CLIMATE RISK ASSESSMENT

Leominster, Massachusetts

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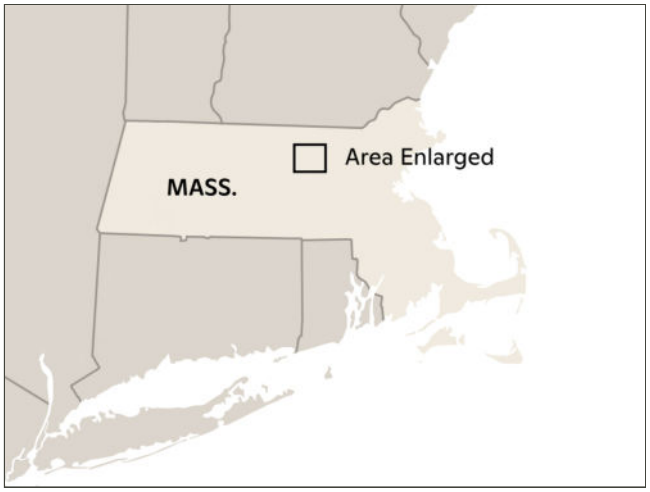
Woodwell Climate Research Center

Introduction

The impacts of climate change on the frequency and severity of physical hazards are putting many communities at risk. As the threat of climate change grows, so too does the need for accessible information, tools, and expertise to support climate-resilient decision making across multiple scales, from communities to countries. Woodwell Climate Research Center believes there is a need to localize and customize climate risk assessments. This information is critical for local government leaders as they make planning decisions, but it is not available to all communities. Woodwell believes that this science should be freely and widely available. To address this gap, Woodwell works with communities across the world, including Leominster, MA, to provide community climate risk assessments, free of charge.



Results summary

As a result of climate change, flood risk is projected to increase for Leominster. The probability of the historical 100-year rainfall event, a useful indicator of flood risk, is expected to almost triple by mid-century and be more than five times as likely by the end of the century. Streamflow for the North Nashua River is also estimated to rise throughout this century with an increase of 12.2% by 2050 and an additional 12.5% by 2080. Both increases in streamflow and heavier rainfall will translate into greater flood depths and extent for Leominster. The vulnerability of Leominster's stormwater system was evaluated under the present and future 100-year rainfall event. Here we present our findings on extreme precipitation and flooding to help Leominster in its plans to create a more resilient future for all residents.

Extreme rainfall

The Fifth National Climate Assessment shows that the U.S. Northeast region has already seen a 60% increase in annual precipitation since the 1950s, the largest in the U.S., occurring from the heaviest 1% of events.[1] Future warming is expected to continue this trend of intensification, meaning more frequent and severe rainfall events. Here we use localized future precipitation data from downscaled global climate models to calculate the change in probability of extreme rainfall events. A detailed explanation of the precipitation data processing can be found in the methodology section of this document.

[1] Marvel et al. (2023). Ch. 2. Climate trends. In: *Fifth National Climate Assessment*. Crimmins, A.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA. https://doi.org/10.7930/NCA5.2023.CH2

In Table 1, we show the changes in the return period of the present-day (2000-2020) 100-year rainfall event for mid-century (2040-2060) and late-century (2070-2090). By mid-century, the present-day 100-year event will occur with a return period of 1-in-37. By late-century, the present-day 100-year event will become a 1-in-19 year event.

According to the National Atlas 14 published by the National Oceanic and Atmospheric Administration (NOAA), the 100-year rainfall amount, based on present-day rainfall records, for Leominster is 7.3 inches (185 mm).[2] For reference, the present-day annual average rainfall for Leominster is 45.2 inches (1148 mm).[3] By mid-century, the 100-year amount will increase to 8.8 inches (224 mm) and by late-century this will further rise to 10.4 inches (264 mm; Table 1).

	Present	**2040-2060**	**2070-2090**
Return Period (yr)	1-in-100	1-in-37	1-in-19
100-Year	7.3 in (185 mm)	8.8 in (224 mm)	10.4 in (264 mm)

Table 1: Mid and Late-21st Century Change in Historical 100-Year Return Period and Rainfall. The mean future return period in years and rainfall amounts in inches and millimeters for Leominster of the present-day, 2040–2060, and 2070–2090 100-year rainfall events.

Flooding

For a detailed explanation of the flood model input data and flood modeling procedures, please refer to the methodology section of this document.

