CLIMATE RISK ASSESSMENT

Chicopee, Massachusetts

NOVEMBER 2024

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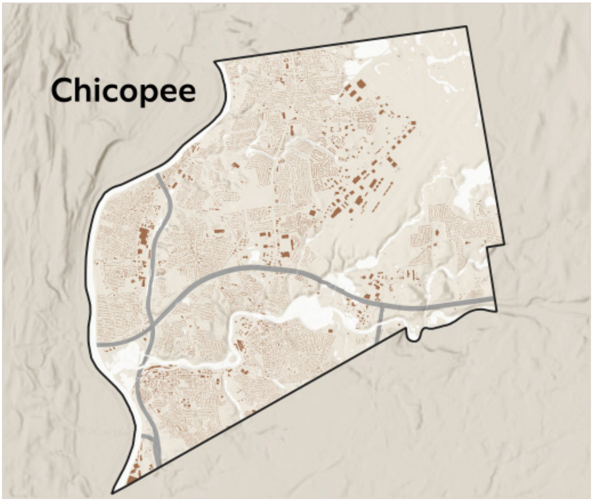
Woodwell Climate Research Center

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 Chicopee, 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 Chicopee. The probability of the historical 100-year rainfall event, a useful indicator of flood risk, is expected to almost double by midcentury and be more than twice as likely by the end of the century. Streamflow for the Connecticut and Chicopee Rivers is also projected to rise throughout this century with an increase of 9% by 2050 and 5% by 2070. Both increases in streamflow and heavier rainfall will translate into greater flood depths and extent for Chicopee. The vulnerability of Chicopee'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 Chicopee 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, the largest in the U.S., in annual precipitation 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. In Table 1, we show the changes in the return period of the present-day (2000–2020) 100-year rainfall event for midcentury (2040–2060) and

[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

late century (2060-2080). By midcentury, the present-day 100-year event will occur with a return period of 1-in-57 years. By late century, the present-day 100-year event will occur with a return period of 1-in-47 years.

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 Chicopee is 8.2 inches (208 mm).[2] For reference, the present-day annual average rainfall for Westfield-Barnes Regional Airport just to the west of Chicopee, MA is 45 inches (1143 mm).[3] By midcentury, the 100-year amount will increase to 9.3 inches (236 mm) and by late century this will further rise to 10.0 inches (254 mm; Table 1).

	Present	2040-2060	2060-2080
Return period (yr)	1-in-100	1-in-57	1-in-47
100-year	8.2 in (208 mm)	9.3 in (236 mm)	10.0 in (254 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 Chicopee of the present-day, 2040–2060, and 2060–2080 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 Chicopee, 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 riverine risk along the Connecticut and Chicopee rivers estimated by FEMA is generally consistent with Woodwell estimates along the majority of the rivers. The FEMA estimate at the confluence of the Connecticut and Chicopee rivers is one location that FEMA shows greater flood extent risk, however, this is likely because of differing digital elevation model (DEM) values in these areas. Finally, FEMA shows no flood risk in areas disconnected from rivers, also known as pluvial flooding, while Woodwell demonstrates extensive non-riverine areas are vulnerable to flooding. In particular the area along the Connecticut River that is west of I-391 and north of the Massachusetts Turnpike (I-90) has substantial flooding. This discrepancy is because FEMA does not account for pluvial flooding. In addition to a lack of pluvial flood risk in FEMA maps, the area including Westover Air Reserve Base (indicated by dashed lines in Figure 1) has not been modeled by FEMA at all. The FEMA report was revised in 2023; however, the analysis for the Connecticut River was conducted in November 2006 while the Chicopee River analysis dates from March 1978, which accounts for differing flood extents especially along the Chicopee River with the analysis being several decades old.[4]

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

3 https://www.weather.gov/wrh/Climate?wfo=box NWS past weather data for Westfield-Barnes Regional Airport

4 Flood Insurance Study Hampden County, Massachusetts Volume 1 of 5. Federal Emergency Management Agency. Preliminary June 1, 2023.

