Chester

Clinton

Cromwell

Deep River

Durham

East Haddam

East Hampton

Essex

Haddam

Killingworth

Lyme

Middlefield

Middletown

Old Lyme

Old Saybrook

Portland

Westbrook

Lower Connecticut River Valley Council of Governments

Long Term Recovery and Land Use Resiliency Through Community Flood Resilience Study

Flood Susceptibility Mapping for the Lower Connecticut River Valley

July 2018

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Photo: Chester Historical Society – Chester Center

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Executive Summary

A summary of the data, methodology, results, and conclusions related to the flood susceptibility analysis of the Lower Connecticut River Valley Region (LCRVR) can be found in Giovannettone et al. (2018).

Regarding climatic factors affecting the LCRVR, an analysis looking at the major climatic mechanisms linked to rainfall in the region was performed through a simple correlation analysis between long-term total precipitation and long-term averages of nearly 40 climate indices. It was found that by incorporating a time difference, or lag time, between the period over which rainfall is totaled and the corresponding period over which climate indices are averaged, 12 and 48 months maximized the predictive skill of the correlation. The reason for incorporating a lag time is based on the assumption that the effects of a particular climate mechanism on rainfall do not occur immediately; there is some delay before the corresponding impact on rainfall manifests itself. The 12-month lag time revealed a strong and significant correlation with El Niño, while the 48-month lag time revealed a strong and significant correlation with the Caribbean SST (sea-surface temperature) index. The correlations at the 48-month lag time were used to create a statistical model to predict future 48-month rainfall totals; predictions were shown to be relatively accurate when compared to historic observations. This model provides a long-term window into the future and can be used to predict the future onset and persistence of extended periods of high rainfall and drought.

Local- and regional-scale statistical analyses were performed for the city of Hartford and for a region encompassing several Mid-Atlantic and Northeastern states to detect changes in historical rainfall statistics over and near the LCRVR. Tests were performed on trends (i) in the Annual Maximum Series (AMS) of 24-hour rainfall and (ii) Peaks-Over-Threshold (POT). Slight linear trends were found at Hartford but were not significant at the 95% and 90% confidence levels. On a regional level, 20% of rain gauges, including gauges in northwestern Connecticut, experienced statistically significant increases in AMS over the period of record, while 32% showed statistically positive trends in POT, which indicates significant increase in heavy rainfall outside of the LCRVR. The change in the 70th and 98th percentiles of rainy day rainfall was also investigated to determine if the change in light/moderate rainfall is consistent with changes in heavier rainfall. Comparing two periods (1955 – 1985 and 1986 – 2016) revealed that even though there are significant increases in heavy rainfall on a regional basis, there are very few locations that experienced a significant change in light/moderate rainfall, suggesting a disproportionate effect of climate change on heavier events as opposed to an overall wetter climate. In contrast, as the local-scale analysis revealed no significant increase in heavy rainfall intensity and frequency, it is likely that the LCRVR has "beat the odds" by not experiencing an increase in heavy rainfall activity. It is also possible that there may be some other effect, perhaps from Long Island Sound, that has caused differences in rainfall trends in the region. This cannot be said for sure without additional analysis.

An analysis of future rainfall projections was then conducted to determine how heavy rainfall will change over the LCRVR in the mid- and long-term future using data from the Intergovernmental Panel on Climate Change's (IPCC's) CMIP5 modeling experiments. The high emission Representative Concentration Pathway (RCP) 8.5 (W/m2) scenario was used to provide an upper bound on expected changes. All raw model data used for future projections were bias-corrected by comparing model results from a historical period (1950 – 2005) to observations at the National Oceanographic and

Atmospheric Administration (NOAA) Global Historical Climatology Network (GHCN) rain gauge (ID# GHCND:USW00014740), at Hartford Bradley International Airport.

Projections in the future Precipitation-Frequency (P-F) curve at Hartford were then investigated. It was found that projected mid-term (2045) and long-term (2075) P-F curves show increases across the full range of frequencies, with higher percentage changes occurring for the more frequent events. Results indicate that today's 100-year 24-hour rainfall event will become a ~53-year event in 2045 and a ~45-year event in 2075, whereas more drastic changes are seen for more frequent events. These and prior results demonstrate the importance of determining which present-day recurrence intervals (e.g. 100-year) are important for land use and recovery planning, hazard mitigation, design standards and/or flood warning plans and then building socioeconomic models to show how a more frequent occurrence of such events will impact response and/or recovery costs. This analysis is also useful for informing the possible changes in the shorter-duration flash flood risk, which is more driven by precipitation compared to riverine flooding (especially on the Connecticut River). Although the latter is also driven by rain and snow, it is also driven strongly by additional factors such as upstream flow, land cover, impervious area and ice jams and dam releases.

A series of three outreach workshops for community officials, an online survey of stakeholders, and a review of planning and regulatory documents throughout the region were conducted. The workshops were used to review methodology and present results, and most importantly, to discuss the practical applications of the susceptibility mapping for community planning and operations, with a focus on resiliency. Practical applications range from quantitative analysis of at risk property and infrastructure, for planning, to modifications of design standards for new development and post disaster recovery.

1. Introduction and Literature Review

The Introduction and Literature Review pertaining to the flood susceptibility analysis can be found in Giovannettone et al. (2018).

2. Data and Method

Flood Susceptibility

A description of the data and methodology used to perform the flood susceptibility analysis can be found in Giovannettone et al. (2018).

Analysis of Climatic Factors

In addition to developing flood susceptibility maps, the impacts of climate variability and climate change on heavy precipitation in the LCRVR were studied. The impact of natural climate variability, which can have significant influence on year to year changes in heavy precipitation, was analyzed through a correlation analysis using large-scale Hydro-Climate Indices (HCI's). HCI's characterize repeated relationships between various climate regimes on a global scale and a host of associated hydrologic responses. The effects of these climate regimes on regional hydrologic flow and reservoir operations have been heavily researched, and the HCI's were developed to provide a quantitative point of reference for these relationships. The relationship between the climate and water supply has quickly evolved into a matter of national interest and concern during the past decade as periods of deep drought gripped several portions of the country creating regional water supply crises. Meanwhile, the impact of climate change was assessed from two perspectives: a historical analysis using observed, long-record rain gauge data, and an analysis of future projections of daily precipitation from relatively high resolution downscaled atmospheric models forced with increasing greenhouse gas emissions. Below, we describe the data used in each analysis in more detail.

Climate Variability

In addition to trends in a changing climate, there also exist various mechanisms of low-frequency climate variability that can result in significant changes in weather over time. The current study attempts to identify the climate mechanisms that affect precipitation in the LCRVR and surrounding region using various hydro-climate indices (HCI's), including those given in Table 2-3. The method used to accomplish this is referred to as "long-window" correlation analysis and entails utilizing a long-duration (60-month) moving average of monthly index values and precipitation to smooth out much of the noise in both time series. It was found that by incorporating a time difference, or lag time, between the period over which rainfall is totaled and the corresponding period over which climate indices are averaged, the predictive skill of the correlation could be optimized. The reason for incorporating a lag time is based on the assumption that the effects of a particular climate mechanism on rainfall do not occur immediately; there is some delay before the corresponding impact on rainfall manifests itself. Various lag times between the two datasets were analyzed, and it was found that lag times near 12 and 48 months resulted in the best correlations; further analyses were therefore limited to these two lag times. Strong correlations provide a type of predictive mechanism by which future annual or multi-annual precipitation can be estimated. Longer lead times also allow a window into the future from which the onset and/or persistence of a long-term extreme event can be identified with substantial lead time.

Precipitation data were obtained from the Global Historical Climatology Network (GHCN; see Menne et al., 2012) for locations throughout the States of Connecticut, Massachusetts, and Rhode Island, while the National Oceanographic and Atmospheric Administration (NOAA) contains a compilation of the climate index data used here (NOAA 2016). Precipitation data were composited into 60-month rainfall totals, while climate index data were averaged over 60-month periods that lagged the rainfall periods by 12 and 48 months for the short- and long-term analyses, respectively.

The current analysis required the use of a frequency analysis software referred to as the HydroMetriks – Frequency Intensity Tool (Hydro-FIT), which was developed, tested, and validated, by HydroMetriks, Ltd. Hydro-FIT allows the identification of any of nearly 40 climate indices that correlate well with total precipitation over a user-specified period, which is defined by a beginning month, duration, and lag

***Table 2-3:* Abbreviations and names of global climate indices analyzed in the current study.**

Index Abbreviation	Index Name
SOI	Southern Oscillation Index
ONI	Oceanic Niño Index
EPI	ENSO Precipitation Index
TNI	Trans-Niño Index
MEI	Multivariate ENSO Index
NAO	North Atlantic Oscillation
AMO	Atlantic Multidecadal Oscillation
AMM	Atlantic Meridional Mode
CAR	Caribbean SST Index
PDO	Pacific Decadal Oscillation
NOI	Northern Oscillation Index
WP	Western Pacific pattern
PNA	Pacific/North American pattern
AO	Arctic Oscillation
EAWR	Eastern Asia/Western Russia Index
CIP	Central Indian Precipitation index
MJO	Madden-Julian Oscillation

time. A previous version of Hydro-FIT had been used to perform such analyses for rainfall in South America and for hurricane genesis in the Atlantic Ocean (Giovannettone, 2017). The strength of each correlation was measured using Pearson's correlation coefficient, while the significance or the likelihood that a given correlation coefficient will occur while assuming there is no relationship in the population (r = 0.0) is measured using the statistical t-value and critical values from the Student's *t* Distribution for two-tailed distributions:

$$t = r\sqrt{\left(\frac{n-2}{1-r^2}\right)}, \qquad (3)$$

where *t* represents the statistical t-value, *r* is the Pearson correlation coefficient, and *n* is the number of data values (*n* – 2 = degrees of freedom). If the computed t-value is greater than a critical value, then the null hypothesis can be rejected and the correlation is significant at the selected confidence level.

Historical Precipitation Analysis

Daily rainfall records from the Global Historical Climatology Network (GHCN) (see Menne et al., 2012) were accessed. We focused on a region that has similar heavy precipitation statistics as the LCRVR, hereafter termed the LCRVR "climate region". The LCRVR "climate region" was subjectively determined by analyzing precipitation-frequency data (e.g. Appendix A) and noting that the LCRVR behaves similarly to other rain gauges roughly within 250 km of the Atlantic Ocean. In all, gauges were selected based on the following criteria:

- Roughly 250 km (155 miles) from Atlantic Ocean coastline,
- Years with more than 9 days of missing data were excluded,
- The last qualifying year was 2007 or later (see Appendix B),
- At least 60 qualifying years.

Quantitative evidence of significant non-stationarity, which suggests that climate and flood risk are being altered through substantial anthropogenic changes, in heavy precipitation statistics was assessed using three methods, trends in Annual Maximum Series (AMS), trends in Peaks over Threshold (POT) and changes in the daily rainfall distribution, from 1955-1985 to 1986-2016 at various percentiles. The AMS consists of a times series of annual maximum 24-hour precipitation totals, while the POT consists of a time series of the total number of days annually experiencing total precipitation over a pre-determined threshold.

Future Projections

The projected impact of climate change on rainfall intensity for medium (2045) and longer term (2075) planning purposes was estimated. This analysis is especially useful for informing the possible changes in the shorter-duration flash flood risk, which is more driven by precipitation than riverine flooding typically is (especially on the Connecticut River). Although the latter is also driven by precipitation, it is also driven strongly by additional factors such as upstream flow as well as land cover and impervious area.

The most comprehensive and commonly used source of climate change projections is organized by the Intergovernmental Panel on Climate Change (IPCC). We used data originating from IPCC's 5th Assessment Report (AR5), which is the latest available report as of 2017. The findings in AR5 are based on the simulation of many Global Climate Models (GCMs) from institutions across the world. While GCMs are adequate for studying continental and global-scale changes in climate, computational limitations constrain their horizontal resolution to be inadequate for the local scale analysis such as the one here. Thus, some manner of "downscaling", or using larger-scale variables to inform smaller-scale conditions, is required. A comprehensive dataset of downscaled Coupled Model Inter-comparison Project Phase 5 (CMIP5) output was developed in 2014 by a joint effort of several federal, academic, and commercial partners (Brekke et al. 2013). Although we considered the use of this data, we ultimately decided against using it because it strongly underestimated daily heavy rainfall statistics over the LCRVR.

Instead, results from a recent high-resolution downscaling effort called the North American Coordinated Regional Climate Downscaling Experiment (NA-CORDEX) were used. The NA-CORDEX was designed by taking the output of the relatively coarse GCMs belonging to CMIP5 and using these as boundary conditions to force much higher resolution atmospheric models centered on North America. Although many NA-CORDEX simulations were available, the analysis was restricted to those with the highest horizontal resolution of 11 km (7 miles). All selected simulations were forced by the Intergovernmental Panel on Climate Change's (IPCC's) CMIP5 modeling experiments high emission Representative Concentration Pathway (RCP) 8.5 (W/m^2) scenario boundary conditions. The focus on just the high emission scenario was done for two reasons: (i) to provide for an estimate of an upper bound to the impact of climate change on heavy precipitation (because previous studies have shown a quasi-linear response of heavy precipitation to scenario in the LCRVR), and (ii) to allow for the investigation of multiple model simulations that would otherwise not be possible if multiple scenarios were chosen.

Table A-1 in Appendix A shows the four model simulations that were analyzed. A fifth simulation, in which the RegCM4 was forced with the MPI-ESM-LR GCM, was available but not used because it had incomplete data.

3. Results

Flood Susceptibility

The overall results of the logistic analysis for each sub-region within the AOI are given in Giovannettone et al. (2018). In summary, it was found that 'elevation' and 'distance to water' have the most influence on flood susceptibility in the urban and coastal sub-regions, whereas 'elevation' has substantially less influence within the rural sub-region with 'distance to water' and 'surficial materials' having the greater influence. It was also found that 'surficial materials' has a strong influence in the coastal and rural sub-regions, whereas it has little influence in the urban sub-region, while 'land cover' has the opposite trend. Finally, it was observed that the urbanization in the sub-region including and surrounding the City of Middletown has resulted in a significant increase (greater than 200 percent) in the contribution of 'land cover' to the flood susceptibility of the area.