Flood extent comparison

Before estimating future flood risk, we compare the present-day flood risk results against the Federal Emergency Management Agency (FEMA) flood maps as a validation exercise. FEMA maps are not ground truth data, but it is useful to compare various model results given the lack of appropriate reference data. Figure 1 shows the differences and similarities between FEMA's estimate and Woodwell's estimate of the 100-year flood extent for the Leominster, MA region. Areas where only FEMA predicts flood risk are shown in green, areas where only Woodwell predicts flood risk are shown in red, and areas where both predict flood risk are shown in purple. Several patterns emerge when comparing the extents visually. The risk along the Nashua River estimated by FEMA is greater than Woodwell estimates in some locations, in particular the Fitchburg Regional Airport and to a lesser extent just south of the airport along Highway 2 and further south near the Leominster Connector. The higher estimate by FEMA has previously been documented in Evaluation of Flood Plain of North Nashua River Adjacent to Fitchburg Easterly Wastewater Treatment Facility by Wright-Pierce. Their research indicated that the 100-year streamflow value used in the flood insurance studies was highly overestimated. The original FEMA maps only used one gauge near the southern boundary of Leominster. A second gauge was added upstream of Leominster but it did not have enough data to be used in the FEMA maps. As more data has been collected, it was discovered the 1936 flood of record was actually a 200-year event, but the 100-year streamflow values used by FEMA exceeded this 1936 event. The most recent FEMA report has updated the streamflow values[4]; however the flood zones outside of the Fitchburg Easterly Wastewater Treatment Facility have not been updated. Further information can

[2] NOAA calculates extreme rainfall frequencies with all available station data.

[3] The period of record is 1998 through 2025. For more information: https://www.weather.gov/wrh/Climate?wfo=box

[4] *Flood Insurance Study Worcester County, Massachusetts Volume 2 of 12*. Federal Emergency Management Agency. July 8, 2025. Flood Insurance Study Number 25027CV002D

be found in the streamflow methodology section. Finally, FEMA shows no flood risk from pluvial (rainfall-induced) flooding, while Woodwell demonstrates extensive pluvial areas are vulnerable to flooding such as between Highway 12 (Central Street) and Mechanic Street/Leominster Connector. This is because FEMA does not account for pluvial flooding.