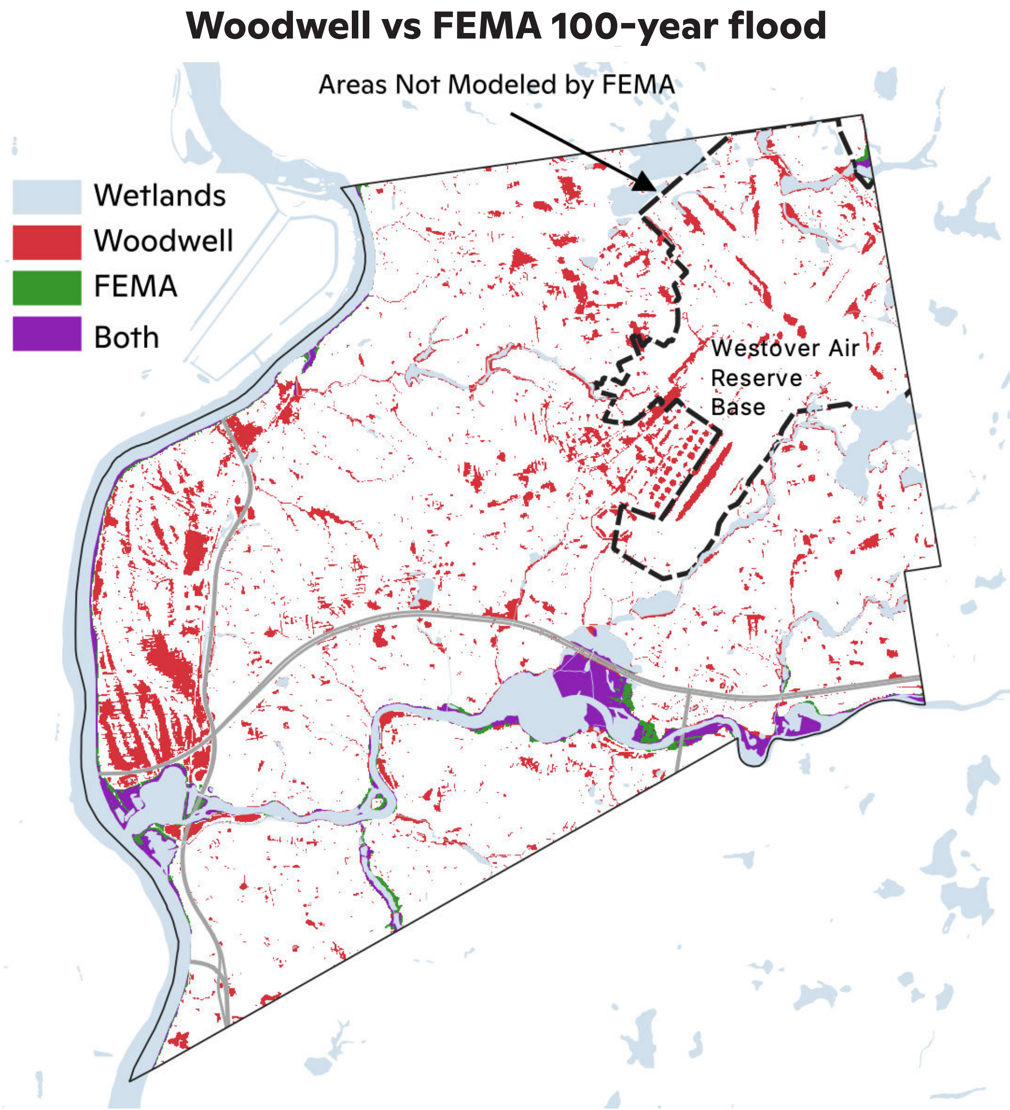


Figure 1: Woodwell vs FEMA 100-year flood. The flood extent comparison between Woodwell's flood model results and the current FEMA flood maps for Chicopee, MA. Areas where only FEMA predicts flood risk are shown in green, areas where only Woodwell predicts flood risk are shown in red, and areas where both predict flood risk are shown in purple. The Woodwell data shows the maximum extent based on both the 100-year pluvial/riverine floods. The dashed line area is not modeled by FEMA.

Present and future flood risk

The primary flood risk in Chicopee, MA is pluvial flooding. In Figure 3, we show the depth of the 100-year flood from both streamflow and rainfall for Chicopee. The highest depth values of roughly 8-10 ft (2.5-3 m) occur at the confluence of the Connecticut and Chicopee Rivers as well as Fuller Road being inundated along the confluence of Chicopee River and Cooley Brook. Pluvial flooding risk is primarily apparent north of the Massachusetts Turnpike and west of Chicopee Street. Values near the Massachusetts Turnpike approach 5 ft (1.5 m) and values northward are roughly 1.64-3.28 ft (0.5-1 m). Areas near the Westover Air Reserve Base and the Westover Metropolitan Airport also experience pluvial flooding. The flooding appears confined to grass areas along concrete pads and the runways. Lastly, along Chicopee Street east of I-391 from Perrault to Blanche Street values are roughly 1.64-3.28 ft (0.5-1 m). We mask wetland areas to focus the analysis on locations where human life and property are at risk.

