CLIMATE RISK ASSESSMENT

Plymouth, Massachusetts

For more information about this analysis, or Woodwell's other climate risk assessments, please contact us at policy@woodwellclimate.org.

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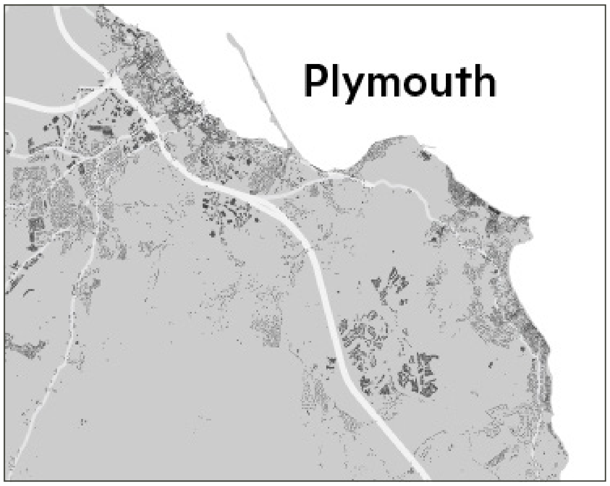
Woodwell Climate Research Center

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 for communities to countries. Woodwell Climate Research Center ("Woodwell Climate") 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 Plymouth, 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 Plymouth. The probability of the historical 100-year rainfall event, a useful indicator of flood risk, is expected to quadruple by mid-century and be ten times more likely by the end of the century. Sea levels are also projected to rise throughout this century with an increase of 1.31 feet (0.4 meters) by 2050 and 2.66 feet (0.81 meters) by 2080. Both sea level rise and heavier rainfall will translate into greater flood depths and extent for Plymouth. The vulnerability of Plymouth's stormwater system was also evaluated under the present and future 100-year rainfall event. Here we present our findings on extreme precipitation and flooding to help Plymouth in its plans to create a more resilient future for all residents.

[1] Reidmiller, D. R., et al. Fourth national climate assessment. *Volume II: Impacts, Risks, and Adaptation in the United States* 440 (2018). https://nca2018.globalchange.gov

Extreme rainfall

The Fourth National Climate Assessment shows that the U.S. Northeast region has already seen a 55% increase in annual precipitation occurring from the heaviest 1% of events.[1] Future warming is expected to continue this trend of intensification, leading to more frequent and severe rainfall events. Here we use localized future precipitation data from a downscaled global climate model 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 Figure 1, we show the changes in the return period of the historical (2000–2020) 100-year rainfall event for 2040–2060 and 2070–2090. By 2040–2060, the historical 100-year event will occur with a return period of 1-in-20 for areas around North Plymouth and 1-in-30 for White Horse Beach and Manomet. By 2070–2090, the historical 100-year event will become a roughly 1-in-10 year event for all of Plymouth.