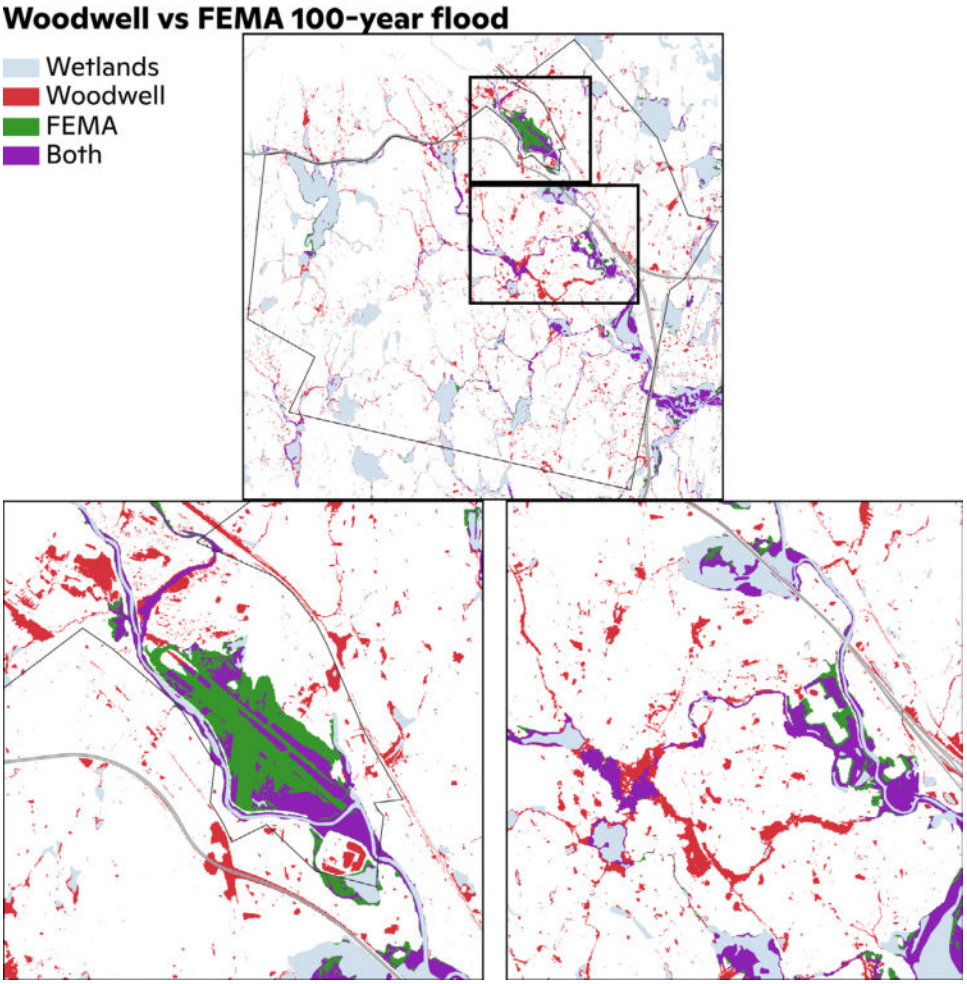


Figure 1: Woodwell vs FEMA 100-Year Flood. The flood extent comparison between Woodwell's flood model results and the current FEMA flood maps for Leominster, MA. Areas where only FEMA predicts flood risk are shown in green, areas where only Woodwell predicts flood risk are shown in red, and areas where both predict flood risk are shown in purple. The Woodwell data shows the maximum extent based on both the 100-year pluvial/riverine floods. Areas boxed in the top map are shown at the zoomed in level in the bottom two panels. The bottom left panel shows the Fitchburg Regional Airport and the bottom right map is downstream of Rockwell Pond over to Whitney Field Mall.

Present and Future Flood Risk

The primary flood risk in Leominster, MA is pluvial flooding. In Figure 2, we show the extent of the 100-year flood from both streamflow and rainfall for Leominster. Pluvial flooding risk exists downstream of Rockwell Pond along Monoosnoc Brook. Peak flood amounts in this area near the brook exceed 6.6 ft (2m) while the surrounding area ranges from 1.6 ft to 3.3 ft (0.5m–1m). Flooding around Whitney Field Mall and Commercial Road is also substantial with similar values of up to 3.3 ft (1m). Commercial Road along Whitney Field Mall was flooded during the September 2023 heavy rainfall event as well.[5]

[5] Leominster Emergency Flooding: Looking Upstream, Learning Downstream. https://leominsterfloodsolutions-bscgroup.hub.arcgis.com

While outside the city limits of Leominster, the Fitchburg Municipal Airport was included in this study due to its regional influence. While we show less flooding than FEMA, the airport is still substantially flooded and should be taken into account for future planning. We mask wetland areas to focus the analysis on locations where human life and property are at risk.

