's Board of Selectmen and Planning Board. We also had several experiential field activities such as walking floodplains. A Citizen's Working Group was established to provide continuous feedback to the process as it was carried out. Figure 6 is an example of one output of participatory mapping exercise used in a public meeting and with the CWG which let the study team connect perceived vulnerabilities to scientific data/model outputs. The white to red scale on the lefthand side is the number of groups expressing an area of concern; the more red an area appears, the more groups listed it as a concern. Examples include: deteriorating water quality, increase in pavement and fertilizer use, need for adequate disposal of sewage in the event of a flood or major storm, location of the new wastewater treatment plant, river pollution, including sources from other towns and areas, evacuation in the event of a major flood/storm, Philips Exeter Academy (PEA) students as a special challenge, concerns for the elderly and/or disabled, possibility of an increase in invasive species with increased water temperature, flood damage to the recreationally and aesthetically important Swazey Parkway bordering the Squamscott River, impacts on several manufactured housing communities (mobile home parks) that are located in present and future floodplains, and impact of long-term loss of electricity from a storm or other event on the elderly or ill who rely on oxygen.

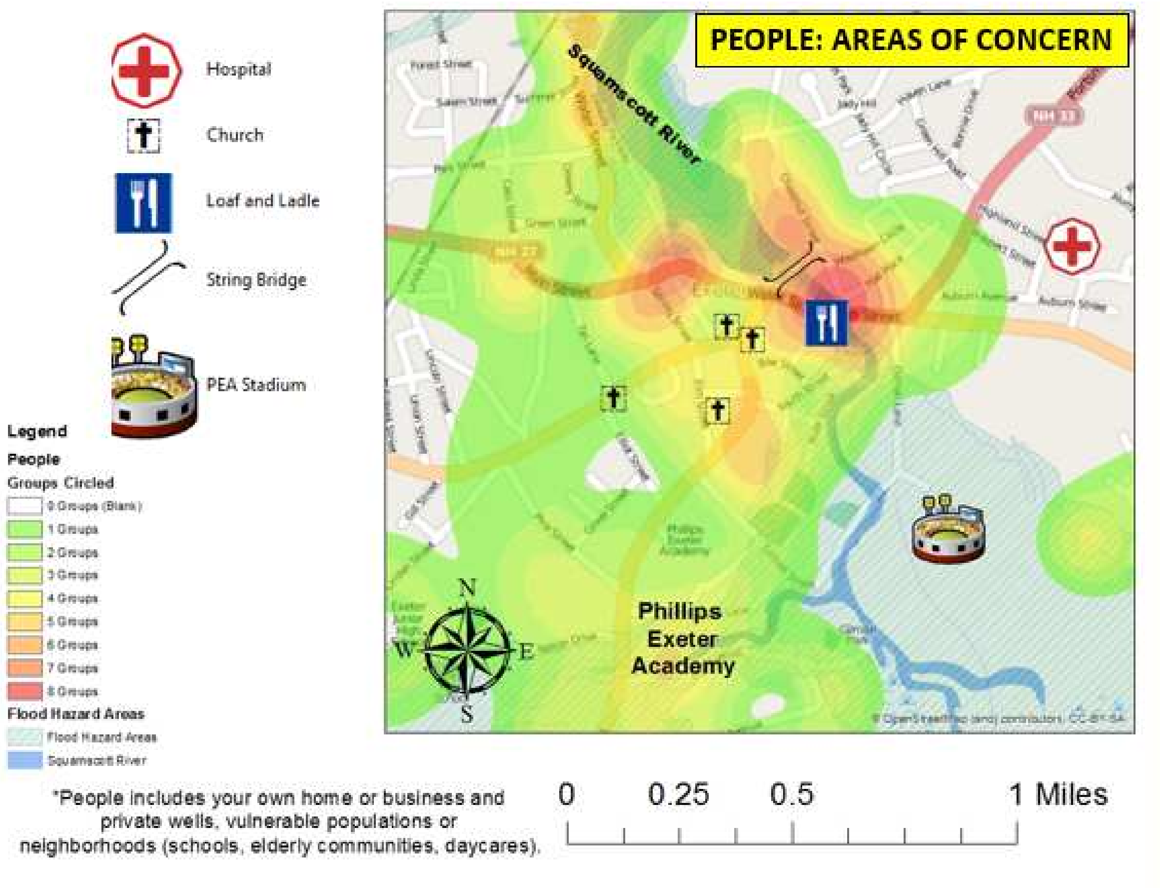

Figure 6. Output of participatory mapping exercise. The white to red scale on the lefthand side is the number of groups expressing an area of concern; the more red an area appears, the more groups listed it as a concern.