There were several areas identified as 'very high' and 'high' risk outside of the FEMA map, which includes various types of critical infrastructure (Giovannettone et al., 2018). When comparing the susceptibility mapping to the FEMA 100-year flood maps, it is important to understand key distinctions between the two. The FEMA 100-year flood maps are limited to the sub-watersheds of greater than one square mile that FEMA chose to study with limited resources. Other limiting factors are the age of the underlying studies illustrated by the FEMA maps (often more than two decades old) and their focus on only areas where development existed or was imminently anticipated. FEMA's flood mapping is developed using physical models to perform hydrologic and hydraulic analysis of a statistical rainfall event with a one percent chance of being equaled or exceeded in any given year (referred to as the 100-year flood). In general terms, hydrologic analysis is the study of transforming rainfall amount into quantity of runoff. Hydraulic analysis takes that quantity of water and uses a physical model to route it through existing terrain, while considering such factors as topography and vegetative density. This modeling is referred to as "detailed analysis." Some areas are studied by "approximate methods." In general, areas studied by approximate methods use a simplified hydrologic analysis methodology and route runoff quantity through best available topography alone.

The susceptibility maps from this study provide a less expensive method of covering all land area within the region. By using the statistical modeling methodology described in this report it was possible to identify the contribution of flood factors within the physically modeled FEMA 100-year floodplain and apply them to the entire study region to identify areas thought to be vulnerable to flooding. One important disclaimer about the flood susceptibility map is that it was created for present-day conditions and is only to be used for planning purposes. It is not intended to replace the FEMA mapping for regulatory or flood insurance decisions.

The scale of the flood susceptibility map and data are most appropriately used at the regional scale. However, use of the data at the municipal scale should allow local officials to examine areas of concern for planning purposes. A GIS tool, which accompanies this report, was developed to enable any location within the region to be looked at in more detail. As more accurate input datasets (e.g. higher resolution LiDAR data and imagery) become available, they can be easily incorporated into an updated flood susceptibility analysis as well as a revised GIS tool. Higher resolution input datasets also allow smaller areas to be analyzed in more detail if desired (e.g. the City of Middletown, which is dominated by an area of 'very high' flood susceptibility in the northern portion of the AOI in Fig. 3-3).

Climate Variability

An idea of the climatic mechanisms that may contribute to precipitation and flooding in the region surrounding and including the LCRVR can be obtained from the results of the climate variability analysis shown in Fig. 3-4.

It can be observed in Fig. 3-4 that there are a few dominant hydro-climate indices that correlate with precipitation throughout the State of Connecticut and the surrounding region for both the 12-month and 48-month lead times, which include indices related to the El Niño/Southern Oscillation (ENSO), the Madden-Julian Oscillation (MJO), and the Caribbean SST (sea-surface temperature) Index (CAR), which is a time series of SST anomalies averaged over the Caribbean Sea. Within the LCRVR itself, ENSO has the highest correlation with precipitation at the 12-month lead time (Fig. 3-4a) using the beginning months given in Table 3-1, which contrasts with other sites within the State of Connecticut that correlate best with the MJO. The strength of these correlations is between R = 0.60 to 0.79 (r^2 = 0.36 to 0.62), which is strong enough to make qualitative predictions concerning whether the following 12 months will experience higher- or lower-than-normal precipitation, but was found not to be sufficient to make

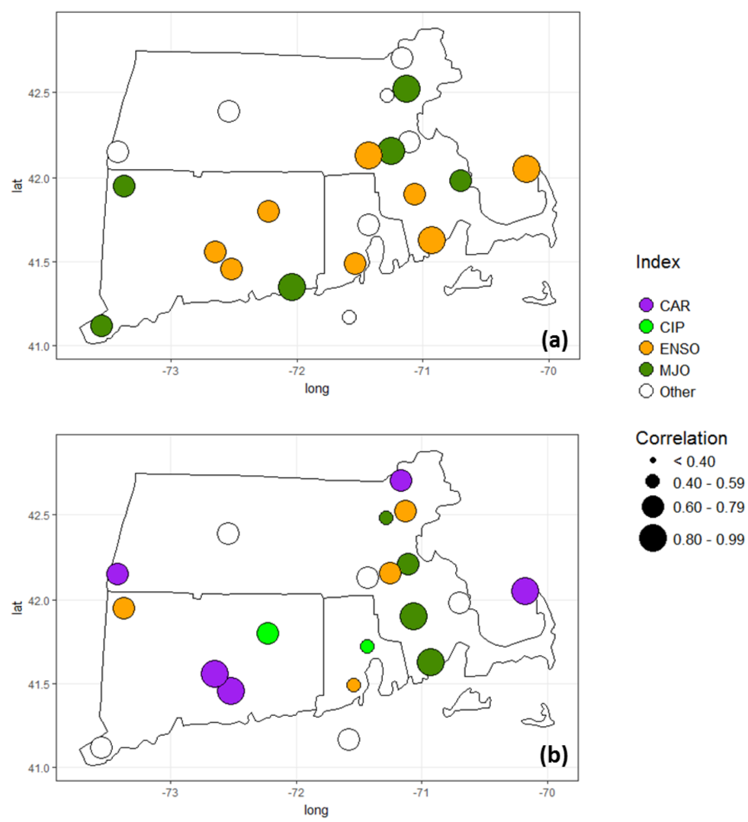

***Figure 3-4:** Results of hydro-climate index analyses at several locations throughout the states of Connecticut, Rhode Island, and Massachusetts using lag times of (a) 12 months and (b) 48 months. The color and size of the circles represent the index and correlation strength, respectively.*

Table 3-1:* *Strong correlations between 60-month average climate index values and 60-month total precipitation were identified for Middletown and Cockaponset State Forest using the climate indices given in Column 3 and beginning months and lead times in Columns 2 and 4, respectively.

City	Precipitation Beginning Month	Index	Lead Time (months)
Middletown, CT	January	ENSO	12
Cockaponset, CT	July	ENSO	12
Middletown, CT	January	CAR	48
Cockaponset, CT	January	CAR	48

quantitative predictions of future rainfall. To perform a complete statistical analysis of each correlation, the significance was also estimated so that the null hypothesis that there is no relationship in the data can be rejected. The results for the Student's *t* test are given in the column labeled t/t_{crit} in Table 3-2. The first value represents the t-value computed for each site using the corresponding correlation coefficient (*r*) and number of data points (*n*). The second value represents the critical value from the Student's *t* distribution at the 0.01% confidence level. The fact that the t-value does not exceed the critical value at Middletown means that the null hypothesis cannot be rejected at the 0.01% confidence level, but it was found that the t-value exceeds the critical value at the 0.05% confidence level (not shown). The t-value for Cockaponset does exceed the critical value by a small amount, which means that the null hypothesis can be rejected at the 0.01% confidence level.

Precipitation within the LCRVR was found to correlate strongest with the CAR at a 48-month lead time (Fig. 3-4b) using the beginning months given in Table 3-1, which again contrasts with other locations in the state. In this case, the strength of the correlations at Middletown and Cockaponset are between r = 0.80 and 0.99. The results for the Student's *t* test are given in Rows 3 and 4 of Table 3-2. The fact that the t-value exceeds the critical value at both locations by a substantial amount means that the null hypothesis can be rejected at the 0.01% confidence level in both cases.

Due to the high strength and significance of the correlations identified at a lag time of 48 months, predictions of 48-month rainfall using the respective linear relationships with CAR are made at Middletown and Cockaponset State Forest and compared to observations in Figs. 3-5a and b, respectively; model parameters are given in Table 3-2 for both the 12-month and 48 month correlations. Predictions closely match observations for almost all years where sufficient rainfall data were available except for a few short periods. These results demonstrate that, using only one variable, long-term total precipitation can be predicted with good accuracy, which can be extrapolated to being able to predict long-term changes in precipitation accurately with sufficient lead time. For example, the onset and end of a drought or an extended period of high rainfall are capable of being detected with a 48-month lead time, thus providing a method by which to estimate persistence long in advance.

***Table 3-2:* Linear regressions were developed for Middletown and Cockaponset State Forest using the climate indices, beginning months, and lead times given in Table 3-1. Columns 3 and 4 give the slope and intercept of the regressions, respectively, while Columns 5 – 7 give Pearson's correlation coefficients (r), number of data points (n), and ratio of t-values to the critical value from the Student's t distribution at the 0.01% confidence level for a two-tailed distribution.**

City	Lead Time (months)	Slope (m)	Intercept	r	n	t/t_{crit}
Middletown, CT	12	-76.75	243.49	0.65	25	4.10/4.69
Cockaponset, CT	12	40.82	241.91	0.74	23	5.04/4.78
Middletown, CT	48	-276.54	241.81	0.81	22	6.18/4.84
Cockaponset, CT	48	-162.10	233.62	0.87	18	7.06/5.13

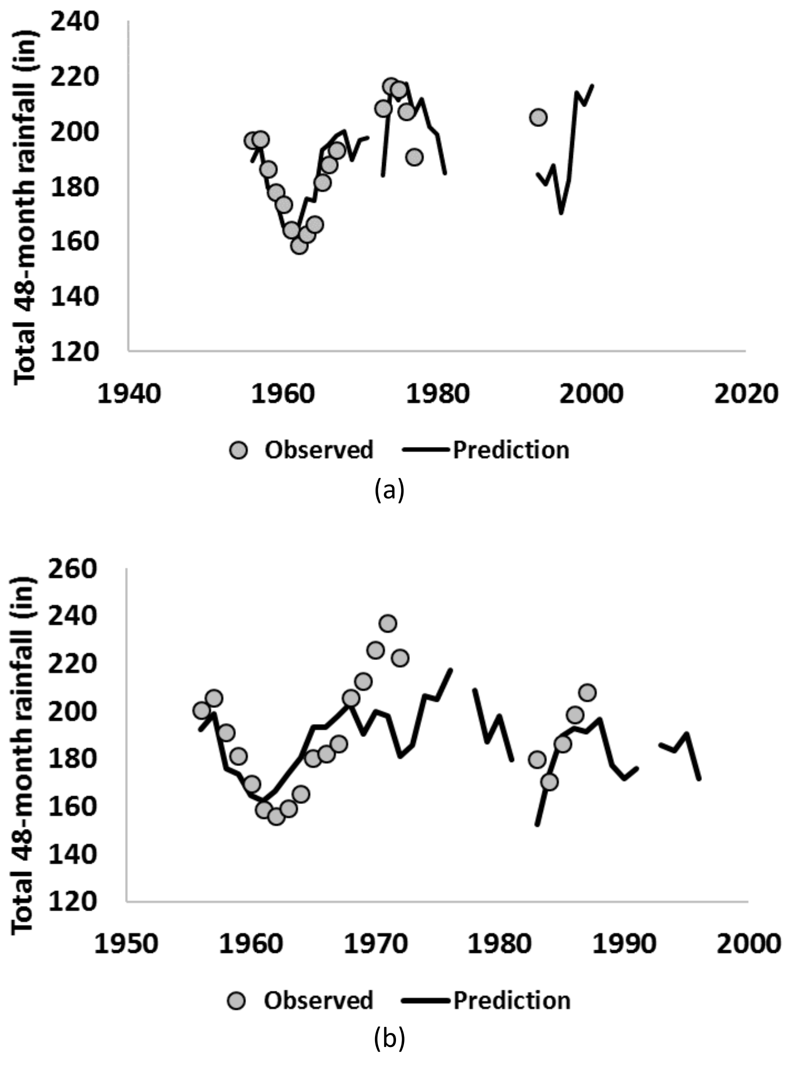

***Figure 3-5:* Time series of projected (line) vs. observed (circles) 48-month total precipitation at (a) Cockaponset State Forest and (b) Middletown.**

Climate Change

Historical Analysis

A local- and regional-scale statistical analyses to detect changes in historical rainfall statistics over the LCRVR was performed. For the local-scale, the Hartford-Bradley International Airport rain gauge was selected, from the Global Historical Climatology Network (id: USW00014740). This gauge had a nearly-complete record of daily data from 1949 – present. Heavy precipitation statistics for the Hartford/Middletown area are shown in Appendix B. The magnitude of the 100-year 24-hour event is about 8.2 inches (Appendix B, Fig. B-1). Meanwhile, there is a distinct seasonality of heavy rainfall occurrence, with highest chances in the late summer and fall (Appendix B, Fig. B-2). For the regional-scale analysis, we selected all long-record rain gauges within about 250 km of the Atlantic Ocean over the Mid-Atlantic and Northeastern states. This region experiences similar heavy rainfall statistics and thus can be considered a more general proxy for trends in the LCRVR's climate.

For the local and regional-scale analyses, we performed tests on trends (i) in the Annual Maximum Series (AMS) of 24-hour rainfall and (ii) Peaks-Over-Threshold (POT), where a threshold of 1.25 inches per day was used. For the regional analysis only, we also investigated the change in the 70th and 98th percentiles of rainy day rainfall. This allowed us to determine if the change in light to moderate rainfall amounts was consistent with changes in heavy rainfall days, respectively.

Local-scale

Figure 3-6 shows the Annual Maximum Series (AMS) of daily rainfall at the Hartford gauge, which ranges from about 1.5 inches to over 7.0 inches. A linear trend test was applied to this time series and revealed a weak positive trend, but the trend was not significant at the 95% and 90% significance levels. Due to the presence of isolated, very high amounts such as in 1955, 1982 and 1999, we also performed a Spearman correlation (less sensitive to outliers) between year and AMS and again found the correlation to be insignificant at the 90% and 95% confidence levels.