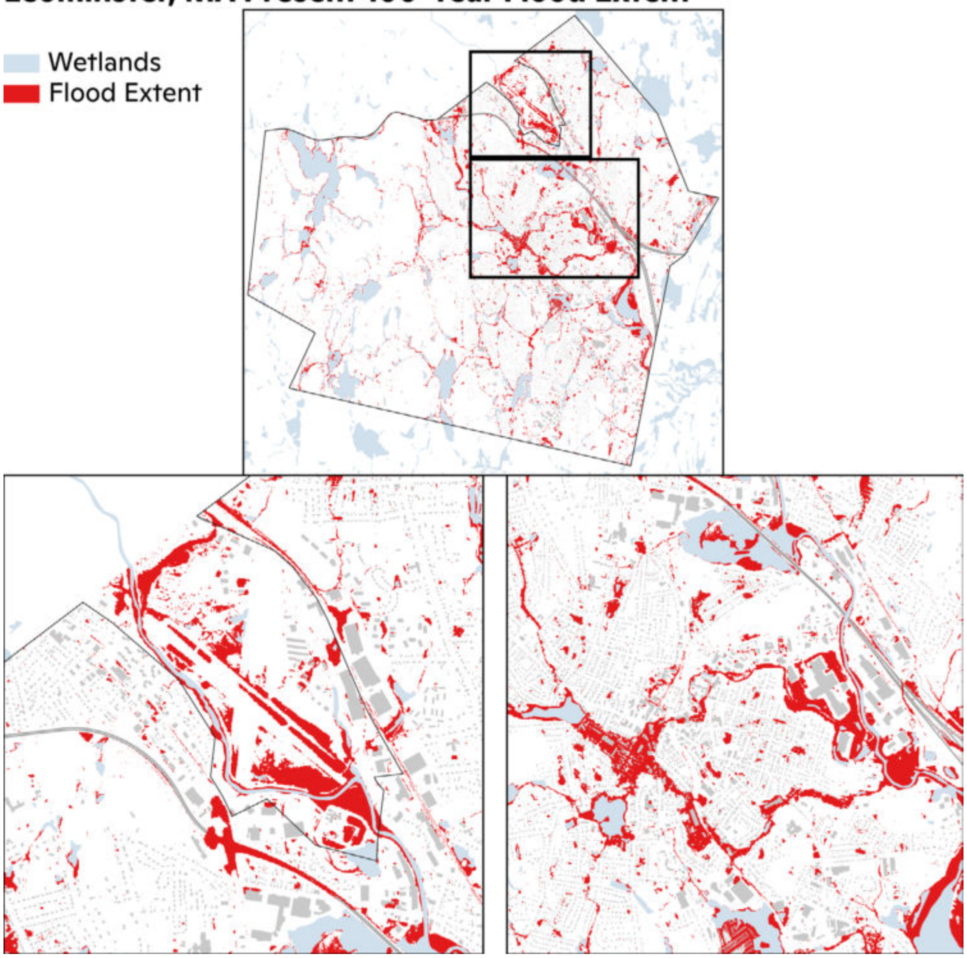


Figure 2: Present-Day 100-Year Flood. The flood extent, quantified as having a depth of at least 0.5 ft (0.15 m), for Leominster, MA. The maximum extent from the 100-year pluvial/riverine flood is shown. Areas boxed in the top map are shown at the zoomed in level in the bottom two panels. The bottom left panel shows the Fitchburg Regional Airport and the bottom right map is downstream of Rockwell Pond over to Whitney Field Mall.

Future flood risk is primarily driven by increased rainfall and not from increased streamflow along the North Nashua River. The largest changes in extent, highlighted in Figure 3, are downstream of Rockwell Pond along the Monoosnoc Brook (this is purely from rainfall and not streamflow) and Whitney Field Mall. This change in pluvial flood risk is due to projected increases in rainfall between 1.5 inches to 3.1 inches (38-69 mm) from the present-day period, as shown in Table 1. The riverine flood extent is impacted by an increase of streamflow (12.2% increase by 2050 and an additional 12.5% by 2080)[6] on the North Nashua River. We also present several flood risk metrics in Table 2. Presently, 9.5% of the structures in Leominster are vulnerable to the 100-year rainfall or streamflow event. That number increases to just over 10% by mid-century and then to

[6] Olson, S.A., Shabestanipour, G., Lamontagne, J., & Steinschneider, S. (2024). *Characterizing future streamflows in Massachusetts using stochastic modeling—A pilot study.* U.S. Geological Survey Scientific Investigations Report 2023–5134, 19p. https://doi.org/10.3133/sir20235134

just over 11% by late-century. The average flood depth in Leominster has a minor increase of 0.4 ft (0.12 meters) through the 21st century, while the area flooded increases by about 275 acres by late-century, representing roughly a 1.5% increase in area flooded.