4. Adaptation to Water Management Stresses in Exeter

There exist many possible adaptation actions in Exeter. Here we review them and then focus upon their interactions in the context of IUWM.

4.1 Social and Institutional Readiness

Emerging research suggests that social networks are important contributors to the adaptive capacity of complex systems (Valente, 2015). Social network analysis (SNA) explores relationships among people and organizations, enabling researchers to identify the flows of communication and resources between them. As part of the community engagement process, we explored the social networks of key stakeholders involved in water management in Exeter. Specifically, we used SNA to explore stakeholders' values, interests, and relationships in order to assess their readiness for IUWM and to examine the social capital that could be leveraged to build capacity for IUWM.

Stakeholders were surveyed using the PARTNER social network survey tool (http://www.partnertool.net/, accessed July 10, 2016) to better understand each stakeholder's social ties and their perceptions of collaborative potential (e.g., the strength of relationships between members and the types of resources exchanged) (Varda et al 2012, Sherchan et al, 2013).

Data were used to yield quantitative network indicators that include measures of density, degree centralization, and trust. Density is an indicator of overall cohesiveness of the network. A density score of 100% would mean that every was stakeholder connected to every other stakeholder. This score demonstrates how many network ties are present in the network in relation to the total number of possible ties. The density score for Exeter was 37.5%, which indicates relatively low density. Increasing the number of 'ties' or connections was explicitly cited as a goal by stakeholders who participated in the community engagement process. Evaluation data from stakeholder surveys suggests that this goal was achieved. Based on a five-point Likert scale of 1 (strongly disagree) to 5 (strongly agree), the majority of respondents reported that new community-academic partnerships were formed (mean=4.63 (sd 0.52) during our planning process. Degree centralization is another network indicator that refers to how well-connected the members of the network are. Lower centralization scores indicate that fewer network members hold central ('hub') positions that are associated with information sharing and power. Higher network centralization indicates greater degrees of interconnectedness, which may be associated with greater collective commitment to the networks goals. The degree centralization score in Exeter was 53.8, indicating moderate levels of centralization. However, certain members of the network, including town staff and some of the academic partners, were highly connected at the individual level and served as central nodes or 'hubs' through which information flowed. Furthermore, because many of these 'hub' partners held knowledge about specific aspects of water management (such as public health or drainage), these connections could be leveraged to implement IUWM.

Trust is another important social network indicator. To achieve a 100% trust score, each member of the network would have to report fully trusting every other member. The trust score for Exeter's network was 79%, indicating high levels of trust overall. Another indicator, "Openness to Discussion", measures the extent to which stakeholders are willing to engage in frank, open, and civil discussion. The mean in Exeter was 3.47 out of 4, indicating a high level of openness to dialogue, which may be important for IUWM. Collectively, these results enabled the research team to identify important contextual characteristics that could affect the implementation of IUWM in Exeter, and to utilize network attributes such as density, degree centrality, and trust to provide a foundation for climate change adaptation planning based on IUWM principles.

A series of stakeholder meetings were held which also enabled us to understand the social context in considerably greater depth (Aytur et al, 2015). For example, participants in community meetings (n=40) indicated that an integrated perspective of water quality was highly valued. The majority of participants reported that providing protection against river and street flooding was "extremely important" (44%) or "very important" (46%) to them. Providing clean water for drinking, recreation, and ecosystems was rated as "extremely important" (97%) or "very important" (3%) to them. One stakeholder's comments underscored the importance of considering risks to people, natural resources, and infrastructure in an integrated manner: "There is a serious risk for housing flooding in (some areas). The Exeter River and wildlife on it are in trouble. Storm drains, culverts, piping, road runoff are problems to be addressed."