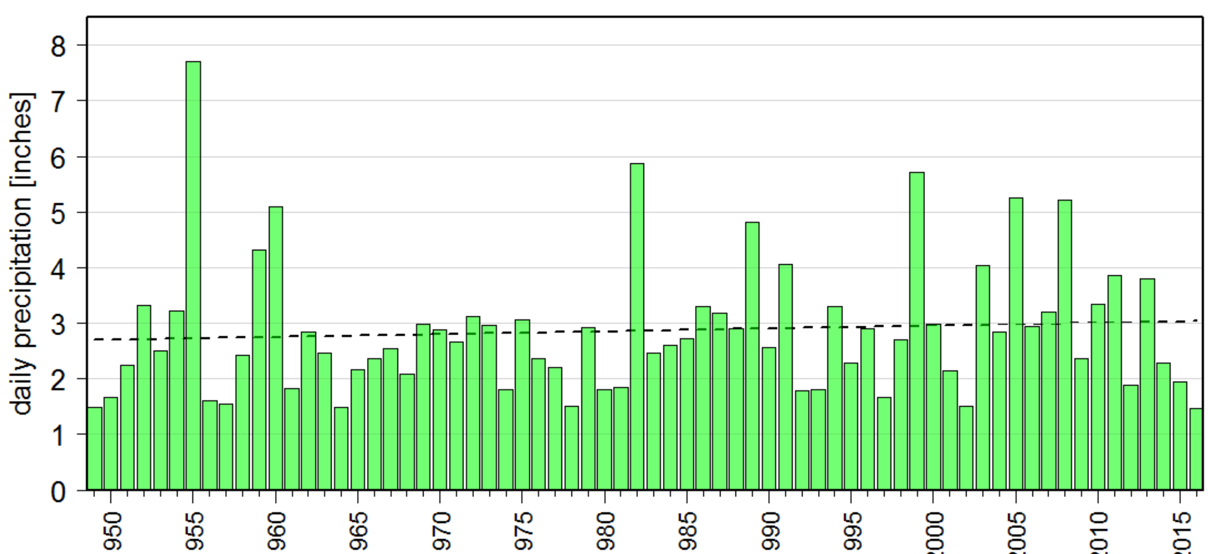

***Figure 3-6:* Annual Maximum Series of daily rainfall at Hartford Airport over the 1949-2016 period. A linear trend is shown for reference, but this trend was NOT significant at the 95% confidence level.**

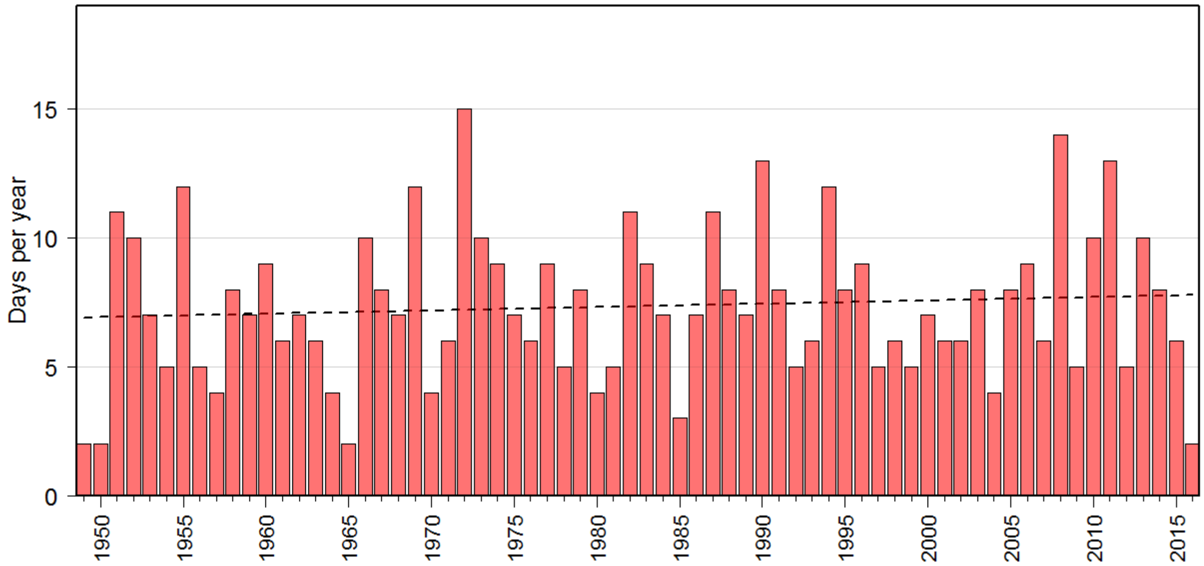

***Figure 3-7:* As in Fig. 3-6, except for annual Peaks-Over-Threshold using 1.25 inches per day as the threshold. The trend line was NOT found to be significant at the 95% confidence level and is shown for reference only.**

Because AMS time series can have significant year-to-year variability that may mask longer-term trends, we also investigated the trend in POT with a threshold of 1.25 inches per day. The result, shown in Fig. 3-7, shows a range of values from 2 to 15 days per year, though a linear trend was once again found to not be significant at the 90% and 95% confidence levels.

Thus, our conclusion from the local-scale analysis was that there has not been a significant change in heavy rainfall statistics using the Hartford Bradley Airport gauge, which serves as a good proxy for the LCRVR. A regional-scale analysis was then performed to determine if the local-scale result can be corroborated when using other nearby rain gauges.

Regional-scale

The 3rd National Climate Assessment (NCA3; Melillo et al. 2014) has documented a substantial increase in heavy rainfall events across the Northeast United States. However, that analysis aggregated the Northeast US into a single region, which could have mixed together sub-regional differences (e.g. we did not find any increases in heavy rainfall at Hartford). Here, we perform a similar analysis as NCA3 but investigate trends in heavy rainfall frequency and intensity on a *gauge-specific level* for gauges in close proximity to the LCRVR. Because heavy precipitation is relatively rare and a single gauge could miss showing a trend due to chance, we include in the analysis gauges across the Northeast and Mid-Atlantic US, roughly within 250 km of the Atlantic Ocean. We chose this region because the heavy rainfall statistics are roughly the same within this region. This can be deduced by looking at the 100-year 24-hour rainfall estimate from NOAA Atlas 14 (Fig. 3-8) – note that the contours roughly parallel the coastline.

Gauges belonging to the Daily Global Historical Climatology Network (GHCN; Menne et al. 2012) were used in this analysis. A gauge must have at least 60 years of data to qualify, where a year is counted as

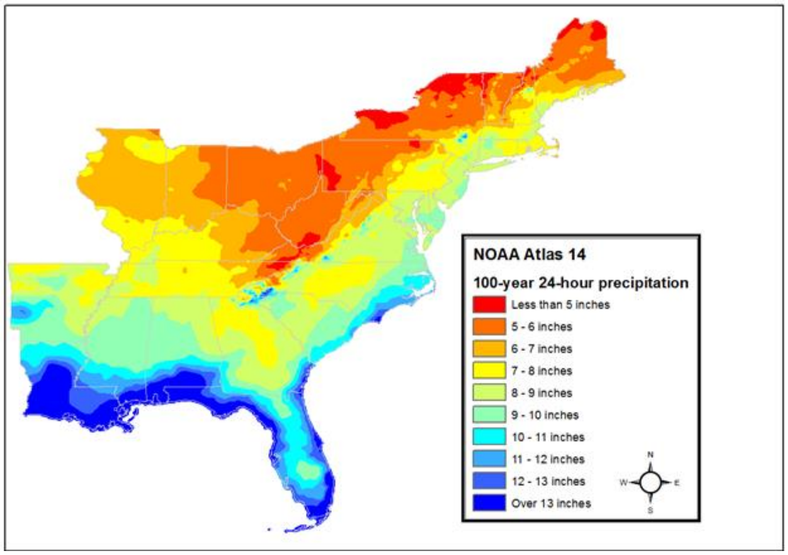

Figure 3-8: ***100-year, 24-hour rainfall across the eastern United States (adapted from NOAA Atlas 14; see Perica et al, 2015 for details).***

qualifying if it had less than 10 missing days of data. A total of 179 qualifying gauges were found (using data through 2016), and trends in the AMS and POT (exceeding 1.25 inches per day), as well as changes in the distribution, were determined in a gauge-by-gauge manner.

Figure 3-9 shows the trends in AMS of 24-hour rainfall for data through 2005 and 2016. The former is shown for comparison to highlight the drastic changes that have occurred over only the past 10 years. Looking at the right panel in Fig. 3-9, it is seen that out of 179 qualifying gauges, 36 (20%) show statistically significant increases in the AMS. By pure chance, we would only expect 10% (or 18 gauges) to show a trend (both positive and negative). Whereas, **it is seen that there are no gauges that show significant decreases in AMS, providing substantial evidence that large-scale AMS trends are positive in the region**. Note that the Hartford gauge does not show an increase, but gauges in northwest Connecticut do show increases.

Figure 3-10 investigates regional trends in a different manner by considering trends in the POT (threshold: 1.25 inches per day). Similar results are observed as in Fig. 3-9, but now 57 (32%) of the gauges show statistically significant positive trends, while only two gauges show significant decreases. Figure 3-10 also shows that most of the gauges with significant positive trends are located in the northeast United States, with less significant results farther south. To some degree, Fig. 3-10 provides more robust evidence of increases in heavy rainfall statistics because this data includes many storms each year, whereas Fig. 3-9 only identifies the wettest storm each year.

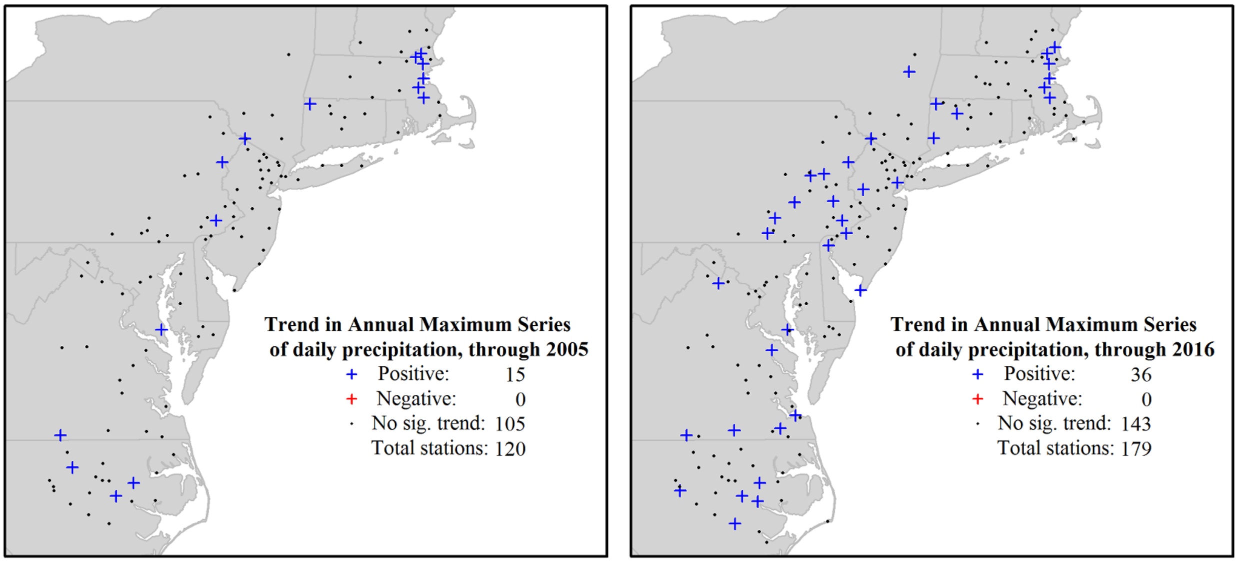

***Figure 3-9:* Trends in the Annual Maximum Series of qualifying long-record gauges using data through (left) 2005, and (right) 2016. A 95% confidence level is used to denote statistical significance.**

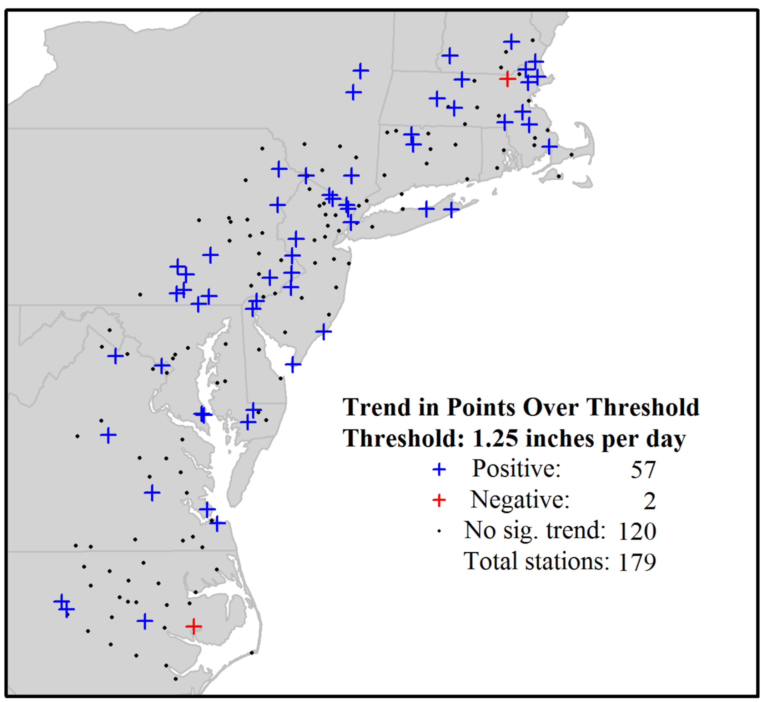

***Figure 3-10:* As in Fig. 3-9, except for annual Points-Over-Threshold. A 95% confidence level is used to denote statistical significance.**

Figure 3-11 shows the changes in 70th and 98th percentiles of rainy day rainfall for each gauge. This was calculated by determining the 70th and 98th percentiles of daily rainfall separately during 1955-1985 and 1986-2016 periods and then dividing the latter value by the former. Statistical significance is more difficult to assign in such a scenario because the value depends on each gauge's distribution; however, a

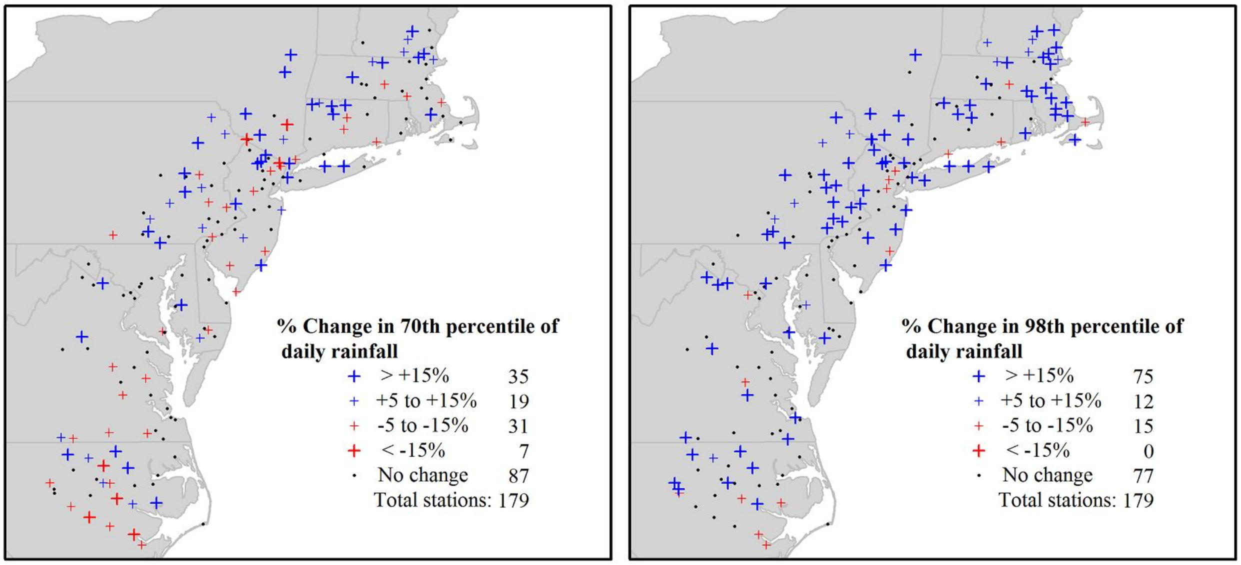

***Figure 3-11:* Percent changes in the (left) 70th and (right) 95th percentiles of rainy day rainfall, when comparing the 1955-1985 and 1986-2016 periods. For the Hartford, CT gauge, the 70th percentile is about 0.40 inches per day; the 98th percentile is about 1.95 inches per day.**

change exceeding +/- 10% can roughly be used as a guideline for statistical significance. Focusing first on the 98th percentile changes, it is seen that the results of Figs. 3-9 and 3-10 are largely corroborated, though even more gauges now show significant increases in heavy rainfall. For example, 75 gauges (42%) now show significant increases, while zero gauges show significant decreases (exceeding 15%). A secondary interesting finding can be seen in the left panel of Fig. 3-11, which shows that there have been no significant changes in the 70th percentile (though regionally, increases are seen in the NY, CT, and MA area). This suggests that it is the heavy rainfall events that are being disproportionately influenced by climate change as opposed to an overall wetter climate.