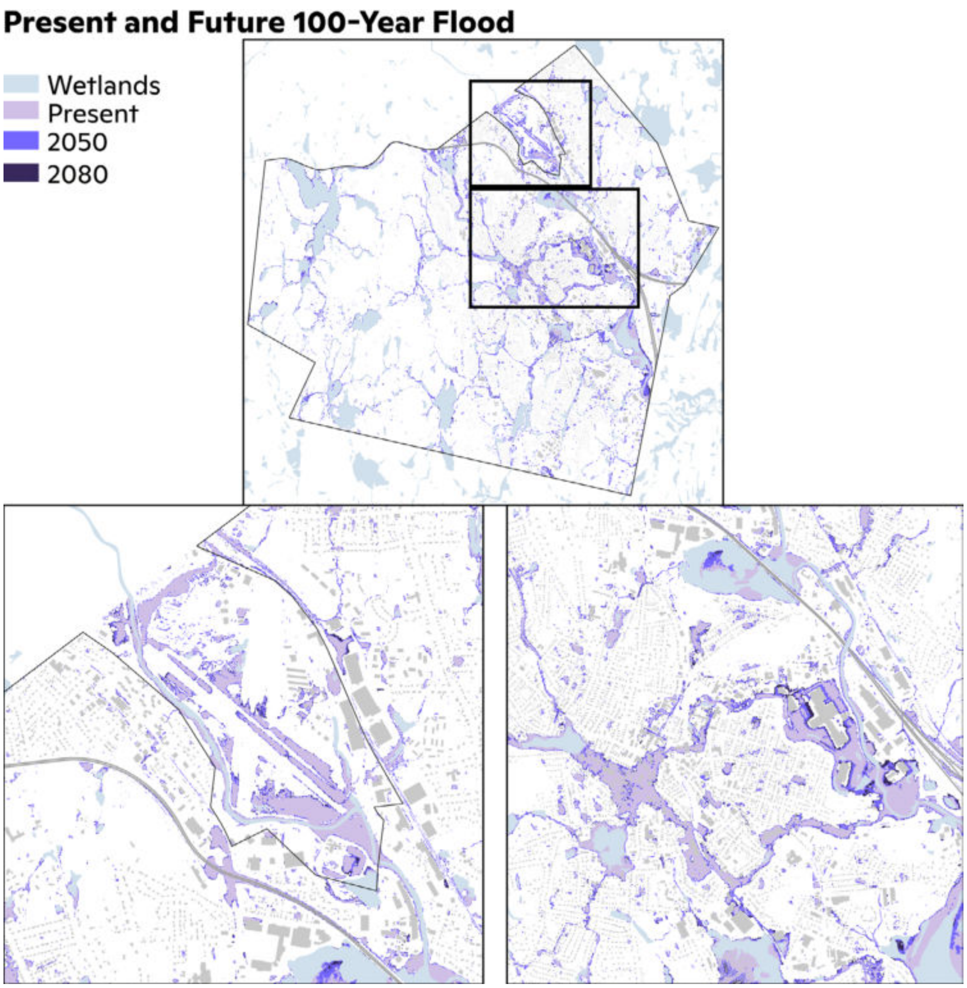


Figure 3: Present-Day and Future 100-Year Flood Leominster, MA. The flood extent, quantified as having a depth of at least 0.5 ft (0.15 m), for Leominster, MA. The maximum extent for the 100-year pluvial/riverine flood is shown. Areas with increased future extent are boxed in the top map, and the bottom left panel shows the Fitchburg Regional Airport and the bottom right map is downstream of Rockwell Pond over to Whitney Field Mall.

	Present	2040-2060	2070-2090
Area Flooded	1,193 acres (6.7%)	1,345 acres (7.6%)	1,470 acres (8.3%)
Average Depth	2.5 ft (0.76 m)	2.7 ft (0.82 m)	2.9 ft (0.88 m)
Structures Flooded	1,417 (9.5%)	1,536 (10.3%)	1,651 (11.1%)

Table 2: Flood Risk Metrics for Mid and Late-21st Century in Leominster. The acres of land area (excluding wetlands; and percent of total non-wetland area) flooded and the number of buildings (and percent of total structures) flooded for Leominster of the present-day, 2040–2060, and 2070–2090 100-year rainfall and streamflow events.

Stormwater System Vulnerability

In addition to flood extents, an analysis of the flood model results for the Leominster stormwater system was conducted to identify bottlenecks in the system. Any manholes or catch basins (sometimes referred to as drainage basins) that overflowed during the simulation were considered flooded. Conduits (pipes) that are capacity-limited (also referred to as at-capacity) were also identified. Capacity-limited is defined as when flow entering the pipe is greater than what the conduit can convey. We show capacity-limited pipes to identify any pipes that may be undersized or undersloped. These pipes may be responsible for causing flooding or upstream backwater conditions to occur at manholes or catch basins. Such pipes would be good starting points when investigating where to perform stormwater system upgrades.

Leominster's stormwater system shows high spatial distribution in the hot spots of vulnerability to the 100-year rainfall event. In Table 3, we show the number and percentage of manholes and catch basins flooded and capacity-limited conduits for the present-day, 2040–2060, and 2070–2090 100-year events. In Figure 4, we show the locations of concentrations of manholes and catch basins flooded as a heat map as well as which conduits are capacity-limited. During the present-day 100-year rainfall event, 50.8% of all conduits in Leominster's stormwater system are capacity-limited. From the present to the late-21st century, the amount of capacity-limited conduits will increase by 6%. The percentage of manholes and catch basins flooded is smaller compared to the conduits, but a similar upward trend is expected with 33.9% of the catch basins and 21.2% of the manholes flooded by the late-21st century. The difference in proportion of manholes/catch basins flooded and conduits at-capacity indicates that the stormwater system is able to reduce street flooding even when the stormwater pipes are filled. We identified several hot spots of stormwater flooding throughout Leominster. These include along Monoosnoc Brook downstream of Rockwell Pond, the intersection of Highway 2 and 12, and the area around the Whitney Field Mall.