The National Levee Database (NLD) was used to include the many levees that surround the city of Chicopee into the DEM shown in Figure 2. We used levees on both sides of the Connecticut River to make the model as accurate as possible. For this study, we used the following levees in the NLD:

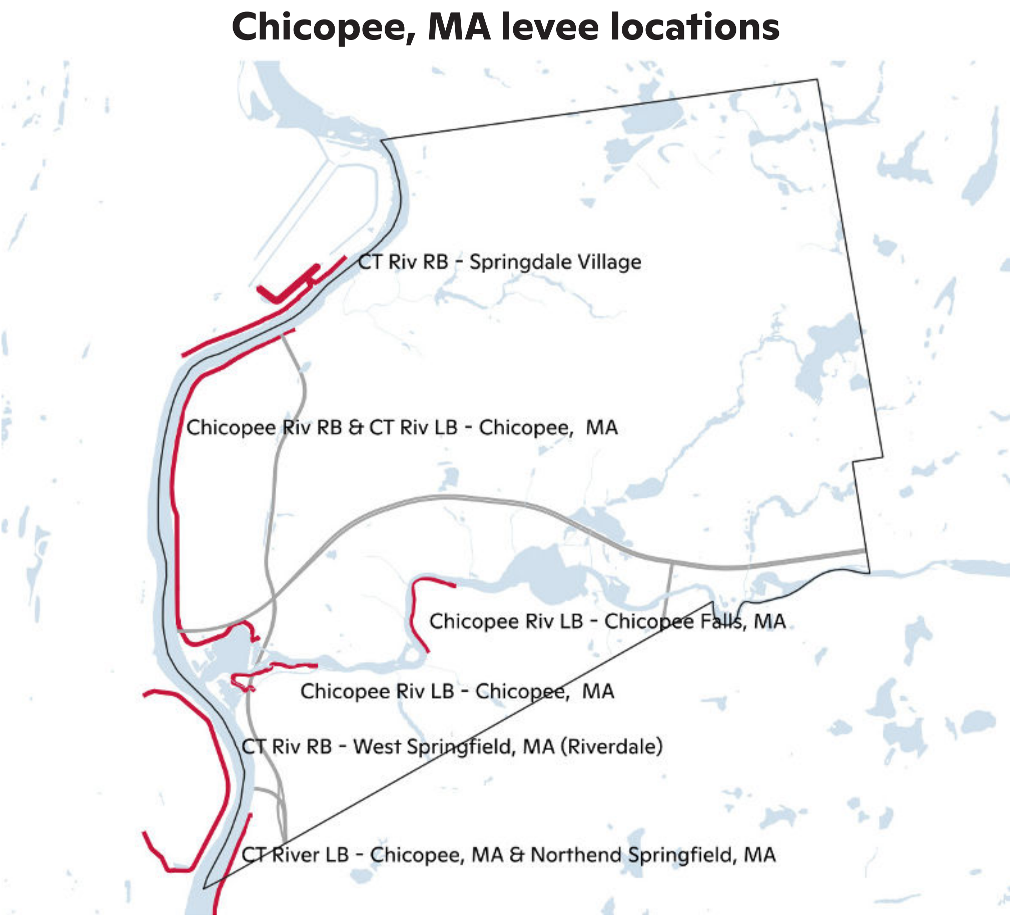


Figure 2: Levee locations around Chicopee. The various levees around Chicopee are shown in red. The names used are provided by the National Levee Database (NLD).

The levees protecting Chicopee are a vital flood defense and none of them are overtopped in our flood simulation. The United States Army Corp of Engineers (USACE) conducted evaluations on these levees in 2012 and 2013 found that the levees are unlikely to breach if water levels reached the top of the levee; however, these levees have only experienced 25%-53% of their load capacity during flood events. This leads the USACE to note that a breach is possible.[5] Water does pool on the landward side of some levees, but this is a result of pluvial flooding, not riverine. Overall, the levees surrounding Chicopee perform extremely well in flood simulations. There is potential that stormwater system upgrades can be made to better allow flow from behind the levee into the Connecticut or Chicopee Rivers.