Whereas the local-scale analysis of Figs. 3-6 and 3-7 show no significant increase in heavy rainfall intensity and frequency at the Hartford gauge, Figs. 3-9 and 3-10 show significant regional-scale increases. Thus, we can conclude that it is likely that the LCRVR has “beat the odds” by not experiencing an increase in heavy rainfall activity at this point. This is not entirely unexpected due to the hit-or-miss character of heavy rainfall events. Next, an analysis of future rainfall projections is conducted to determine how heavy rainfall will change over the LCRVR in the mid- and long-term future.

Future Projections

To investigate future projections of heavy rainfall events in the LCRVR, data from the IPCC’s CMIP5 modeling experiments were used. However, using raw Global Climate Model (GCM) data would be insufficient for informing regional and local-scale rainfall. Thus, we used output from the North American Coordinated Regional Modeling Experiment (NA-CORDEX; Castro et al. 2015). NA-CORDEX is a set of medium- to high-resolution regional models that uses boundary conditions from the CMIP5 GCMs (refer to Table A-3 in Appendix A). Although NA-CORDEX used both RCP4.5 (medium emission) and RCP8.5 (high emission) scenarios, we accessed only the latter. The rationale for this was that if a strong signal was found for RCP8.5, it may warrant consideration of other conditions. On the contrary, if no significant changes were found for RCP8.5, then it is unlikely that other scenarios would show significant changes.

Daily model output of precipitation was accessed over the 1950 – 2100 period. The 1950-2005 period was termed a "historical hindcast" where observed greenhouse gas forcing was used, whereas, the 2006-2100 period was forced by RCP8.5 emissions. Greenhouse gas forcing refers to the effects of changes in atmospheric greenhouse gas concentrations on radiative forcing (see the Atmospheric Concentrations of Greenhouse Gases indicator). Energy that radiates upward from the Earth's surface is absorbed by these gases and then re-emitted to the lower atmosphere, which results in a warming of the Earth's surface. After obtaining the required data, the first step in assessing future rainfall was to compare model climatology with the Hartford gauge over the historical period. Figure 3-12 shows that three of the four models were slightly wetter than observations, while one model was drier than observations. Figure 3-12 was used to perform a bias correction through quantile mapping (Themeßl et al. 2011). In this procedure, the model daily rainfall amount is first converted into a quantile (quantile increment was 0.005) and then mapped to its analogous quantile using the Hartford rain gauge data.

To determine future rainfall amounts, the raw model data for the 2006 – 2100 period was corrected using the same quantile mapping transfer function. Thus, **the key assumption is that the future quantile-quantile relationship is identical to the past** (Themeßl et al. 2011). However, in situations where future modeled rainfall exceeded the highest value over the historical modeled period, the quantile-quantile ratio of the highest historical modeled value was applied. In practice, this was only noted to happen on, at most, five different future days for any given model simulation.

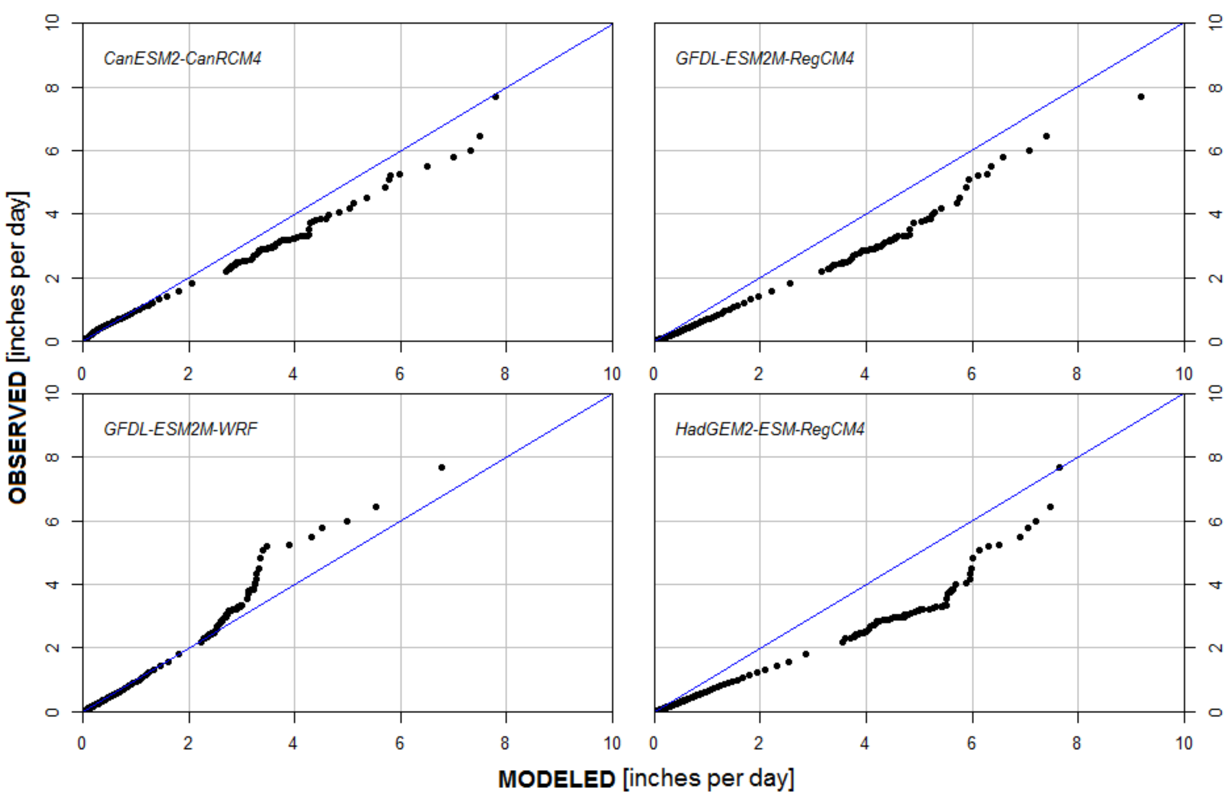

Figure 3-12: ***Quantile-quantile plots comparing modeled 24-hour precipitation with the Hartford gauge over the historical period. The blue line represents the result for a perfect model. Points to the right of the line imply the model is wetter than observations, while points to the left of the line show the model is drier.***

After bias corrected future projections of daily rainfall were computed using quantile mapping, potential changes in the future Precipitation-Frequency (P-F) curve were investigated. The P-F curve is derived by fitting a distribution to Annual Maximum Series of daily rainfall. Analogous P-F curves can be developed for other durations, but our model output, and thus our focus, was restricted to daily rainfall.

Figure 3-13 shows that after bias-correction, a Generalized Extreme Value (GEV) distribution provides an excellent fit to the *observed* empirical Hartford P-F data within the 90% confidence level. The 90% uncertainty band was calculated by randomly sampling the historically modeled time series 1000 times and calculating a Generalized Extreme Value (GEV) for each randomization. Similar uncertainty estimates were prepared for future projections. The excellent fit in Fig. 3-13 confirmed that we could use the historical model simulations as a baseline to which future model simulations could be compared.

Figures 3-14 and 3-15 show the projected mid-term (2045) and long-term (2075) P-F curves compared to the historical period. The mid-term value was calculated using data from 2026-2065, while the long-term value was calculated using data from 2056-2095. Bias-corrected model projections were concatenated into a single 160-year time series to estimate future P-F curves. This was done after testing each individual model's projection and finding little difference between each model, which was somewhat expected because bias-correction was applied. Figures 3-14 and 3-15 show increases in the P-F curve across the full range of frequencies. However, the highest fractional changes occur for higher frequency (i.e. more frequent, lower intensity) events.

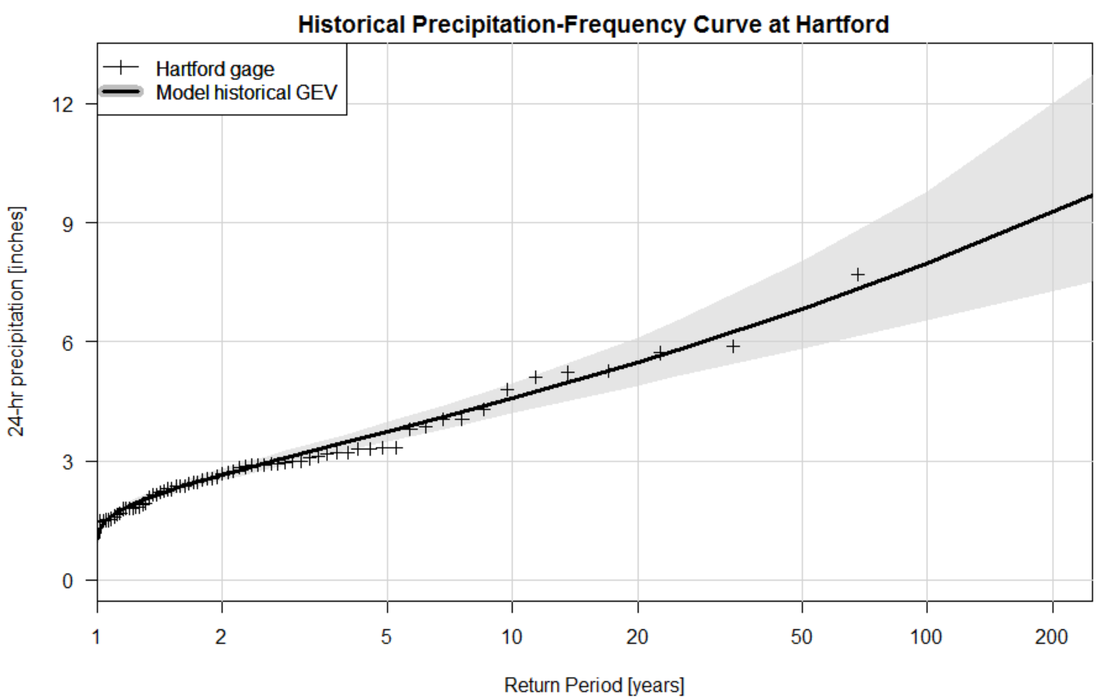

***Figure 3-13:* Hartford rain gauge empirical Precipitation-Frequency curve (+) compared to a Generalized Extreme Value distribution fit to bias-corrected historical model output. The GEV is assumed to be the best distribution for the Hartford gauge.**

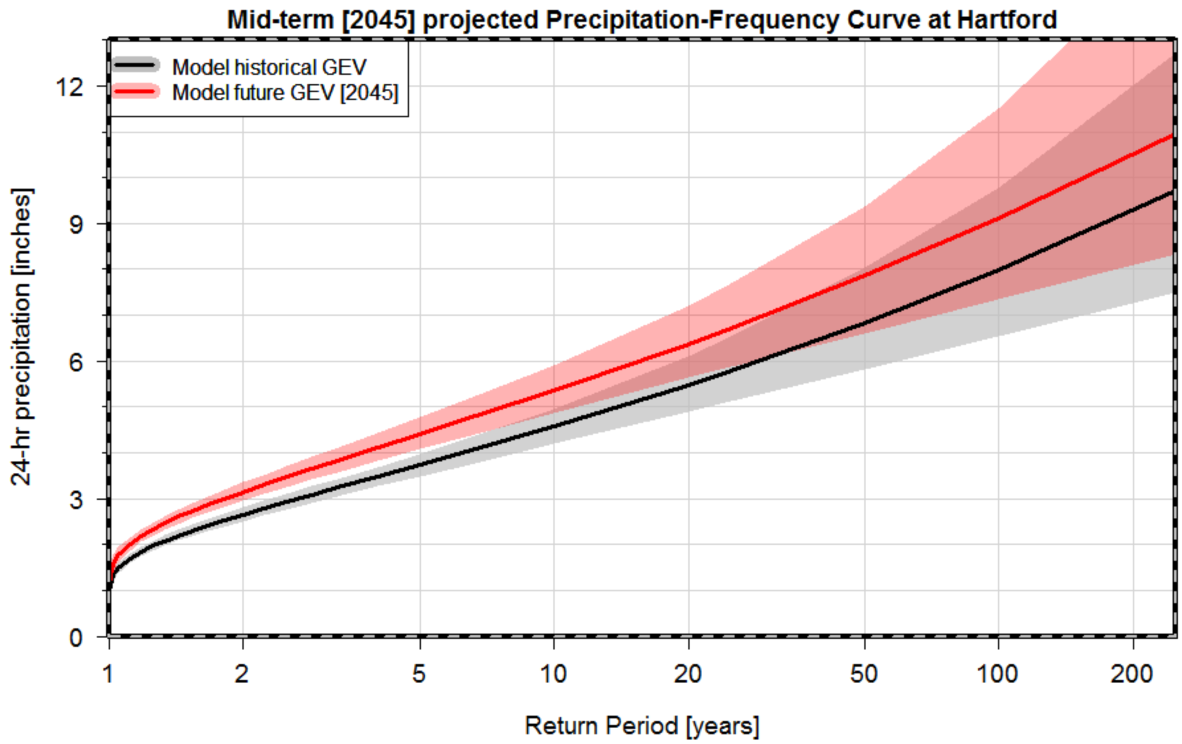

***Figure 3-14:* Modeled Precipitation-Frequency curves for the Hartford area. The black line and gray shading denote historical (1950-2005) conditions while the red line and light red shading denote the estimate for the 2045 period.**