It is important to note that we show all conduits that are capacity-limited regardless of the duration they were capacity-limited during the simulation. The vast majority of conduits in the present time period that were at-capacity (67.7%) spent only 36 seconds in a limited flow state. We include these conduits in the flooding metrics to give a system-wide perspective on the capacity of the stormwater system.

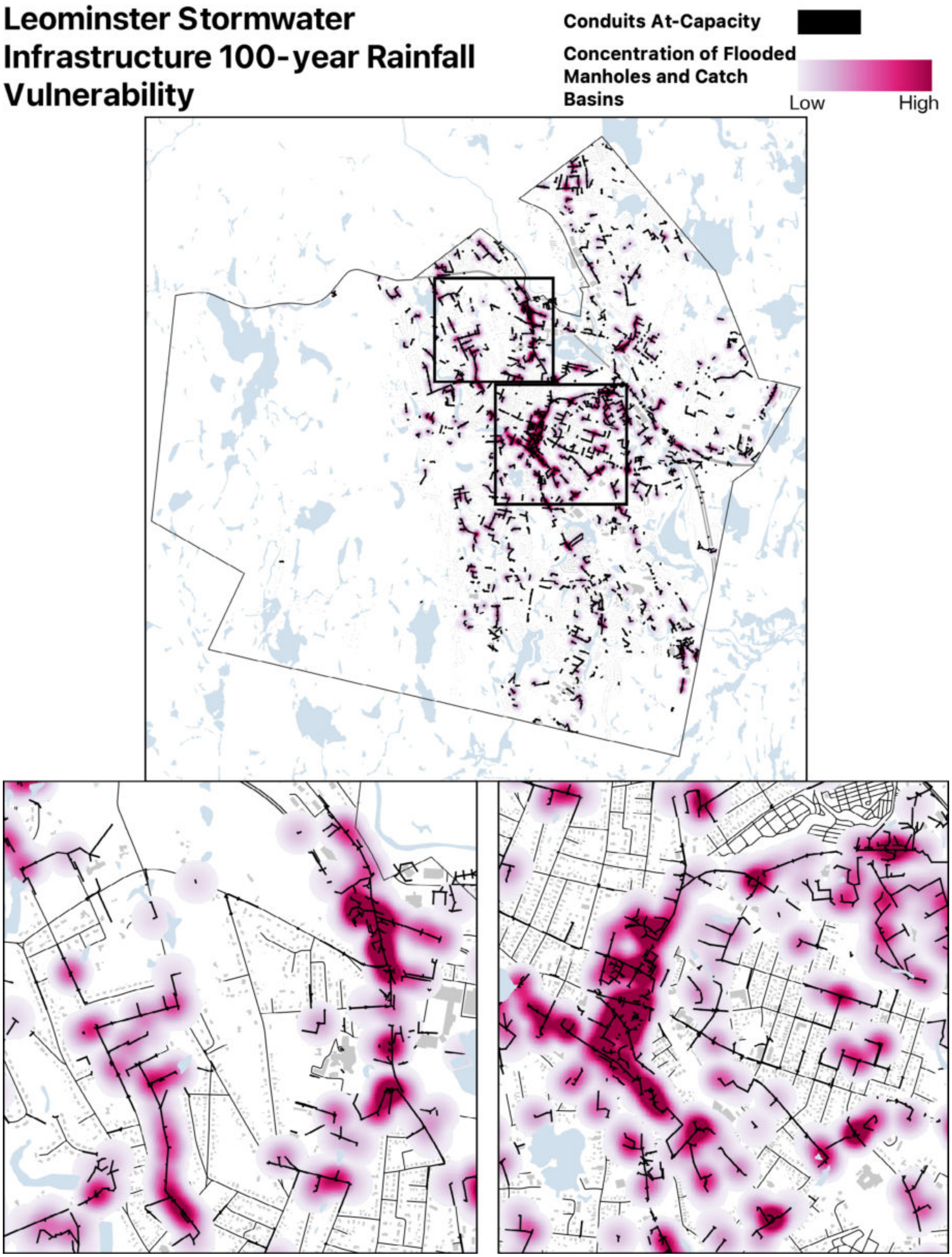


Figure 4: Leominster Stormwater System Flooding Heat Map. The concentration of flooded manholes and catch basins shown as a heat map for the present-day 100-year rainfall event. Areas with no flooded manholes or catch basins are shown in white. Capacity-limited conduits are shown in black. Areas boxed in the top map are shown at the zoomed in level in the bottom two panels. The bottom left panel shows the area just southwest of the Fitchburg Regional Airport, while the bottom right is downstream of Rockwell Pond over to Whitney Field Mall.