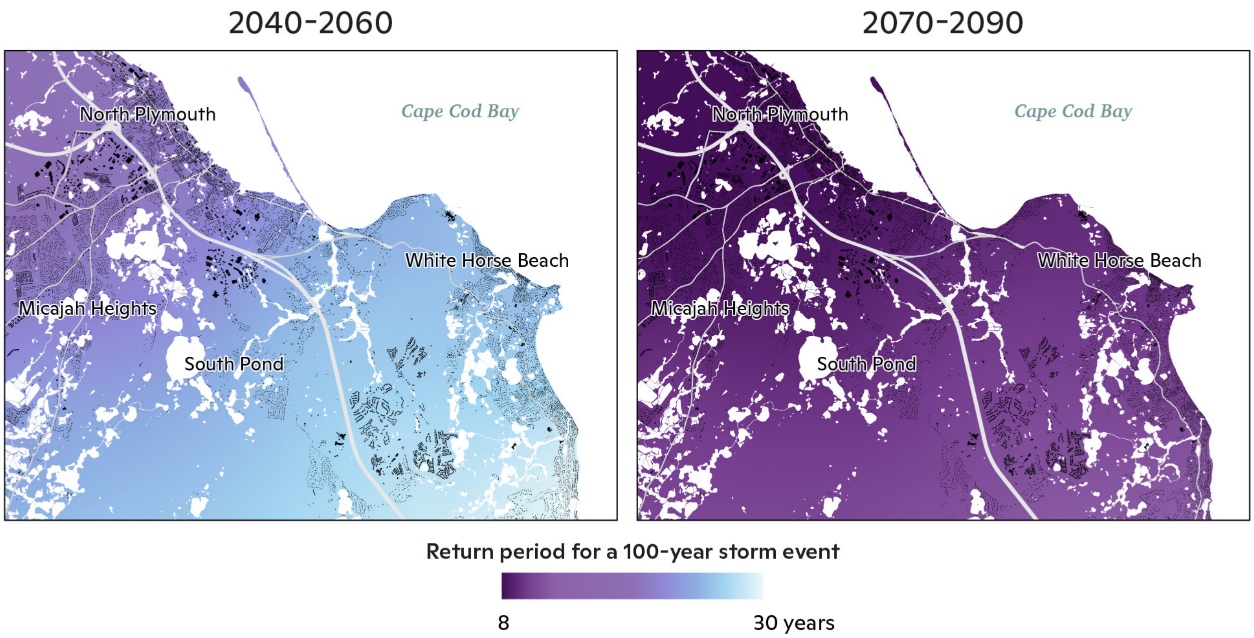


Figure 1: Mid and Late 21st Century Change in Historical 100-Year Return Period. The future return period of the 2000–2020 100-year rainfall event in 2040–2060 (left) and 2070–2090 (right) with the darker the hue, the smaller the return period (greater frequency of occurrence). By the mid 21st century, the historical 100-year rainfall event is expected to become between a 1-in-20 year event for North Plymouth and 1-in-30 year event for White Horse Beach and Manomet. For the end of the century, the historical 100-year rainfall event is expected to become a 1-in-10. Black polygons are buildings.

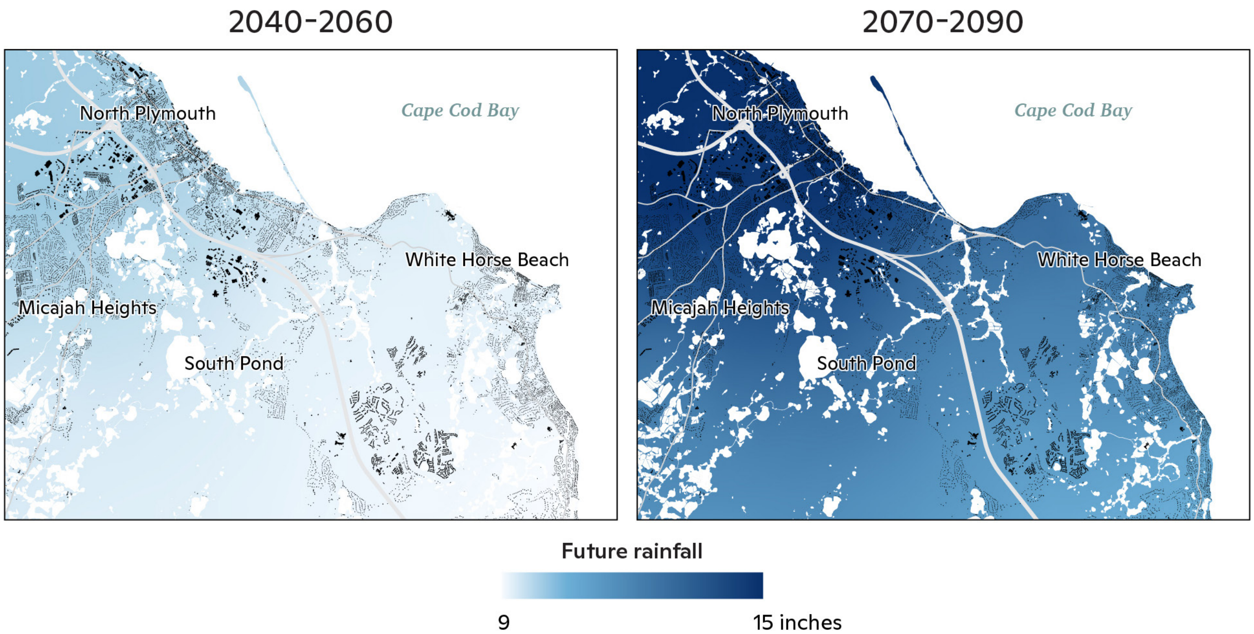


Figure 2: Mid and Late 21st Century Change in Historical 100-Year Rainfall. The future rainfall amounts in inches of the 2040–2060 (left) and 2070–2090 (right) 100-year rainfall event with the darker the blue, the greater the rainfall amount. By the mid 21st century and the late 21st century, the 100-year rainfall event is expected to drop 9.68 inches and 12.98 inches, respectively, for most of Plymouth. Black polygons are buildings.