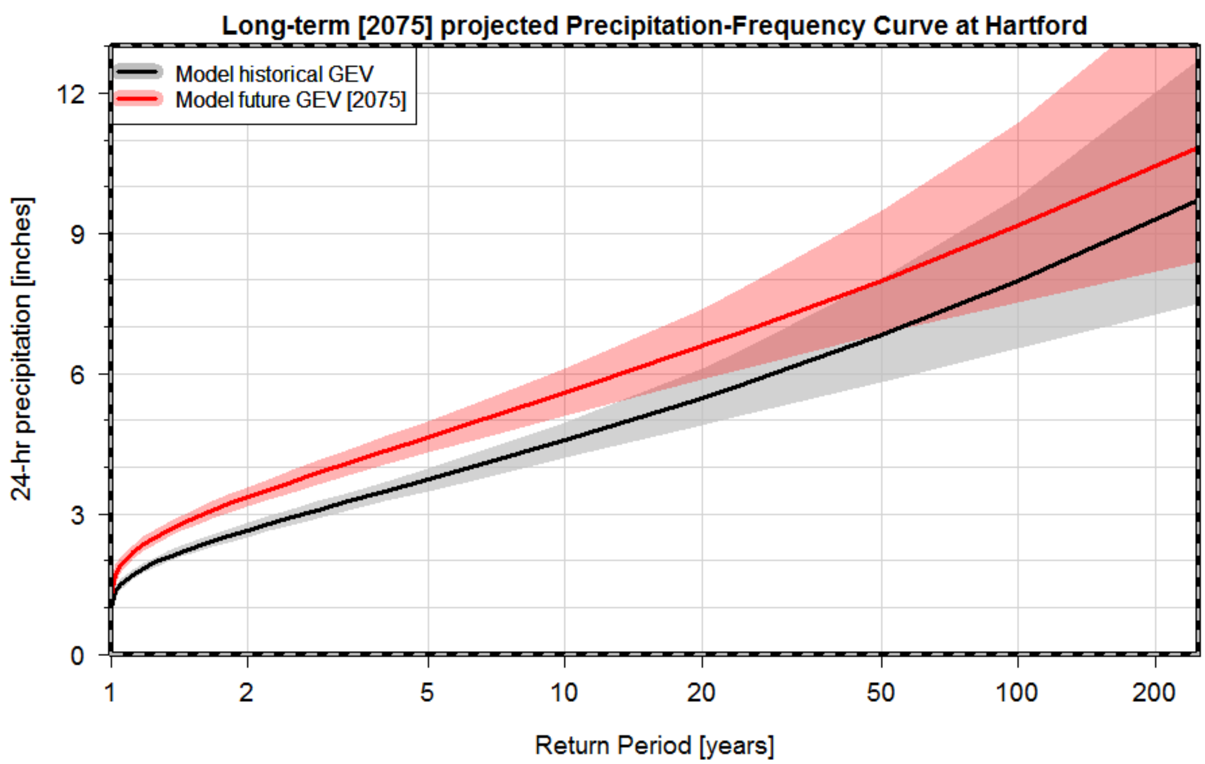

***Figure 3-15:* As in Fig. 3-14 except for the 2075 period.**

***Table 3-3:* Percent changes in projected 24-hour rainfall at Hartford by 2045 and 2075. Bold font denotes projections are outside the band of historical uncertainty.**

Return Period	Change in 2045	Change in 2075
1 year	**+17%**	**+25%**
2	**+19%**	**+27%**
5	**+18%**	**+24%**
10	+17%	**+22%**
20	+16%	+20%
50	+15%	+17%
100	+14%	+15%

Table 3-3 summarizes the percent changes in the most likely P-F curve value for the 2045 and 2075 periods. In general, increases up to 19% are found by 2045, while increases up to 27% are found by 2075. Comparing the uncertainty bands between the future and historical periods shows that the future band is completely outside of the historical band for up to the 5-year event by 2045 and up to the 10-year event by 2075. Increases found here appear to be slightly less than those described by Prein et al. (2016), who found increases of between 30 and 50% in the statistics of shorter duration hourly heavy rainfall across the LCRVR.

Another perspective on interpreting the results in Figs. 3-14 and 3-15 is to compare how current return periods are projected to change. For example, Fig. 3-14 shows that today's 100-year 24-hour rainfall event will become a ~53-year event in 2045, while Fig. 3-15 shows that it will become a ~45-year event in 2075. More drastic changes are seen for more frequent events. For example, a current 20-year event will become a ~12-year event by 2045 and a ~8-year event by 2075. Thus, one method of assessing the practical impacts from these changes is by determining which present-day recurrence intervals (e.g. 100-year) are important for design standards and/or flood warning plans and building socioeconomic models of how a more frequent occurrence of such events will impact response and/or recovery costs.

A notable disclaimer about the analysis presented herein is that there was little effort placed in investigating the *climate dynamics* causing the changes. For example, it is not entirely clear whether the changes are arising from stronger Nor'easters, tropical cyclones, and/or stationary frontal systems, all of which can cause heavy rainfall in the LCRVR. It is suggested that any further analyses on this topic more closely investigate these respective processes, which could increase the confidence that we can place in the final results.

4. Practical Applications of Study Findings

Another part of the study included outreach to community officials from the 17 municipalities and select additional stakeholders. An online survey and a series of three workshops were held throughout the LCRV region. A cursory review of representative planning and regulatory documents was also performed to determine how, in general, communities are addressing flooding conditions outside of FEMA mapped flood hazard areas. Table 4-1 lists the municipal departments and stakeholders that were invited to participate in the workshops and the survey.

Table 4-1: ***Survey and Workshop Participant Invitees.***

Municipal Officials	Other Stakeholders
Town Planners	CT Maritime Trades
Town Engineers	U.S. Coast Guard
Public Works Directors	CT Institute of Resilience and Climate Adaptation (CIRCA)
Emergency Management Directors	U.S. Army Corp of Engineers
Economic Development Directors	Land Trusts
Public Health Officials	Nature Conservancy
Agricultural Commission	CT Department of Energy and Environmental Protection
	CT Department of Housing

Workshops

The workshops included the following content:

Workshop 1 – March 28th, 2017 - 1-3pm, **Haddam Fire Department Rec, 439 Saybrook Rd, Higganum**
Provided an overview of the project and an update on its status. A brief overview of planning in the region around this hazard was presented and input sought on factors that contribute to flooding. Input was also sought on the format of the subsequent workshops.

Workshop 2 – April 18th, 1-3pm, **Old Lyme Town Hall Meeting Room, 52 Lyme St., Old Lyme**
Provided an overview of the flood susceptibility model and near final mapping. There was a breakout session to review mapping in the GIS viewer and to provide feedback.

Workshop 3 – May 9th, 1-3pm, **Middletown City Hall, Council Chambers, 245 DeKoven Dr., Middletown** Focused on using the results and products of the study to foster public awareness, resilience action and public policy for the region. It included recommendations or best practices for planning documents, capital budgeting, and regulatory tools.

Survey

The survey was completed by 27 respondents, nearly all of whom answered all questions asked. The distribution of respondents among the community officials listed in Table 4-1 was nearly even, with the exception of no responses from agricultural commissions and fewer from economic development officials. There were more responses from Town Planners. Approximately 30% of the overall responses came from those listed in the stakeholder column. Distribution of survey responses were also fairly even across the communities in the region, with noticeably higher responses from Old Saybrook, Essex and East Haddam and none from Lyme and Middlefield.

Notable findings of the survey included:

- 48% of respondents felt there have been moderate increases in flooding due to high intensity rainfall events in the last 10-years
- 65% of respondents believed that the stormwater system capacity in their community needed at least some improvements to handle future storm events

- 60% of respondents believed that community plans (e.g. Hazard Mitigation, Conservation and Development, Emergency Management) do not adequately address the impacts of climate change on future flooding conditions
- 55% of respondents indicated the residents are somewhat (50%) or very (5%) concerned about the impacts of climate change
- When asked which planning, regulatory or policy documents were best suited to address future flooding issues, the distribution was fairly even, with the most respondents indicating Hazard Mitigation Plans and Plans of Conservation and Development as the best places. Zoning Regulations were a close third.
- Roads and bridges, residences and businesses, and the environment were ranked as most at risk, respectively.

Full results of the survey are included in Appendix D.

Review of Planning Documents

As part of a previous project, Dewberry conducted a review of planning and regulatory documents from the 17 communities in the region. To supplement that review, representative plans from urban, rural and coastal communities were also performed as part of this project. Reviews included:

- Plans of Conservation and Development (POCD)
- Hazard Mitigation Plans (HMP)
- Coastal Resilience Plans (CR)
- Zoning / Subdivision Regulations

Findings from the review included:

- Thirteen of the 17 communities have a flood/hazard element or chapter in their POCD.
    - East Hampton, Lyme, Middletown and Old Lyme do not
    - Most do not get specific about flooding type and trends as they are broader-based, long term policy documents.
    - Older plans (not updated in the last 3-5 years) do not address climate change in a comprehensive way.
    - Most or all do not call out increased intensity rainfall events and associated drainage flooding issues.
- All of the communities have or participate in a regional hazard mitigation plan.
    - Most plans use FEMA inundation mapping, coastal storm surge, and sea level rise layers to evaluate risk
    - Some plans mention high intensity rainfall events as problematic, but most do not address it in terms of climate change.
    - Many plans address “hot spots” of localized flooding, mostly anecdotally.
    - Many plans have mitigation actions that address specific infrastructure or drainage improvements.
- Old Saybrook is the only community in the region that is developing a Coastal Resiliency Plan.
- Most Zoning and National Flood Insurance Program (NFIP) ordinances rely on FEMA mapping alone for regulating flood prone development.
- Subdivision and site plan review usually include peak flow and stormwater volume provisions.
    - Most look at existing sources of rainfall data to design – not future conditions.

Applications of Flood Susceptibility Mapping and Climate Data

This section builds upon the findings from the survey, review of plans, and discussions at the workshops (primarily Workshop 3) to outline some of the ways that the data from this study can be practically utilized at the local level to increase flood resilience. It is not intended to be an exhaustive analysis of practical applications. The U.S. Environmental Protection Agency (EPA) published a document entitled: *Planning for Flood Recovery and Long-Term Resilience in Vermont: Smart Growth Approaches for Disaster-Resilient Communities (EPA 231-R-14-003 – July 2014).* In addition to the applications discussed below, that document provides an excellent overview of flood recovery and resilience actions that can be taken at the local level. In the appendices of the document is a Flood Resilience Checklist. That appendix is included for reference in this document as Appendix E.

Plans of Conservation and Development

Communities can use the study and associated mapping to incorporate discussion of flooding other than the Federal Emergency Management Agency (FEMA) mapped flood hazard area. Plans could reference the flood susceptibility mapping and the importance of increased scrutiny on development and infrastructure siting in areas outside of the FEMA mapping that share flood risk factors in common. The susceptibility mapping is more granular than the FEMA mapping and includes areas outside of the FEMA mapped floodplain. The FEMA mapping program typically only studied sub-watersheds greater than one square mile. The focus was on developed areas and those where development was anticipated at that time. Many areas were purposefully not mapped by FEMA to save limited resources or because development was not expected to occur there at the time of mapping, which in most cases was more than a decade ago. A complete listing, by water body, including dates studied and methods used can be found in Sections 1.0 and 2.0 of the February 6, 2013 FEMA Flood Insurance Study report for Middlesex County, Connecticut. The susceptibility mapping created by this project includes all land area in the region. For the towns of Lyme and Old Lyme, the same listings are available in the same sections of the August 5, 2013 FEMA Flood Insurance Study report for New London County, CT.

Discussion of the factors that contribute to flooding, as identified in the report, can be used to guide policy that will ensure that future activities are not making those factors contribute more (e.g. increases in impervious surfaces). Areas outside of the FEMA mapped floodplain could be noted for further evaluation and, if warranted, conservation.

In general, POCDs can use the data to encourage review of subdivision and development review policies to incorporate flood susceptibility outside of the FEMA floodplain. POCDs can reference Hazard Mitigation Plans for more specific strategies and actions. Use of climate change projections to compare how current return periods are projected to change. For example, Fig. 3-14 (above) shows that today's 100-year 24-hour rainfall event will become a ~53-year event in 2045, while Fig. 3-15 (above) shows that it will become a ~45-year event in 2075. More drastic changes are seen for more frequent events. For example, a current 20-year event will become a ~12-year event by 2045 and a ~8-year event by 2075. Thus, one method of assessing the practical impacts from these changes is by determining which present-day recurrence intervals (e.g. 100-year) are important for design standards and/or flood warning plans and building socioeconomic models of how a more frequent occurrence of such events will impact response and/or recovery costs.

Hazard Mitigation Plans

Many of the applications noted for POCDs can also be applied to Hazard Mitigation Plans (HMPs). Additionally, the following uses should be considered:

- Use flood susceptibility mapping to overlay and quantify what is at risk in areas outside of the FEMA Special Flood Hazard Area (SFHA).
- Evaluate contributing factors to determine what mitigation could be done to minimize their impacts.
- Compare and align mapped areas of susceptibility with community identified "hot-spots" of flooding.
- Use the model and mapping to prioritize mitigation actions.
- Build in a strategy to periodically update the model with new storm data or higher resolution datasets in general.
- Identify strategies to further study most impactful susceptible areas (e.g. physical models).

Zoning and Ordinances

The following are a few examples of considerations for updating zoning regulations or ordinances:

- Consider using flood susceptibility mapping to create or contribute to a flood hazard overlay zone.
- Create a future flood conditions overlay based on climate change analysis.
- Consider using flood susceptibility mapping done at a local scale to help inform some level of protection for new construction in susceptible areas not on FEMA mapping (e.g. graduated risk zones).
- Require developers to conduct further analysis of flood potential (e.g. physical models) in susceptible areas not mapped by FEMA.

Design Standards for Subdivisions and Site Plan Review

Many communities already use some or all of the techniques described below to reduce increase flood flows and volume resulting from new development. In general, development in areas identified on the susceptibility mapping should undergo additional scrutiny. If further "in-field" analysis confirms that areas outside the FEMA Special Flood Hazard Areas (SFHA) that are identified as susceptible, based on common flood risk factors, are indeed at risk, floodplain building design and development standards should be used in those areas.