We also explore the intersection of redlined districts, created by the Home Owners' Loan Corporation (HOLC) in 1937 from Mapping Inequality: Redlining in New Deal America, and flood risk within Chicopee in Figure 3. Redlining was the discriminatory practice of withholding mortgages and other services from neighborhoods with African American and

[5] The USACE summary reports are available for each levee from the National Levee Database: https://levees.sec.usace.army.mil

immigrant residents. We show the redlined districts with the highest and lowest grades. In Chicopee, the highest grade given to a neighborhood by the HOLC was B (shown as green in Figure 3) and the lowest was D (shown as blue in Figure 3). Areas graded as D were also highly flood-prone and residents had limited resources to relocate. We focus our discussion of climate justice within the context of these redlined neighborhoods. The neighborhood just east of the Connecticut River was flooded in 1936 with areas experiencing over 15 ft of depth. Shortly after this severe flood, in 1939, construction of a levee began along the Connecticut River (Chicopee Riv RB & CT Riv LB - Chicopee, MA) to protect this region from constant flooding and was finalized in 1941. Our results show this area is still susceptible to the 100-year flood, especially the southern portion. Moreover, the region protected by this levee (Chicopee Riv RB & CT Riv LB - Chicopee, MA) has a median income of $54,301 compared to the greater Chicopee median household income of $63,866. The area graded as D by the HOLC in Chicopee Falls along the Chicopee River was flooded in 1936. To reduce flooding in this region, a levee was constructed and completed by 1965 (Chicopee Riv LB - Chicopee Falls, MA). In our simulations, areas on the landward side of the levee still flood as a result of rainfall and water pooling there as mentioned above. Additionally, the median income in this area behind the levee southwestward along the Chicopee River, $41,652, is also substantially under the median Chicopee household income.[6] We find there is an unequal distribution of flood risk within Chicopee where those with the fewest resources bear the greatest risk. The impacts of redlining persist today, as historically redlined neighborhoods continue to face both higher flood risks and lower income levels.

[6] Justice Map containing Income data brokedown by parcel: https://www.justicemap.org