According to the National Atlas 14 published by the National Oceanic and Atmospheric Administration, the 100-year rainfall amount, based on historical rainfall records, in Plymouth, MA is 7.47 inches.[2] By 2040-2060, the 100-year amount increases to 9.68 inches and by 2070-2090 this further rises to 12.98 inches (Figure 2; Table 1).

	Present	2040-2060	2070-2090
100-Year	7.47 in (189 mm)	9.68 in (246 mm)	12.98 in (329 mm)

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

Flooding

In addition to the intensification of extreme rainfall events, sea levels are also expected to rise significantly through the 21st century under climate change. According to the IPCC AR6 projections, sea levels will rise 1.31 feet (0.40 meters) by 2050 and 2.66 feet (0.81 meters) by 2080 under the SSP5-8.5 Low Confidence scenario (Low Confidence refers to more significant Antarctica and Greenland ice sheet melting than the SSP5-8.5 Medium Confidence scenario).[3] With increased rainfall amounts and higher sea levels comes greater flood risk. For a detailed explanation of the flood model input data and flood modeling procedures, please refer to the methodology section of this document.

[2] NOAA calculates extreme rainfall frequencies with all available station data. In Plymouth, daily rainfall records go back to 1893.

[3] Fox-Kemper, B., H.T. Hewitt, C. Xiao, G. Aðalgeirsdóttir, S.S. Drijfhout, T.L. Edwards, N.R. Golledge, M. Hemer, R.E. Kopp, G. Krinner, A. Mix, D. Notz, S. Nowicki, I.S. Nurhati, L. Ruiz, J.-B. Sallée, A.B.A. Slangen, and Y. Yu, 2021: Ocean, Cryosphere and Sea Level Change. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1211–1362, doi:10.1017/9781009157896.011.

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 3 shows the differences and similarities between FEMA's estimate and Woodwell's estimate of the 100-year flood extent for the Plymouth, MA region. Areas where only FEMA predicts flood risk are shown in turquoise, areas where only Woodwell predicts flood risk are shown in brown, and areas where both predict flood risk are shown in blue. Several patterns emerge when comparing the extents visually. First, both datasets show similar levels of coastal flooding. This is to be expected as the Woodwell extent was created using the storm surge elevations from the FEMA Flood Insurance Study. A few areas such as sections of Long Beach and White Horse Beach appear at-risk in the FEMA data but protected in the Woodwell data. This discrepancy appears to be due to FEMA accounting for wave action. In the example of White Horse Beach, this wave action led to the entire area being flooded in FEMA predictions. Second, the riverine risk estimated by Woodwell is slightly less than FEMA estimates. This is likely due to differing hydrologic and hydraulic methodologies. Some of the flood studies that make up parts of Plymouth's FEMA flood map are over 30 years old which use estimates of streamflow based on drainage area and nearby stream gauges and elevation data from that time which has likely changed significantly since then. Finally, FEMA shows no flood risk in areas disconnected from rivers, also known as pluvial flooding, while Woodwell demonstrates extensive inland areas are vulnerable to flooding. This is because FEMA does not account for pluvial flooding.