	Present	2040-2060	2070-2090
Manholes	630 (16.6%)	735 (19.3%)	807 (21.2%)
Catch Basins	1,538 (25.9%)	1,815 (30.6%)	2,014 (33.9%)
Conduits	5,481 (50.8%)	5,853 (54.2%)	6,143 (56.9%)

Table 3: Leominster Stormwater System Flooding. The number, and percentage of total, flooded manholes and catch basins and capacity-limited conduits for the present-day, 2040–2060, and 2070–2090 100-year rainfall event.

Conclusion

Leominster is currently at risk from flooding, primarily from rainfall, and this exposure will only increase under climate change. The results presented in this study were compared to FEMA's flood maps, revealing significant discrepancies primarily due to the exclusion of pluvial flooding in FEMA's analysis and overestimation of the North Nashua River. Our findings show an expected increase in the frequency and intensity of heavy rainfall with the probability of the present-day 100-year rainfall event to be nearly three times as likely by the mid-21st century and just over five times as likely by the end of the century. Leominster's stormwater system will also face greater stress as rainfall intensifies with over 21% of manholes and nearly 34% of catch basins flooding by the late-21st century. This report provides insight into the vulnerability of the city of Leominster, where an increasing number of buildings and areas will be exposed to flood waters by the end of the century. Lastly, the 100-year streamflow of the North Nashua River is estimated to increase by 12.2% by 2050 and an additional 12.5% by 2080.

Methodology

To simulate flood risk we use the LISFLOOD-FP v8.1 flood model (LISFLOOD-FP developers, 2022; Shaw et al., 2021). LISFLOOD-FP is a two-dimensional raster hydraulic model that solves all terms of the shallow water equations. LISFLOOD-FP has been extensively used from the river reach scale to continental simulations and we refer the reader to Shaw et al. (2021) for a detailed explanation of LISFLOOD-FP.

All flood model results show flooding above 15 cm (~0.5 ft) as this is an average curb height and any flooding above this threshold would likely result in flood damages. All areas that are wetland and permanent water cover are as determined by MassDEP Dataset (https://www.mass.gov/info-details/massgis-data-massdep-wetlands-2005).

Three time periods were used for this study: 2000-2020 (also referred to as present-day), 2040-2060, and 2070-2090. These time periods can also be interpreted as warming levels in the context of climate policy. The 2000-2020, 2040-2060, and 2070-2090 periods correspond to 1, 2 and 3 degrees Celsius of warming respectively. For each time period, a pluvial (rainfall) and riverine (streamflow) flooding run were performed. We combine the two runs by taking the maximum depth for each pixel across the two model runs unless otherwise noted.

Any analysis involving structures used the MassGIS Data: Building Structures (https://www.mass.gov/info-details/massgis-data-building-structures-2-d).

The following are the coupled LISFLOOD-FP and SWMM inputs:

1 Rainfall

A | Historical rainfall

The 24-hour 1-in-100 year rainfall event was used from NOAA Atlas 14 (NA14) point precipitation frequency estimates for Leominster, MA (Perica et al., 2015, revised 2019). The temporal distribution, also from NOAA Atlas 14, of the 24-hour rainfall is taken from the combined cases of the four quartiles and uses the 90% cumulative probability.