Chicopee, MA present 100-year flood extent

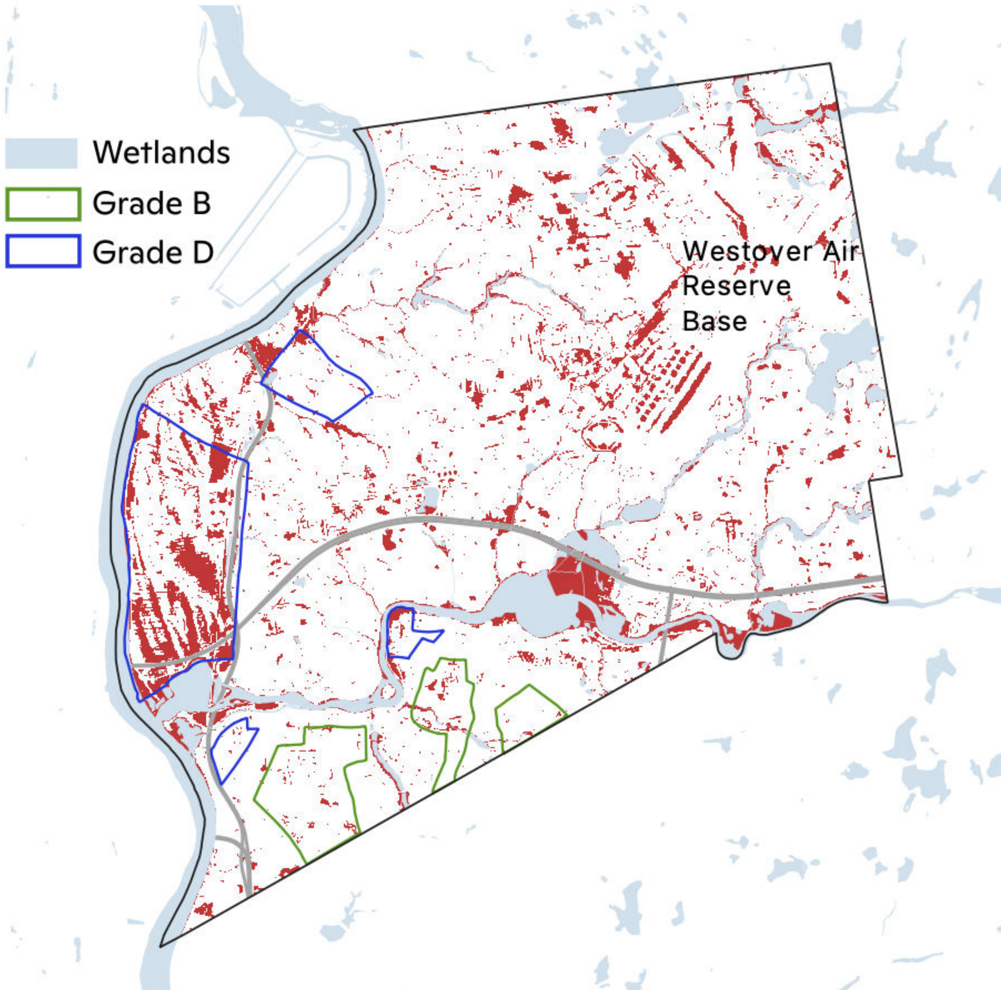


Figure 3: Present-day 100-year flood. The flood depth for Chicopee, MA. The maximum depth from the 100-year pluvial/riverine and 100-year streamflow flood is shown. Darker hues indicate deeper flood waters. Redlining data is shown by grade with grade B shown as green polygons and grade D shown as blue.

Future flood risk is primarily driven by increased rainfall and not from increased streamflow along the Connecticut and Chicopee rivers. The largest changes in extent, highlighted in Figure 4, are in northeast Chicopee along Stony Brook, areas inside Westover Air Reserve Base, central Chicopee between Memorial Drive and Westover Road, and along the Connecticut River north of the Massachusetts Turnpike (I-90). This change in pluvial flood risk is due to projected increases in rainfall between 1.1 inches to 1.8 inches (28-46 mm) from the present-day period, as shown in Table 1. The riverine flood extent is impacted by an increase of streamflow (9.03% increase by 2050 and 5.03% by 2070)[7]; however, all the levees around Chicopee withstand this increase with none of the levees being overtopped. Areas not protected by levees show slight increase in extent (less than 100 ft; 30.5 m beyond present extent). We also present several flood risk metrics in Table 2. Presently, just over 8% of the structures in Chicopee are vulnerable to the 100-year rainfall or streamflow event. That number increases to just under 10% by midcentury and then to 12% by late century. The average flood depth in Chicopee increases by 0.36 ft (0.11 meters) through the 21st century, while the area flooded increases from over 17% in the present day to over 21% by late century.

[7] Palmer and Siddique 2019: Estimating Future Changes in 100-year Floods on the Connecticut and Merrimack Rivers. Massachusetts Department of Transportation. https://www.mass.gov/files/documents/2019/12/10/EstimatingFloodsFinalNov_2019%20.pdf