Similarly, results from a baseline meeting (2012) with stakeholders representing 12 different sectors indicated broad-based support for a holistic perspective of water management and climate adaptation. On a five-point Likert scale (1 (strongly disagree) to 5 (strongly agree)), most stakeholders rated messages about co-benefits as very effective ((mean=4.58 (sd 0.51)). They also indicated that the engagement process enabled them to make new connections between climate variability, water quality, land use, biodiversity, health, and economic impacts ((mean= 4.67 (sd 0.49)).Participants also reported that the elements they felt would contribute most significantly to achieving climate adaptation goals included enhancing social networks through mechanisms such as connecting scientists to citizens and community groups, bringing together diverse stakeholders, and meeting regularly with residents. These activities were cited as important by over 90% of participants.

Taken together, our results confirmed the importance of social networks as a foundation for building capacity for IUWM within a community. Other researchers have drawn similar conclusions (e.g.,Crossin and Naylor (2013), Navarro-Navarro et al, 2017).

4.2 Flood Management

The Community Rating System (CRS) of the US National Flood Insurance Program (NFIP) provides vulnerability reduction incentives by reducing the insurance rates of property owners in the community when different structural and non-structural measures are implemented. Exeter is already enrolled in the NFIP and therefore is eligible to participate in the CRS. There exist several approaches to flood management. These could include flood proofing or elevating flood prone structures or removing them from floodplains, using permanent or temporary flood walls or levees, diverting flood flows around critical locations, elevating the High Street bridge, adding flood control reservoirs in the watershed, expanding the floodplain/natural valley storage, preserving and expanding wetlands, evacuation and emergency management services, and decreasing the impacts of development on peak flows through Low Impact Development (LID). LID is further described below since it is particularly relevant for IUWM.

LID reduces rainfall runoff through non-structural methods, such as the preservation of natural/undisturbed land, increasing local infiltration, and disconnection of impervious surfaces from direct runoff (US EPA n.d.). The impacts of large scale LID were examined for 2, 10, 25 year events floods as well as the 100 year flood for Exeter by Mather (2014). Three time periods were analyzed: 2010 (current); 2040; and 2070, where 2070 refers to the CAPE 2070 high scenario. Design rainfall was increased each time period as was done in the flood analysis. Additionally, each time period was assigned an incremental (phased) LID implementation level to account for potential LID conversion rates, where 2010 included a 25% conversion of all developed lands to LID, 2040 converted 66% LID, and 2070 attained 100% LID implementation of all developed lands. In addition, it was assumed that there would be the conversion of existing and new paved surfaces to porous pavements. All analyses were done assuming the removal of Great Dam.

To model the impacts of LID, HEC-HMS curve numbers (CN), which are used for estimating catchment losses and runoff as a function of land use, soil type, and other physical system parameters, were adjusted using procedures from Scholz (2011).

It was found that the larger relative decreases in peak flood flows occur for the higher frequency events (e.g., the 2 year storm has the largest flow decrease) and, as expected, the change in the 100 Year flows are relatively less than the others. The relatively small changes in discharges due to LID in the entire watershed for the larger storms are also not unexpected as presently 60 % of the watershed is forested and with the development scenario in 2070, the forested amount decreases only to approximately 50 %. If LID is implemented throughout the watershed instead of just in Exeter, then larger decreases are also found. Additional analysis found that the more urbanized a sub-basin is, the greater the effectiveness of LID.

The resulting surface water elevations at several stations were also calculated for the 2 and 100 year floods. As expected, the largest change in water surface elevation resulted from a 2 year storm in 2070 when LID had been applied throughout the entire watershed, 19 centimeters at a relatively narrow portion of the Exeter River approximately 6.5 kilometers upstream of High Street. Just upstream of High Street in the downtown section of Exeter, the elevation change under this condition was 11 centimeters. If LID was only implemented in Exeter, then the corresponding elevation changes were 0.3 centimeters and 2.1 centimeters. All the elevation changes for the 100 Y storm under all LID scenarios were less than 15 centimeters with a change of 13 centimeters just upstream of High Street. The elevation changes from LID implementation throughout the basin as described here may result in the reduction in the flood damages in 2 and 100 year storm scenarios of $2 million each. Thus, coupled with the other impacts of flooding on infrastructure and the possible water quality benefits described subsequently, aggressive LID implementation may be worth considering in more detail.