- Consider using or developing a stormwater model ordinance for green infrastructure.
- Require developers to make decisions informed by future climate, and local governments to incorporate climate change into decision-making processes.
- Use Bioretention to collect stormwater runoff.
- Use permeable pavement to allow runoff to flow through and be temporarily stored prior to discharge.
- Use Underground storage systems to detain runoff in underground receptacles.
- Use retention ponds to manage stormwater.
- Use extended detention wetlands to reduce flood risk and provide water quality and ecological benefits.

Capital Improvement Planning

During the annual budgeting cycle, the results of this study could be used to:

- Assist with prioritization of stormwater improvement projects;
- Assist with decision making around siting infrastructure and public facilities; and,
- Make arguments for the funding of additional studies in identified susceptible areas.

Emergency and Evacuation Planning

Areas on the flood susceptibility mapping, particularly those that are not mapped by FEMA and which intersect with roads and bridges, should be considered when developing flood evacuation routes. Overlaying the mapping with more local transportation layers will identify areas to be further evaluated for low lying roadways.

Long Term Recovery Planning

In the event of a catastrophic flooding event, such as Hurricane Sandy, or a large dam breach, mapped areas of susceptibility could be considered in the rebuilding decision making process.

5. Summary

Flooding is one of the most severe and potentially devastating natural disasters that can occur. Awareness of areas that are currently prone and will be more prone to flooding in the future is essential to consider in short-term, as well as long-term, planning. Such awareness comes from an understanding of a combination of not only regional climatic factors, but also of non-climate factors that relate to regional and site characteristics.

A summary and conclusions from the flood susceptibility analysis can be found in Giovannettone et al. (2018). One important disclaimer about the flood susceptibility map that was developed herein is that it was created for present-day conditions and is only to be used for planning purposes. There are several prominent factors that could affect the *future* flood susceptibility map: changes in impervious area (through urbanization), a higher sea level (for coastal areas) and heavier precipitation. A *future* flood susceptibility map can be created by studying how these factors are expected to change. However, it is expected that the present-day flood susceptibility map provides an excellent relative foundation from which to consider future changes. In other words, it is logical to assume that higher-risk present-day regions will remain as higher-risk regions in the future. As part of this study an Environmental Systems Research Institute, Inc. (ESRI) geographic information system ArcGIS software map document file is available for the region's municipalities for future planning analysis containing the flood susceptibility, land use, and critical infrastructure datasets created as part of this project. Please contact the Lower Connecticut River Valley Council of Governments to obtain this data.

Regarding climatic factors affecting the LCRVR, it was found that El Niño correlates with total rainfall at Middletown and Cockaponset State Forest (significance at the 0.05% and 0.01% levels, respectively) when using a lead time of 12 months, whereas the Caribbean SST index showed stronger correlation strength at a 48-month lead time (significance at the 0.01% level for both). The strength and significance of these correlations and the fact that future 48-month precipitation could be predicted with substantial skill using statistical models based on these correlations demonstrates the potential for using such an analysis as a tool to estimate the onset and persistence of long-term extreme events. Insight into the onset and persistence of a present or future drought with a 48-month or even a 12-month lead time represents valuable information within the water resources management and agricultural sectors, for example.

Local- and regional-scale statistical analyses were also performed for the city of Hartford and for a region encompassing several Mid-Atlantic and Northeastern states, respectively, to detect changes in historical rainfall statistics over the LCRVR. Slight linear trends in the Annual Maximum Series and Peaks-Over-Threshold were identified at Hartford but were not found to be significant. In contrast, several gauges, including some within Connecticut, revealed statistically positive trends. It was also found that there were significant increases in heavy rainfall at several locations on a regional basis, but less so when looking at more frequency rainfall events. Also, even though local-scale analyses of rainfall within the LCRVR revealed no significant increase in heavy rainfall intensity and frequency at Hartford, the fact that significant regional-scale increases were identified suggests that it is likely against the odds that the LCRVR has not seen an increase in heavy rainfall activity. The contrast between the local and regional analyses is likely due to the hit-or-miss character of heavy rainfall events. An analysis of future rainfall projections was then conducted to determine how heavy rainfall will change over the LCRVR in the mid- and long-term future.

An analysis of future rainfall projections was then conducted to determine how heavy rainfall will change over the LCRVR in the mid- and long-term future using bias-corrected data from the IPCC's CMIP5 modeling experiments and the high emission scenario. Final conclusions related to future projections, in addition to the historical analysis, can be summarized as follows:

- Results from the local-scale historical analysis reveal that a significant change in heavy rainfall statistics at Hartford, which serves as a good proxy for the LCRVR, has not been detected.
- A regional-scale historical analysis did reveal that heavy rainfall events are being disproportionately influenced by climate change, as opposed to a transition to an overall wetter climate, at additional locations in close proximity to the LCRVR.
- Local future analyses revealed increases in projected mid-term (2045) and long-term (2075) Precipitation-Frequency curves at the city of Hartford for all event frequencies.
- Future analyses at Hartford also revealed that today's 100-year 24-hour rainfall event is estimated to become a ~53-year event in 2045 and a ~45-year event in 2075
- Even though the historical analysis revealed a heavier influence of climate change on less frequency events, future projections are suggesting that more drastic changes will occur for more frequent events.

These conclusions demonstrate the importance of determining which present-day recurrence intervals (e.g. 100-year) are important for land use and recovery planning, hazard mitigation, zoning, design standards and/or flood warning plans and then building socioeconomic models to show how a more frequent occurrence of such events will impact response and/or recovery costs.

6. Future Work

Projects and studies that utilize novel methods in accomplishing their final objectives typically identify several additional new directions in which to extend the work as well as additional questions that come up as a result of the analysis and final conclusions. The current project is no exception with the following list providing potential avenues for future work:

- Utilize local experts' and residents' experiences related to flooding in the region to ground-truth the 100-year flood susceptibility map that was developed in the current study.
- Maintain awareness of data collection for future events. Given the increase in forecast skill of severe floods, it may be possible for River COG to work with its neighbors/partners to make sure that any future flood inundation events are well sampled by specialized satellite and/or synthetic aperture radar missions. These would provide the horizontal resolution to significantly enhance the current model past the 30-m grid size.
- Create additional flood susceptibility maps for more frequent flood exceedance frequencies using the method used for the 100-year flood events. This is limited by the availability of satellite data during maximum inundation caused by the flood, but images for very frequent events (e.g. 5-year) should be available and would provide inundation information for floods that are considered a frequent annoyance rather than a potentially rare disaster.
- Re-run the analysis for future flood events. If and when a flood event occurs in the future over the LCRVR and resources and satellite imagery permitting, recreate a flood susceptibility map for the exceedance frequency associated with the event. The final goal would be to analyze a sufficient number of events of varying frequencies to enable interpolation of the risk factor regression coefficients for any flood event exceedance frequency.
- Test the effect of the flood risk factor 'impervious area' by performing the logistic regression while excluding the flood risk factor 'land cover'. 'Impervious area' did not show a strong correlation with flooding as indicated by the low regression coefficients in Table 2-2, while 'land cover' did show an increasing trend between the rural and urban sub-regions. One hypothesis for this result concerns the fact that 'land cover' and 'impervious area' overlap in terms of the type of information that they convey; this may affect the results in that one of these risk factors (e.g. 'land cover') drowns out the effects of the other (e.g. 'impervious area'). This hypothesis can be tested by rerunning the analysis without considering 'land cover' to determine if the contribution of 'impervious area' becomes more significant.
- Encourage the development of improved datasets related to flood risk factors that were identified as having substantial impacts on flooding in each sub-region; this would include the flood-risk factors 'elevation', 'distance to water', and 'land cover'. Improved resolutions (e.g. 30 meters to 1 meter) of each input dataset would contribute substantially to improved flood susceptibility maps at any desired exceedance frequency.
- As resources permit, flood susceptibility map(s) should be revised, which includes rerunning the analysis described in this report, as improved datasets of flood risk factors become available.

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APPENDIX A: Input Data Metadata

***Table A-1:* NA-CORDEX experiments used for this analysis. All simulations were conducted using 11-km resolution modeling and RCP8.5 scenario boundary conditions.**

Modeling Agency Responsible for Global Climate Model	Global Climate Model (Boundary)	Regional Climate Model
Canadian Centre for Climate Modeling and Analysis (Canada)	CanESM2	CanRCM4
Geophysical Fluid Dynamics Lab (United States)	GFDL-ESM2M	RegCM4
Geophysical Fluid Dynamics Lab (United States)	GFDL-ESM2M	WRF
Met Office Hadley Centre (United Kingdom)	HadGEM2-ESM	RegCM4

APPENDIX B: NOAA Atlas 14 Heavy Precipitation Statistics for the Lower CT Region

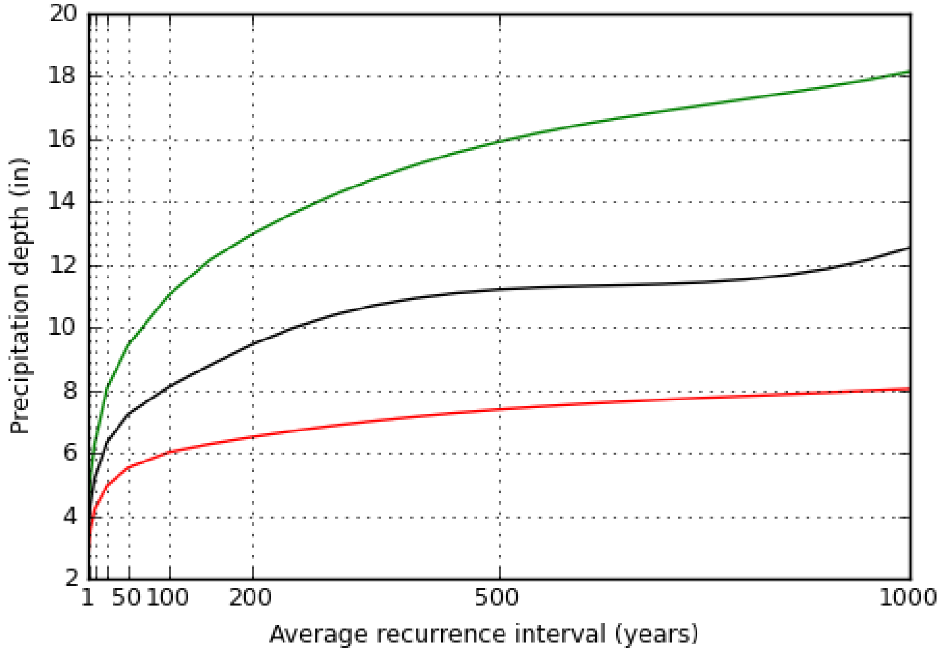


***Figure B-1:* Precipitation-frequency curves for 24-hour rainfall for a location near Middletown, CT. The black curve is the most likely estimate, while the green and red curves denote the high and low bounds using the 90% confidence level.**

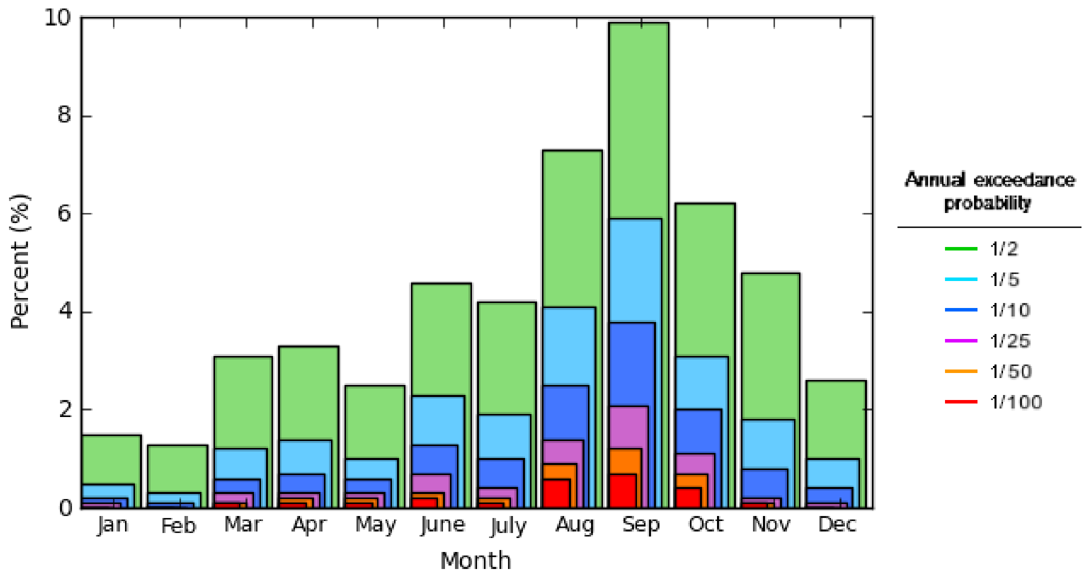


***Figure B-2:* Seasonality analysis for 24-hour precipitation for a location near Middletown, CT (same location as Fig. B-1). The percent chance of observing an event exceeding the indicated threshold is shown for the 2-, 5-, 10-, 25-, 50- and 100-year recurrence interval. Note that the late summer and fall months show the highest probabilities of occurrence.**

APPENDIX C: Climate Modeling

A substantial amount of evidence (Flato et al. 2013) exists showing that climate change has already begun to affect the distributions of atmospheric variables. Figure C-1 shows the simulation of global temperature from a complementary set of Global Climate Model experiments with (red line) and without (blue line) anthropogenic emissions of greenhouse gases (Kam et al. 2016). Note the simulations with anthropogenic emissions are in excellent agreement with historically observed temperature (black line). The modeling suggests that, at least for temperature, the separation point after which the anthropogenic-forced climate differs from its natural state occurred in the late 1970s. This provides a complication for the stationarity analysis herein, since choosing stations (even those with long records) that have limited observations after the 1970s will be less affected by climate change those with a more recent record. To address this issue, we removed stations that did not have a qualifying record after 2007, providing about 30 years of “climate-change affected” data.