Present and future 100-year flood

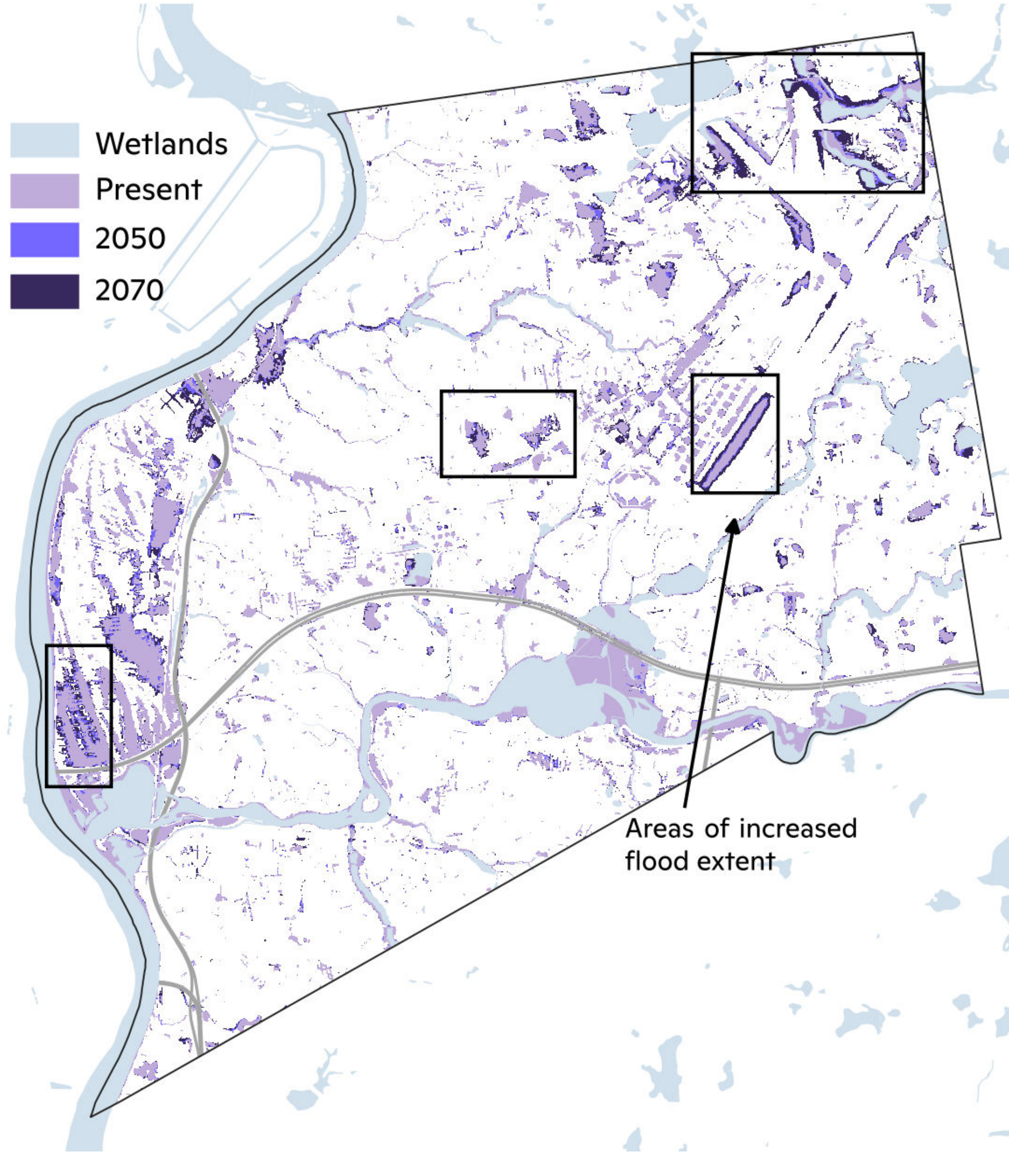


Figure 4: Present-day and future 100-year flood. The flood extent, quantified as having a depth of at least 0.5 ft (0.15 m), for Chicopee, MA. The maximum extent for the 100-year pluvial/riverine flood is shown. Areas with increased future extent are boxed.

	Present	2040-2060	2060-2080
Area flooded	17.41%	18.95%	21.30%
Average depth	4.63 ft (1.41 m)	4.76 ft (1.45 m)	4.99 ft (1.52 m)
Structures flooded	1,601 (8.40%)	1,889 (9.91%)	2,305 (12.10%)

Table 2: Flood risk metrics for mid- and late-21st century in Chicopee. The percent of land area (excluding wetlands) flooded and the number of buildings (and percent of total structures) flooded for Chicopee of the present-day, 2040–2060, and 2060–2080 100-year rainfall events.

Stormwater system vulnerability

In addition to flood extents, an analysis of the flood model results for the Chicopee 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.

Chicopee'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 2060–2080 100-year events. In Figure 5, 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, 81.5% of all conduits in Chicopee's stormwater system are capacity-limited. From the mid-21st century to the late-21st century, the amount of capacity-limited conduits will only increase by 4%. The percentage of manholes and catch basins flooded is significantly smaller compared to the conduits, but a similar narrow upward trend is expected with 44% of the catch basins and 24.5% 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. It is worth noting that there are several areas where the stormwater system was not connected to an outfall. Two of these areas are highlighted on Figure 5 with a blue box. We identified several hot spots of stormwater flooding throughout Chicopee. These include the communities of Chicopee Falls, Aldenville, and Willimansett south to the Massachusetts Turnpike.

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 (73.7%) 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.