Using event mean concentrations and the Simple Method from the New Hampshire Stormwater Management Manual (http://des.nh.gov/organization/divisions/water/stormwater/manual.htm, accessed December 15, 2016), the relative portion of the pollution loads coming the present land uses in all of the basin upstream of High Street were compared to the portion originating from the land area in the Town of Exeter above Great Dam. It was found that approximately 10 percent of the loads of TSS, TP, and TN originated in Exeter.

LID approaches such as bioretention basins, infiltration basins, and porous pavement can remove from 50 to 90 percent of TSS, 45 to 70 percent of TP, and 35 to 85 percent of TN depending upon the method (New Hampshire Stormwater Manual, http://des.nh.gov/organization/divisions/water/stormwater/manual.htm, accessed December 15, 2016.) Similar values were found in US EPA (1999). Here we assumed a planning level value of 50 percent for all pollutants from developed areas. LIDs were not applied to undeveloped areas or landscapes such as parks. It was found that under present climate conditions, aggressive LID implementation throughout the entire watershed can remove approximately 20 % of the loads from the area of the watershed just in Exeter above High Street, above Exeter itself, and throughout the entire watershed above the former Great Dam.

4.3 Stormwater

There are some actions that could be taken to attempt to manage the impacts of present and future climates. Flap gates could be placed on outfalls to minimize inflows into the drainage network during high flow events. While very expensive, some conduits could be increased in size. Drainage could be delayed or lessened from part of the drainage area to the pipe network by installing surface or sub-surface storage. Regulations could be implemented to require new development to not increase runoff compared to present undeveloped conditions. Best Management Practices such as public education, good construction practices, and closing illicit connections (https://www.epa.gov/npdes/national-menu-best-management-practices-bmps-stormwater#ill, accessed December 20, 2016) are also important management strategies.

Since LID can manage 2.5 centimeters to 5 centimeters of precipitation in the best case, it is possible that extensive LID in Exeter could result in no significant changes in drainage problems compared to the present as the 25 year design rainfall increases from 15 cm inches to possibly as much as 18 cm by 2070. However, if other actions were taken to manage the drainage flooding now, it is possible that extensive LID could maintain the effectiveness of those changes as the climate changes. Another attractive aspect of LID is that it would significantly improve the water quality of the stormwater.

4.4 Water Supply and Wastewater Treatment

The wastewater treatment system downstream of the downtown is being upgraded in a new site at higher elevation than the present site so it will be climate change resilient. The components of the water supply and wastewater systems that are impacted by present and increased river flooding can be locally protected by flood-proofing or elevation (http://des.nh.gov/organization/commissioner/pip/newsletters/dwgb/documents/2014-spring-supply-lines.pdf, accessed December 20, 2016). The increased use of groundwater in Exeter may be used to respond to the threat of poorer surface quality water and lower summer flows under climate change. Weston and Sampson (2010) recommended that if Exeter used the principles of Integrated Water Supply management by optimizing its use of surface and groundwater coupled with conservation when needed, then it can manage future water supply demands. These actions can also assist Exeter in managing water supply if system yields become less dependable under climate change. Some nearby towns are also considering artificial recharge through surface recharge basins (A Walker, personal communication, September 14, 2016). Thus capture and recharge of flood peak flows (known as flood skimming) and/or recharge of stormwater may also be promising for Exeter. In addition, individual actions such as the use of rain barrels will also help Exeter manage future water supply problems.

4.5 Wetlands and Ecosystem Resources

Healthy ecosystems and especially wetlands provide a variety of ecosystem services (Table 1) that support recreational activities (including hunting and fishing) and overall quality of life in Exeter. Recently, the work of several town departments, especially the Conservation Commission, was important in reestablishing an adequate tidal connection to Norris Brook and restoring freshwater wetlands along the section of the brook that runs through Swasey Parkway to the Squamscott River. The result is that the seawall along Swasey Parkway (where the tidal wetlands are subject to coastal squeeze) is interrupted at Norris Brook. This section of the Brook receives daily tidal flow and the freshwater floodplains around it are not subject to coastal squeeze – they can convert to tidal marsh as sea level rises. Norris Brook restoration is one example of steps that can be taken now to improve wetland health and provide space for wetlands to adapt to future climate change. In addition, as noted in the flood management section, additional or restored wetlands could also help relieve flooding and improve water quality. Possible locations are first and second order streams draining to the Little and Exeter Rivers. Invasive plants are likely to adapt to changing climate; thus plan to identify and control invasive plants along the Exeter River should be developed.