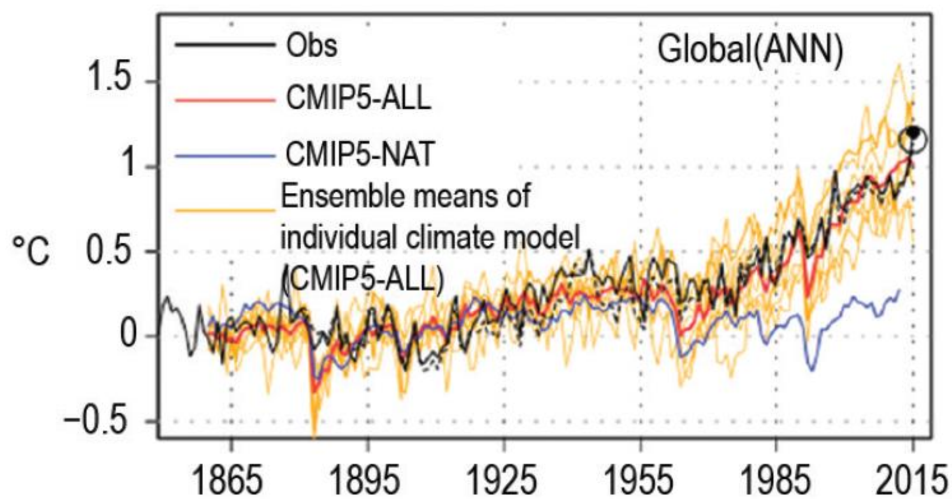
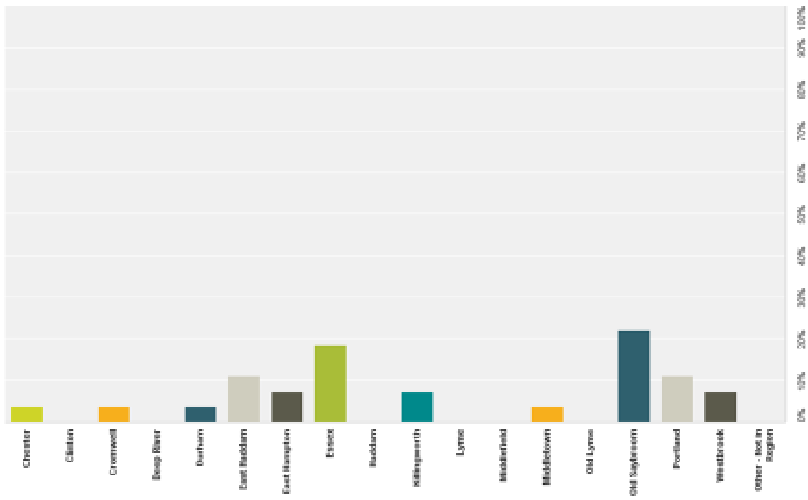


Figure C-1: ***Annual mean surface temperature anomalies (°C) for the globe. Red (CMIP5–ALL) and blue (CMIP5–NAT) curves indicate ensemble mean simulated anomalies through 2015 and 2012, respectively, with each available model weighted equally; orange curves indicate individual CMIP5–ALL ensemble members. Black curves indicate observed estimates from HadCRUT4v4 (solid) and NOAA NCEI (dotted). All time series are adjusted to have zero mean over the period 1881–19. [Reproduced from Kam et al. 2016; their Fig. 2.1(e)].***

APPENDIX D: Community and Stakeholder Survey Results

Q2: Community you are from or represent?



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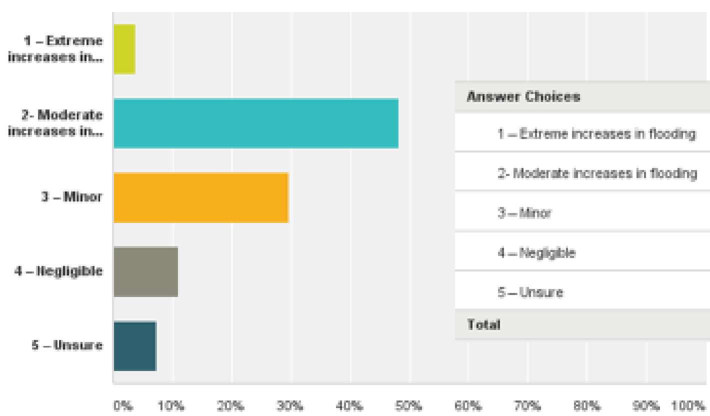
Dewberry

Q3: On a Scale of 1-5, in the last ten years, how would you rate changes in flood conditions due to high intensity rainfall events in your community?



Answer Choices	Responses	
1 – Extreme increases in flooding	3.70%	1
2- Moderate increases in flooding	48.15%	13
3 – Minor	29.63%	8
4 – Negligible	11.11%	3
5 – Unsure	7.41%	2
Total		27

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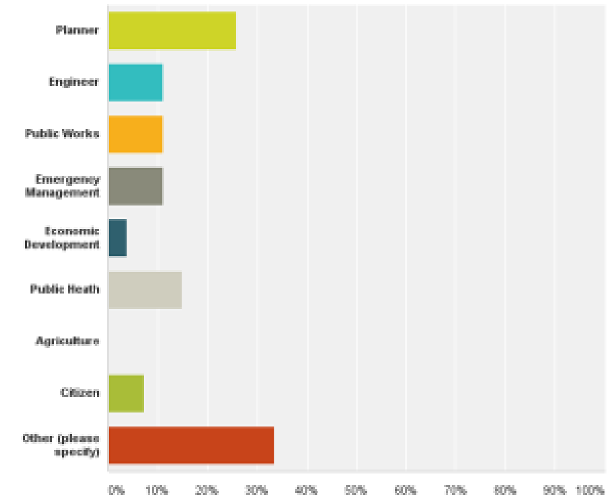
Dewberry

Q1: What is your position in your Community?



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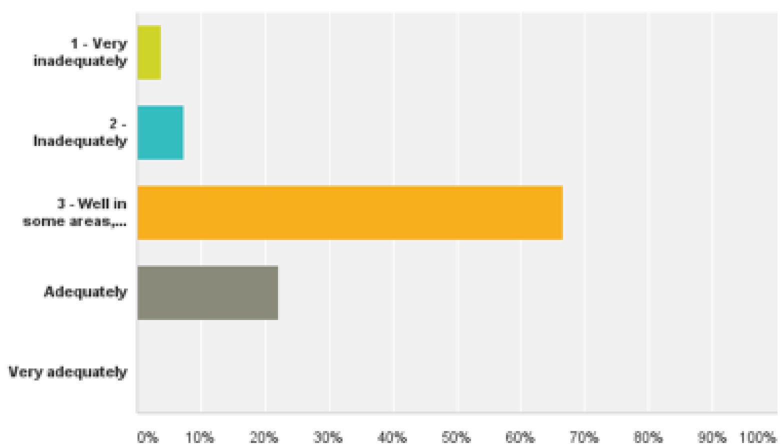
Dewberry

Q4: Overall, how would you rank your municipal storm water systems' ability to handle future storm events?



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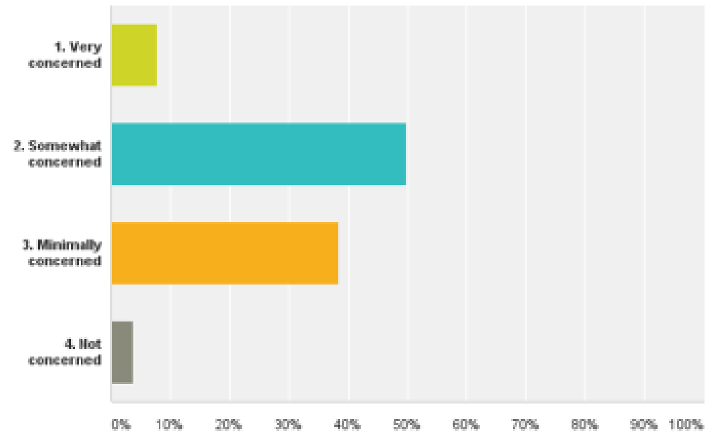
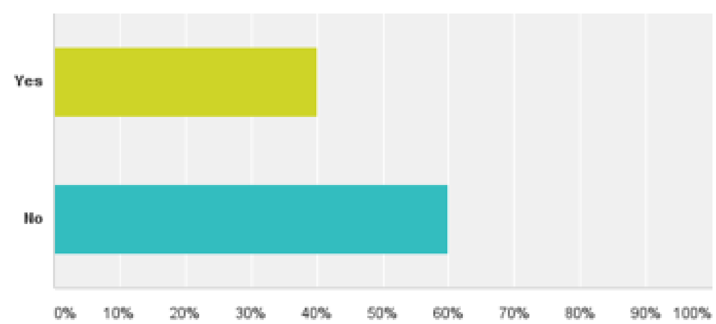
Dewberry

Q6: On a scale of 1-4, how concerned are residents in your community/region with the impacts of climate change?



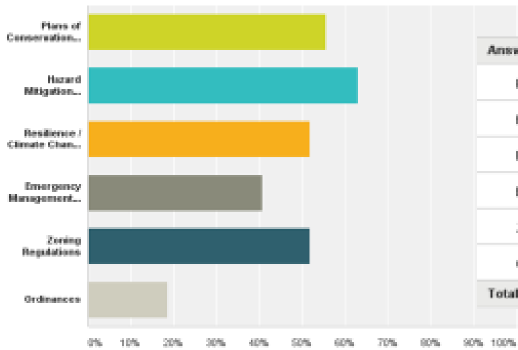
Dewberry

Q5: Do you believe that your community's Region's plans (e.g. hazard mitigation, conservation and development, emergency management, etc.) adequately address the impacts of climate change on future flooding conditions?



Dewberry

Q7: Please choose the top three planning or regulatory instruments that you believe are best suited to address future policy and implementation strategies for reducing future damage due to increased flooding as a result of climate change.



Answer Choices	Responses	
Plans of Conservation and Development	55.56%	15
Hazard Mitigation Plans	62.96%	17
Resilience / Climate Change Adaptation Plans	51.85%	14
Emergency Management Plans	40.74%	11
Zoning Regulations	51.85%	14
Ordinances	18.52%	5
Total Respondents: 27		

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Dewberry

Q8. Please list what you believe to be the most effective way to educate the public on changing hazard conditions.

#	Responses	Date
1	Articles in local papers and posting on Town websites	3/24/2017 9:17 AM
2	A community education program focusing on increasing disaster risks that includes print and social media as well as public presentations. Inclusion in the POCD of flood sensitive areas as designated by the local Inland Wetlands Commission/Agent or state designated areas..	3/23/2017 3:47 PM
3	Regulation change, public hearings, articles in publications, social media, email newsletter(constant contact)	3/22/2017 11:19 AM
4	Give power point presentations of a certain area both before and after severe weather conditions adversely affected structure and surrounding area.	3/21/2017 7:21 PM
5	Saybrook Events quarterly magazine.	3/21/2017 4:21 PM
6	Town website information; mailed brochures; emergency text broadcasts	3/21/2017 8:07 AM
7	modelling and providing overlays on GIS mapping made available on Town's website.	3/21/2017 7:27 AM
8	Reverse 911	3/20/2017 7:36 PM
9	Routine education and outreach required by the MS4 Permits (which would have been among 3 choices in answering Q #7).	3/20/2017 1:02 PM
10	mailings, internet	3/20/2017 12:43 PM
11	Small public information meetings in the high hazard areas	3/20/2017 12:41 PM

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Dewberry

Q8: Please list what you believe to be the most effective way to educate the public on changing hazard conditions.

12	Public awareness campaigns	3/20/2017 12:36 PM
13	Too much money is being wasted on projects such as this. Phone should be used to actually make a difference and not just talk about It.	3/20/2017 12:31 PM
14	Offering local workshops	3/20/2017 12:27 PM
15	A major event can go a long way, as sarcastic as that comment may be.	3/20/2017 12:10 PM
16	Not sure. Those who believe in climate/flood change seem to be attentive. The challenge is educating those who believe this is a myth and reason for higher insurance rates.	3/16/2017 2:06 PM
17	Historical photos of previous events have the most effect. 1936, 1938, 1955, 1982, 1984. Some are so young that they have never been exposed to hazardous events.	3/16/2017 11:55 AM
18	Town Website Town Meetings Outreach Info Tents at events	3/15/2017 2:38 PM
19	direct mail in simple to understand terminology	3/15/2017 10:22 AM
20	Short, easily read articles for our Events magazines and local papers. These cannot be one-off, but sustained over time b/c of the publics' short memory and attention span. Outreach to civic groups who are always looking for speakers.	3/13/2017 4:33 PM
21	Mailing/emailing followed by public information meetings	3/13/2017 3:40 PM

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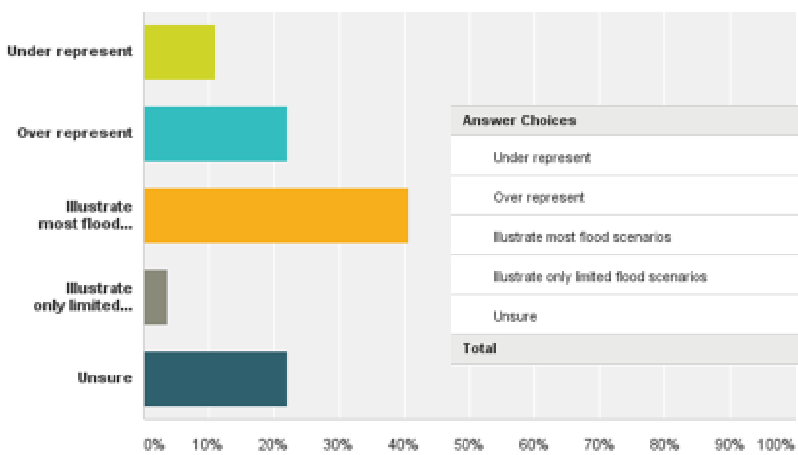
Dewberry

Q9: How do you feel the current FEMA Flood Insurance Rate Maps represent flood risk?



Answer Choices	Responses	
Under represent	11.11%	3
Over represent	22.22%	6
Illustrate most flood scenarios	40.74%	11
Illustrate only limited flood scenarios	3.70%	1
Unsure	22.22%	6
Total		27

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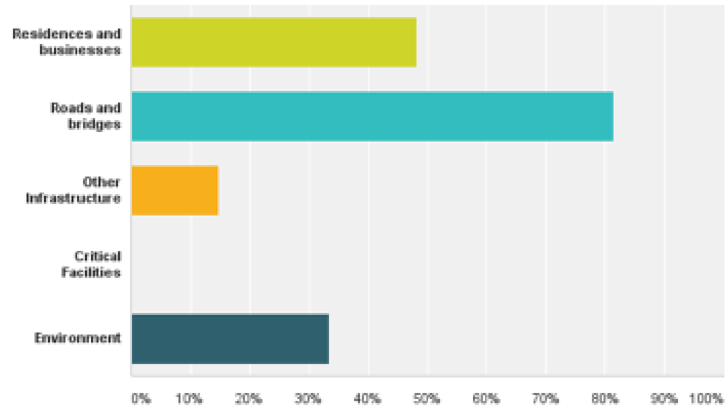
Dewberry

Q10: What assets do you believe are at most risk to flooding from increased rainfall intensity (e.g. flash, riverine, drainage flooding)?