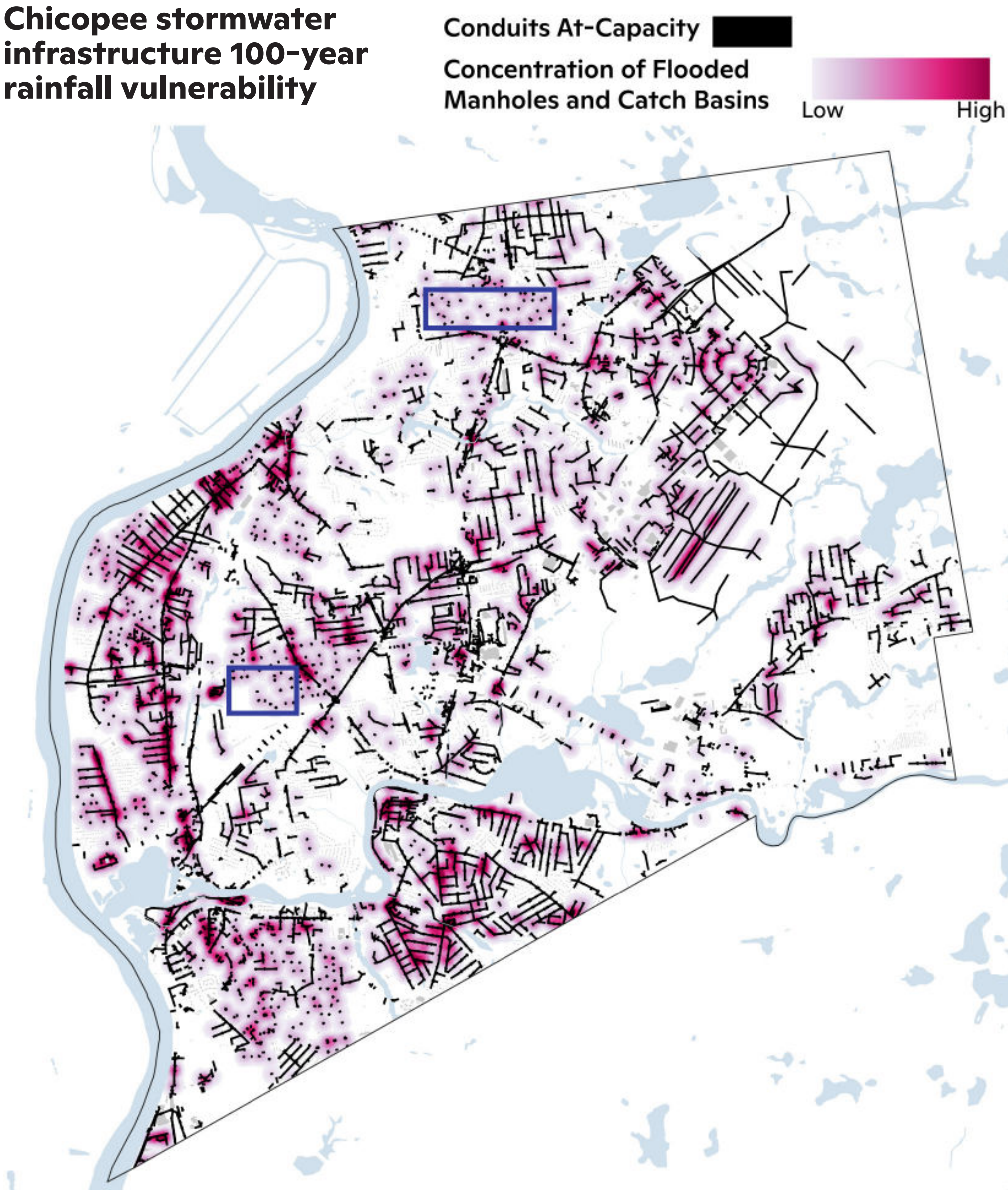


Figure 5: Chicopee stormwater system flooding heat map. The concentration of flooded manholes and catch basins shown as a heat map for the present-day 100-year rainfall event. Areas with no flooded manholes or catch basins are shown in white. Capacity-limited conduits are shown in black. Blue boxes indicate examples of no outfalls connected to the conduits/nodes.

	Present	2040-2060	2060-2080
Manholes	919 (18.5%)	1,032 (20.8%)	1,217 (24.5%)
Catch basins	3,422 (36.0%)	3,741 (39.3%)	4,190 (44.0%)
Conduits	12,736 (81.5%)	13,034 (83.4%)	13,376 (85.6%)

Table 3: Chicopee 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 2060–2080 100-year rainfall event.