Flood and stormwater flow management, reduced runoff and pollution from impervious surfaces, use of groundwater instead of surface water for drinking water supplies, and management of wetland and ecosystem resources to enhance the quality and to expand existing habitats will all serve to enhance water quality and improve habitats for aquatic species, including anadromous fish that are currently threatened and in historical declines. Continued reductions in nutrient, toxic and pathogenic contamination via wastewater and stormwater treatment efforts will further improve conditions and aid in fish reproduction and migration. Further improvement in riparian ecosystem functions with fish habitat in mind can help reduce the expected negative impacts of warming and acidification of surface waters that pose significant threats to fish and other aquatic species. In addition, enhanced implementation and enforcement of fishery restrictions will serve to further lower present and future ecosystem stresses.

5. Integrated Urban Water Management

While many of the adaptation actions described above can be implemented independently and have minimal consequences for other sectors, some of the actions do interact with other sectors. By examining these interactions in a holistic manner, it is possible to determine how IUWM might be implemented in Exeter to achieve sound water management under present and future climates in a cost-effective, ecologically sound manner.

Table 2 shows the management strategies (columns) and their relevance to manage present and future water stresses (rows) in the Town of Exeter. They are rated as Low (L), Medium (M), High (H), and Not Applicable (NA) based on their possible impacts on managing the stresses as determined by the CAPE study team. Most can be flexibly or incrementally implemented as climate changes. Some, unfortunately, may increase the threats. We also include an estimate of their relative costs based upon judgement of the CAPE study team. It is interesting to note that in many cases the more traditional approaches to water management such as flood proofing, flood levees, detention basins, expanding surface and ground water supplies, and conventional wastewater treatment either have limited impacts on mitigating multiple stresses or actually exacerbate them. By their very nature, more holistic approaches such as increasing natural valley storage, LID, and reducing social vulnerability have more potential for mitigating multiple stresses.

Management/ Stress	Water Quality	Flow Regime	River Floods	Storm-water	Wetlands and Ecosystems	Water Supply	Waste-water System	Relative Imple-mentation Costs
Flooding								
Accommodation (e.g., by elevation of buildings and equipment, flood proofing, diverting, flood skimming, elevating High Street Bridge, flood insurance)	NA	NA	M	L	NA	NA	NA	$$/$$$
Protection (e,g., by levees, floodwall, reservoirs)	NA	Worsen	M or Worsen in some places	Worsen	Worsen	May Worsen	NA	$$$
Expanding the floodplain/natural valley storage, preserve/expand wetlands	M	M	M	M	H	M	NA	$$$
Retreat	L	NA	H	L-M	L-M	NA	NA	$$
LID throughout entire basin	M	L	L	L	L-M	L	NA	$/$$$
Stormwater	**Water Quality**	**Flow Regime**	**River Floods**	**Storm-water**	**Wetlands and Ecosystems**	**Water Supply**	**Waste-water System**	**Relative Imple-mentation Costs**
Standard Best Management Practices (e,g., Street Cleaning, Public Education)	L-M	NA	NA	L-M	L-M	NA	NA	$
Detention/Reten-tion Basins	L	NA	NA	M	L	L	NA	$$
Local LID	L	NA	NA	L	L	L	NA	$/$$
Expand Conveyance Capacity of Stormwater System	May Worsen	NA	NA	M	May Worsen	May Worsen	NA	$$
Install flap gates	NA	NA	NA	M	NA	NA	NA	$