B | Future rainfall

CMIP6 climate model data were bilinearly interpolated to a 1-km grid and then bias-adjusted using phase 3 of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) version 2.5 methodology (ISIMIP3BASD v2.5) (Lange, 2019; Lange, 2021). High-resolution, 1-km Daymet reanalysis data (Thornton et al., 2022) were selected as the observation dataset for bias adjustment. We utilize a nonstationary (NS) approach to estimate future-projected extreme rainfall. In the NS approach, precipitation estimates are calculated for the entire time period (i.e., 1971-2100) using a temporal parameter to represent changes in extreme precipitation through time. NOAA recommends using a NS approach since it considers the whole time series in addition to any trends in the data, offering a more robust analysis and more stable estimate of future extreme precipitation in a changing climate. The NS approach is better suited for engineering applications as future relative changes are more realistic compared to a quasistationary approach. We use a regional fitting method to estimate the parameters of the Generalized Extreme Value (GEV) distribution. For each target pixel, a 40-mile radius is used to capture the annual maxima of the surrounding pixels. Each pixel's annual maxima is given a weight using a triweight kernel function based on distance (e.g., pixels ≥ 40 miles have zero weight). The log-likelihood function of the GEV distribution is then minimized with the Nelder-Mead algorithm using the annual maxima and pixel weights to estimate the GEV parameters. The beta distribution of penalized coefficients ranging between -0.5 and 0.5 is used to constrict the shape parameter as specified by NOAA.

To estimate future daily precipitation frequency estimates (PFEs), the biases (ratio) between the baseline period and the NA14 daily PFEs are calculated and then multiplied by the future climate model daily PFEs. We assume the daily temporal distribution of rainfall does not change in the future so we continue the use of the historical temporal distribution.

2 Digital Elevation Model

The 2021 USGS Lidar DEM: Central Eastern Massachusetts was used to download the DEM files for Leominster, MA. The resolution of the raw data was 0.5m. The final DEM resolution was set to 3m to allow for faster model run times with the stormwater system being incorporated. We did also remove what appears to be a quarry north of Highway 2, just outside of the northeast city limits. This was done to fix a model instability that the quarry was creating.

3 Friction coefficients

Friction coefficients, or Manning N values, were determined based on the land cover type of the area. The 2019 land cover was used for this from the National Land Cover Database (NLCD). Based on each classification of land cover, an associated friction coefficient is provided. See table here: https://rashms.com/wp-content/uploads/2021/01/Mannings-n-values-NLCD-NRCS.pdf

4 Infiltration

To calculate soil infiltration rates, the USDA Soil Survey Geographic Database (SSURGO) for Massachusetts was used to obtain the soil hydrologic groups. These hydrologic groups have defined infiltration rates depending on the type of soil. Infiltration values per hydrologic group were used from Musgrave (1955). These rates in combination with the 2023 NLCD impervious surface percentages were used to compute more accurate infiltration rates. The impervious surfaces take into account built-up areas where rainfall will not be able to infiltrate. We do not incorporate the impact of stormwater systems to convey runoff from streetscapes.

5 Streamflow

We use the FEMA Flood Insurance Study for Worcester County, MA Volume 2 of 12 to obtain the 100-year streamflow values for the northern boundary of the domain.[7] For the North Nashua River, USGS gauge at Fitchburg, MA (No. 01094400), a streamflow value of 6,650 ft^3/s is put into the model. Other studies have shown that previous FEMA reports have values substantially higher in flow, but work by Wright-Pierce 2015, showed those values too high in comparison to the 1936 flood of record. While the streamflow values have been updated, it does seem that the flood zones FEMA provides have only been updated with regard to the Fitchburg Easterly Wastewater Treatment Facility and not the surrounding areas, such as the Fitchburg Regional Airport. Our modeling effort produces a flood zone similar to that produced by Wright-Pierce using the new streamflow value FEMA provides, which is also very similar to the estimated values by Wright-Pierce.

For future streamflow, we used estimated values described by Olson et al. (2024). A study specific to the North Nashua River was not discoverable, so this study which

[7] *Flood Insurance Study Worcester County, Massachusetts Volume 2 of 12*. Federal Emergency Management Agency. July 8, 2025. Flood Insurance Study Number 25027CV002D

focuses on the Squannacook River watershed that drains into the main branch of the Nashua River was used as an estimate for the North Nashua River. The tables provided in this paper point to a 12.2% increase in streamflow values for 2050 and a 24.7% increase from present-day to 2080, so an additional 12.5% increase from 2050. It should be noted that the paper provided estimates for 2070 and 2090, so the values from 2070 were used to avoid interpolating future projections. Like our 21-year time span, 2070-2090, the authors use a 30-year average for each target decade, so using 2070 streamflow values in this scenario gives a good estimate of future risk. This means a streamflow value on the North Nashua River of 7,461 ft^3/s and 8,293 ft^3/s for 2050 and 2080, respectively.

Methodology references

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Cover: Aerial view of a city section. / photo by Nick Allen, CC BY-SA 4.0

Above: Monument Square. / photo by Daderot, CC0 1.0 Universal

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