Conclusion

Chicopee 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. 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 almost twice as likely by the mid-21st century and just over twice as likely by the end of the century. Chicopee's stormwater system will also face greater stress as rainfall intensifies with over 24% of manholes and 44% of catch basins flooding by the late-21st century. This report provides insight into the vulnerability of the city of Chicopee, 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 Connecticut and Chicopee Rivers are expected to increase by 9.03% by 2050 and 5.03% by 2070, respectively, but are not projected to overtop Chicopee's levee system.

Methodology

To simulate flood risk we use a coupled version of the LISFLOOD-FP v8.1 flood model (LISFLOOD-FP developers, 2022; Shaw et al., 2021) and the US Environmental Protection Agency's (EPA) Stormwater Management Model (SWMM). 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. SWMM was introduced in 1971 by the EPA and has been continuously developed since. SWMM is a one-dimensional stormwater system model solving the one-dimensional Saint-Venant equations.

LISFLOOD-FP and SWMM are coupled based on the methodology presented in Leandro and Martins (2016). SWMM and LISFLOOD-FP were coupled using SWMM's dynamic link library (DLL). LISFLOOD-FP's source code was modified to allow for bidirectional interaction between the two models at outfalls, catch basins, and manholes by calling SWMM functions during each LISFLOOD-FP time step. Time step synchronization between LISFLOOD-FP and SWMM is controlled by LISFLOOD-FP. Flow from LISFLOOD-FP to SWMM through manholes and catch basins is governed by the orifice and weir equations. Flood volumes that occur at manholes and catch basins are transferred to LISFLOOD-FP. Further detail on flow interactions can be found in Chen et al. (2016).

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 National Wetland Inventory (https://fwsprimary.wim.usgs.gov/wetlands/apps/wetlands-mapper).

Three time periods were used for this study: 2000-2020 (also referred to as present day), 2040-2060, and 2060-2080. These time periods can also be interpreted as warming levels in the context of climate policy. The 2000-2020, 2040-2060, and 2060-2080 periods correspond to 1, 2 and 3 degrees Celsius of warming respectively. For each time period, a pluvial/riverine flooding run and a coastal 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 USA Structures dataset (https://gis-fema.hub.arcgis.com/pages/usa-structures). This dataset was created through a collaboration between DHS, FIMA, FEMA's Response Geospatial Office, Oak Ridge National Laboratory, and the U.S. Geological Survey.

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 point precipitation frequency estimates for Chicopee, MA (Perica et al., 2015). 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 2015 USGS Lidar DEM: Maine & Massachusetts QL1 & QL2 was used to create the Chicopee, MA elevation domain. The resolution of the raw data was 1m. The final DEM resolution was set to 5m to sync better with the stormwater system. It was discovered that the Connecticut River elevation was far too high to accurately be modeled, so the river bed elevation was put into the DEM using the FEMA Flood Insurance Study for Hampden County, MA volume 3 of 5, discussed more in the streamflow section below.

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 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 Hampden County, MA Volume 1 of 5 to obtain the 100-year streamflow values for the boundaries of the domain. For the Connecticut River at Holyoke's upstream corporate limit, a streamflow value of 187,000 ft^3/s is put into the model. The Chicopee River at the USGS gauge at Indian Orchard has a streamflow value of 32,000 ft^3/s. Another river needed to be included but wasn't part of the FEMA report, so the streamflow value from USGS StreamStats was used. This river was Fuller Brook and the streamflow value of 766 ft3/s was obtained west of Harris Pond(east of Chicopee).

It was discovered that the DEM values for the Connecticut River were far too high compared to the USGS gauge that is near I-391 by Holyoke leading to levee's being overtopped incorrectly, so the DEM would need to be adjusted. A test case was run for tropical storm Irene that occurred at the end of August 2011. The streamflow value from this event was 107,000 ft^3/s. We were able to use this value to compare the elevation at this location against the historic crest that occurred after adjusting the DEM to the river bottom elevation from the FEMA study and then applying a four meters increase to the river bottom elevation. The model starts with no water, so a river bed estimation wasn't realistic but was a starting point to get to the correct elevation (this essentially starts the Connecticut River with four meters of depth). The crest value was 27.73 feet and the gauge height was 32.42 feet for a total of 60.15 feet. The model result of this test case resulted in an elevation of 61.16 feet at that gauge site indicating a good agreement between the historic crest and the model result.

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