on outfalls								
Water Supply	**Water Quality**	**Flow Regime**	**River Floods**	**Storm-water**	**Wetlands and Ecosystems**	**Water Supply**	**Waste-water System**	**Relative Imple-mentation Costs**
Expanding Surface Water	May worsen	May worsen	NA	NA	May Worsen	H	NA	$$/$$$
Expanding Groundwater	May Worsen	May worsen	NA	NA	May worsen	H	NA	$$
Conservation	L	NA	NA	NA	L	M	M	$
Flood Skimming/ Stormwater Recharge	NA	L	L	L	L	M	NA	$$
Wastewater Management	**Water Quality**	**Flow Regime**	**River Floods**	**Storm-water**	**Wetlands and Ecosystems**	**Water Supply**	**Waste-water System**	**Relative Imple-mentation Costs**
Conventional Treatment	M	NA	NA	NA	L	NA	M	$$
Advanced Treatment	H	NA	NA	NA	L	NA	L	$$
Reuse/Recycle	H	L	NA	NA	L	H	H	$$
Wetlands Protection	**Water Quality**	**Flow Regime**	**River Floods**	**Storm-water**	**Wetlands and Ecosystems**	**Water Supply**	**Waste-water System**	**Relative Imple-mentation Costs**
Restoration	M	L	M	NA	H	L	NA	$
Allow Migration	M	L	M	NA	H	L	NA	$
Create Additional Wetlands	M	L	M	NA	H	L	NA	$$
Manage Invasive Plants	NA	L	NA	NA	M	NA	NA	$
Social Vulnerability	**Water Quality**	**Flow Regime**	**River Floods**	**Storm-water**	**Wetlands and Ecosystems**	**Water Supply**	**Waste-water System**	**Relative Imple-mentation Costs**
Integrated urban water management strategies (above) to ensure access to safe water	M	M	M	M	L-M	L-M	M	$
Floodproof housing stock	NA	NA	L-M	L	NA	NA	NA	$$
Develop targeted emergency preparedness plans to reach vulnerable neighborhoods	NA	NA	L-M	L-M	NA	NA	NA	$
Implement local climate change	M	M	M	M	NA	M	M	$/$$$

adaptation plan that reduces social vulnerability and implement the BRACE framework								

Table 2. Management strategies and IUWM. Relative positive impacts on managing the stress – High (H), Moderate (M), Low (L). $ is relative cost of implementation.

It appears there are opportunities for IUWM in Exeter. Protecting, restoring, and expanding tidal and freshwater wetlands and expanding floodplains offer the potential for improved flood management while at the same time enhancing ecosystems and water supply through increased groundwater recharge, and mitigating some of the impacts from the local drainage system. In addition, more vegetation will provide recreation and cooling from urban heat island effects. The damage from large river floods will not be entirely solved by more natural recharge and more reservoir or natural valley storage. Thus local strategies such as elevation of roads, buildings, and equipment will also be needed as well as possibly retreating from frequently flooded areas. Basin and local LID would definitely lead to improvements in water quality as well as possibly decrease flood peaks and have other benefits in terms of water supply. Flood skimming for water supply also offers part of an integrated approach to flood management and water supply. Local LID would also benefit stormwater management in Exeter. LID also may offer other co-benefits for public health including supporting ecosystems, park and recreational systems, providing greenspace, buffers, and building social capital (Wolf, 2014). Implementation of stormwater Best Management Practices also provides many co-benefits. Water demand conservation provides many benefits in addition to water supply management. Water reuse and recycling also has many benefits but implementation, at least for now, will be hindered by its high cost. However, at least one utility, Hampton Roads Sanitation District in coastal southeastern Virginia, is voluntarily treating wastewater to essentially drinking water standards before recharging to water supply aquifers (Landers, 2016). While facing more environmental and regulatory challenges than Exeter, the example of Hampton Roads does provide evidence of the value of planning 20 to 30 years ahead to respond to changed conditions. Improving social resilience lowers by varying amounts present and future stresses. Effective adaptation will also lessen social vulnerabilities. Implementing the BRACE framework also lessens impacts across all sectors. The strong social networks in Exeter can provide a foundation for building capacity for IUWM within the community.These integrated approaches drawing upon the principles of IUWM and One Flood Management can be incrementally implemented over time as climate changes; this allows for cost effective adaptation.

6. Summary and Conclusions

With its emphasis on holistic solutions and systems thinking, the IUWM concept is an excellent framework for assessing the vulnerability of urban water systems and developing adaptation strategies. Exeter's flooding, water quality, drainage, aquatic ecosystems, water supply and wastewater treatment systems and social conditions will be further stressed by climate and other changes. Strategies undertaken by the managers of each system to individually adapt to the changes may exacerbate the performance of other systems. It is shown that by looking at the suite of challenges through the lens of IUWM there are possibilities for integrated strategies that may lower overall adaptation costs and provide wide-scale multi-criteria benefits.

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