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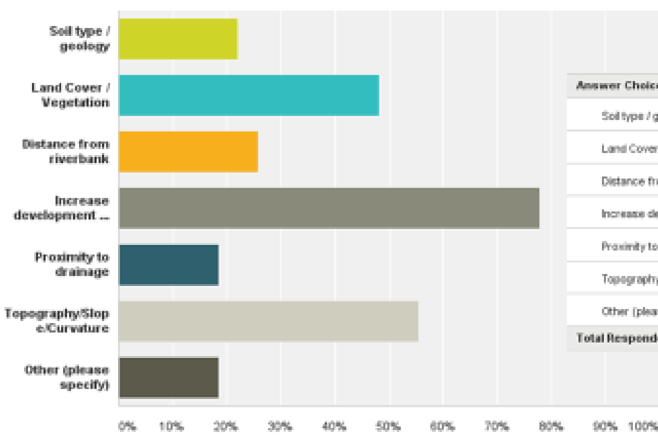
Dewberry

Q11: What factors do you think contribute the most to increase flooding from high intensity rain events?



Answer Choices	Responses	
Soil type / geology	22.22%	6
Land Cover / Vegetation	48.15%	13
Distance from riverbank	25.93%	7
Increase development / impervious surfaces	77.78%	21
Proximity to drainage	18.52%	5
Topography/Slope/Curvature	55.56%	15
Other (please specify)	18.52%	5
Total Respondents: 27		

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Dewberry

Q11: What factors do you think contribute the most to increase flooding from high intensity rain events?

#	Other (please specify)
1	Why are you asking this?
2	Dams. We have several dams in succession which if either were to fail could cause a major flooding event downstream.
3	Inadequately desinged drainage systems in some areas
4	Higher rate of intense storms
5	Cromwell has a lot of assets in low lying flood plain areas of the Ct River

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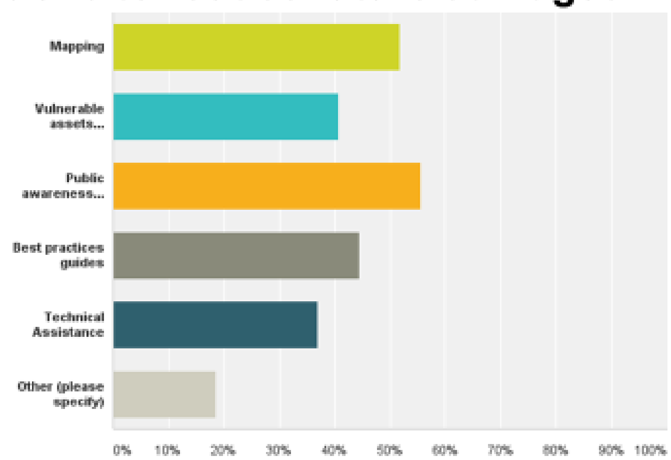
Dewberry

Q12: What tools would best assist your community/organization to engage in planning, policy or other actions to reduce future damages from flooding?



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Dewberry

Q12: What tools would best assist your community/organization to engage in planning, policy or other actions to reduce future damages from flooding?

#	Other (please specify)
1	Relocation assistance.
2	funding
3	funding for mitigation
4	Again stop the foolish waste of money on projects that just discuss change rather than actually implementing it
5	money

Q13: Opportunity to Provide Comments

#	Responses
1	Portland has experienced multiple flash flood events in our Village District/Main Street business zone as a result of high intensity rainfall events since 2011. These floods have resulted in damage to municipal, school, and commercial buildings.
2	Killingworth has damaging flooding events every few years; I'm not sure the frequency has increased. Would like to see some data on this.
3	How will you orient the staff at the local level to the results of your Study and how it can be used throughout the Region? (Please don't say: by handing it to the First Selectman at a COG meeting.)
4	We know what is needed to be able to address flooding from high intensity/short duration rainstorms, but we don't have the funds to address the needs
5	This issue could be the biggest challenge facing our shoreline towns, without much progress seen to date to deal with rise in sea level.
6	Please fix the spelling of Old Saybrook
7	it is our understanding that FEMA will be updating maps in 2018?

APPENDIX E: Flood Resilience Checklist

Appendix C: Flood Resilience Checklist

Is your community prepared for a possible flood? Completing this flood resilience checklist can help you begin to answer that question.

What is the Flood Resilience Checklist?

This checklist includes overall strategies to improve flood resilience as well as specific strategies to conserve land and discourage development in river corridors; to protect people, businesses, and facilities in vulnerable settlements; to direct development to safer areas; and to implement and coordinate stormwater management practices throughout the whole watershed.

Who should use it?

This checklist can help communities identify opportunities to improve their resilience to future floods through policy and regulatory tools, including comprehensive plans, Hazard Mitigation Plans, local land use codes and regulations, and non-regulatory programs implemented at the local level. Local government departments such as community planning, public works, and emergency services; elected and appointed local officials; and other community organizations and nonprofits can use the checklist to assess their community's readiness to prepare for, deal with, and recover from floods.

Why is it important?

Completing this checklist is the first step is assessing how well a community is positioned to avoid and/or reduce flood damage and to recover from floods. If a community is not yet using some of the strategies listed in the checklist and would like to, the policy options and resources listed in this report can provide ideas for how to begin implementing these approaches.

FLOOD RESILIENCE CHECKLIST		
Overall Strategies to Enhance Flood Resilience (Learn more in Section 2, pp. 9-11)		
1. Does the community's comprehensive plan have a hazard element or flood planning section?	☐ Yes	☐ No
a. Does the comprehensive plan cross-reference the local Hazard Mitigation Plan and any disaster recovery plans?	☐ Yes	☐ No
b. Does the comprehensive plan identify flood- and erosion-prone areas, including river corridor and fluvial erosion hazard areas, if applicable?	☐ Yes	☐ No
c. Did the local government emergency response personnel, flood plain manager, and department of public works participate in developing/updating the comprehensive plan?	☐ Yes	☐ No
2. Does the community have a local Hazard Mitigation Plan approved by the Federal Emergency Management Agency (FEMA) and the state emergency management agency?	☐ Yes	☐ No
a. Does the Hazard Mitigation Plan cross-reference the local comprehensive plan?	☐ Yes	☐ No

Planning for Flood Recovery and Long-Term Resilience in Vermont

FLOOD RESILIENCE CHECKLIST		
b. Was the local government planner or zoning administrator involved in developing/updating the Hazard Mitigation Plan?	☐ Yes	☐ No
c. Were groups such as local businesses, schools, hospitals/medical facilities, agricultural landowners, and others who could be affected by floods involved in the Hazard Mitigation Plan drafting process?	☐ Yes	☐ No
d. Were other local governments in the watershed involved to coordinate responses and strategies?	☐ Yes	☐ No
e. Does the Hazard Mitigation Plan emphasize non-structural pre-disaster mitigation measures such as acquiring flood-prone lands and adopting No Adverse Impact flood plain regulations?	☐ Yes	☐ No
f. Does the Hazard Mitigation Plan encourage using green infrastructure techniques to help prevent flooding?	☐ Yes	☐ No
g. Does the Hazard Mitigation Plan identify projects that could be included in pre-disaster grant applications and does it expedite the application process for post-disaster Hazard Mitigation Grant Program acquisitions?	☐ Yes	☐ No
3. Do other community plans (e.g., open space or parks plans) require or encourage green infrastructure techniques?	☐ Yes	☐ No
4. Do all community plans consider possible impacts of climate change on areas that are likely to be flooded?	☐ Yes	☐ No
5. Are structural flood mitigation approaches (such as repairing bridges, culverts, and levees) and non-structural approaches (such as green infrastructure) that require significant investment of resources coordinated with local capital improvement plans and prioritized in the budget?	☐ Yes	☐ No
6. Does the community participate in the National Flood Insurance Program Community Rating System?	☐ Yes	☐ No
Conserve Land and Discourage Development in River Corridors (Learn more in Section 3.A, pp. 14-19)		
1. Has the community implemented non-regulatory strategies to conserve land in river corridors, such as:		
a. Acquisition of land (or conservation easements on land) to allow for stormwater absorption, river channel adjustment, or other flood resilience benefits?	☐ Yes	☐ No
b. Buyouts of properties that are frequently flooded?	☐ Yes	☐ No
c. Transfer of development rights program that targets flood-prone areas as sending areas and safer areas as receiving areas?	☐ Yes	☐ No
d. Tax incentives for conserving vulnerable land?	☐ Yes	☐ No

FLOOD RESILIENCE CHECKLIST		
e. Incentives for restoring riparian and wetland vegetation in areas subject to erosion and flooding?	☐ Yes	☐ No
2. Has the community encouraged agricultural and other landowners to implement pre-disaster mitigation measures, such as:		
a. Storing hay bales and equipment in areas less likely to be flooded?	☐ Yes	☐ No
b. Installing ponds or swales to capture stormwater?	☐ Yes	☐ No
c. Planting vegetation that can tolerate inundation?	☐ Yes	☐ No
d. Using land management practices to improve the capability of the soil on their lands to retain water?	☐ Yes	☐ No
3. Has the community adopted flood plain development limits that go beyond FEMA's minimum standards for Special Flood Hazard Areas and also prohibit or reduce any new encroachment and fill in river corridors and Fluvial Erosion Hazard areas?	☐ Yes	☐ No
4. Has the community implemented development regulations that incorporate approaches and standards to protect land in vulnerable areas, including:		
a. Fluvial erosion hazard zoning?	☐ Yes	☐ No
b. Agricultural or open space zoning?	☐ Yes	☐ No
c. Conservation or cluster subdivision ordinances, where appropriate?	☐ Yes	☐ No
d. Other zoning or regulatory tools that limit development in areas subject to flooding, including river corridors and Special Flood Hazard Areas?	☐ Yes	☐ No
Protect People, Buildings, and Facilities in Vulnerable Settlements (Learn more in Section 3.B, pp. 19-26)		
1. Do the local comprehensive plan and Hazard Mitigation Plan identify developed areas that have been or are likely to be flooded?	☐ Yes	☐ No
a. If so, does the comprehensive plan discourage development in those areas or require strategies to reduce damage to buildings during floods (such as elevating heating, ventilation, and air conditioning (HVAC) systems and flood-proofing basements)?	☐ Yes	☐ No
b. Does the Hazard Mitigation Plan identify critical facilities and infrastructure that are located in vulnerable areas and should be protected, repaired, or relocated (e.g., town facilities, bridges, roads, and wastewater facilities)?	☐ Yes	☐ No
2. Do land development regulations and building codes promote safer building and rebuilding in flood-prone areas? Specifically:		

FLOOD RESILIENCE CHECKLIST		
a. Do zoning or flood plain regulations require elevation of two or more feet above base flood elevation?	☐ Yes	☐ No
b. Does the community have the ability to establish a temporary post-disaster building moratorium on all new development?	☐ Yes	☐ No
c. Have non-conforming use and structure standards been revised to encourage safer rebuilding in flood-prone areas?	☐ Yes	☐ No
d. Has the community adopted the International Building Code or American Society of Civil Engineers (ASCE) standards that promote flood-resistant building?	☐ Yes	☐ No
e. Does the community plan for costs associated with follow-up inspection and enforcement of land development regulations and building codes?	☐ Yes	☐ No
3. Does the community require developers who are rebuilding in flood-prone locations to add additional flood storage capacity in any new redevelopment projects such as adding new parks and open space and allowing space along the river's edge for the river to move during high-water events?	☐ Yes	☐ No
4. Is the community planning for development (e.g., parks, river-based recreation) along the river's edge that will help connect people to the river AND accommodate water during floods?	☐ Yes	☐ No
5. Does the comprehensive plan or Hazard Mitigation Plan discuss strategies to determine whether to relocate structures that have been repeatedly flooded, including identifying an equitable approach for community involvement in relocation decisions and potential funding sources (e.g., funds from FEMA, stormwater utility, or special assessment district)?	☐ Yes	☐ No
Plan for and Encourage New Development in Safer Areas (Learn more in Section 3.C, pp. 26-27)		
1. Does the local comprehensive plan or Hazard Mitigation Plan clearly identify safer growth areas in the community?	☐ Yes	☐ No
2. Has the community adopted policies to encourage development in these areas?	☐ Yes	☐ No
3. Has the community planned for new development in safer areas to ensure that it is compact, walkable, and has a variety of uses?	☐ Yes	☐ No
4. Has the community changed their land use codes and regulations to allow for this type of development?	☐ Yes	☐ No
5. Have land development regulations been audited to ensure that development in safer areas meets the community's needs for off-street parking requirements, building height and density, front-	☐ Yes	☐ No

Planning for Flood Recovery and Long-Term Resilience in Vermont

FLOOD RESILIENCE CHECKLIST		
yard setbacks and that these regulations do not unintentionally inhibit development in these areas?		
6. Do capital improvement plans and budgets support development in preferred safer growth areas (e.g., through investment in wastewater treatment facilities and roads)?	☐ Yes	☐ No
7. Have building codes been upgraded to promote more flood-resistant building in safer locations?	☐ Yes	☐ No
Implement Stormwater Management Techniques throughout the Whole Watershed (Learn more in Section 3.D, pp. 27-31)		
1. Has the community coordinated with neighboring jurisdictions to explore a watershed-wide approach to stormwater management?	☐ Yes	☐ No
2. Has the community developed a stormwater utility to serve as a funding source for stormwater management activities?	☐ Yes	☐ No
3. Has the community implemented strategies to reduce stormwater runoff from roads, driveways, and parking lots?	☐ Yes	☐ No
4. Do stormwater management regulations apply to areas beyond those that are regulated by federal or state stormwater regulations?	☐ Yes	☐ No
5. Do stormwater management regulations encourage the use of green infrastructure techniques?	☐ Yes	☐ No
6. Has the community adopted tree protection measures?	☐ Yes	☐ No
7. Has the community adopted steep slope development regulations?	☐ Yes	☐ No
8. Has the community adopted riparian and wetland buffer requirements?	☐ Yes	☐ No