Woodwell vs FEMA 100-year flood

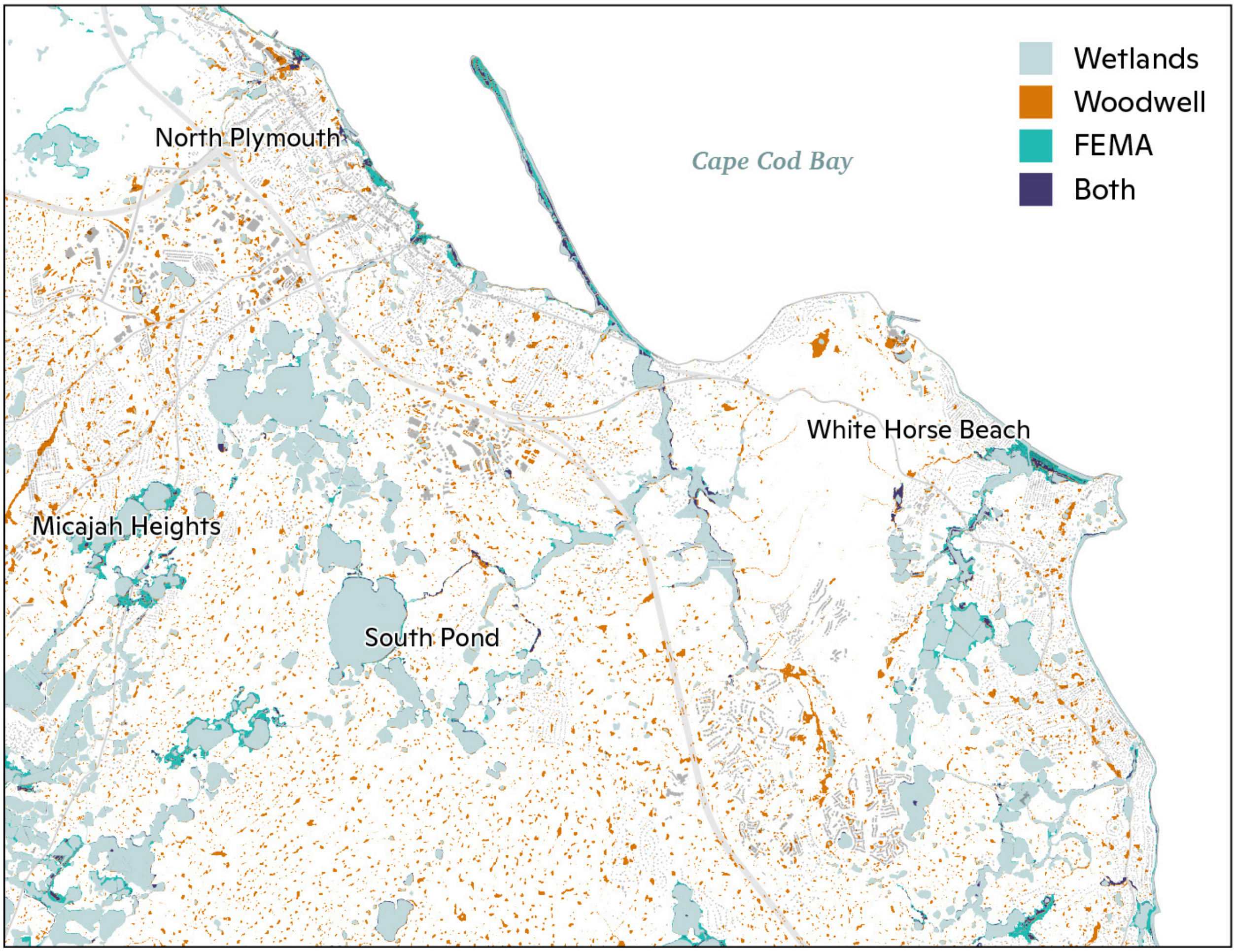


Figure 3: Woodwell vs FEMA 100-Year Flood. The flood extent comparison between Woodwell's flood model results and the current FEMA flood maps for Plymouth, MA. Areas where only FEMA predicts flood risk are shown in turquoise, areas where only Woodwell predicts flood risk are shown in brown, and areas where both predict flood risk are shown in blue. The Woodwell data shows the maximum extent based on both the 100-year pluvial/riverine and the 100-year coastal floods. Brown polygons are buildings.

Present and Future Flood Risk

The city of Plymouth is quite expansive so different areas have differing primary flood risks. The area near Long Beach is strongly influenced by tides and coastal flooding, while riverine and pluvial flooding poses significant risk further inland. In Figure 4, we show the depth of the 100-year flood for Plymouth. We mask wetland areas as these would be inundated during an extreme flood event and to focus the analysis on locations where human life and property are at risk. The city of Plymouth, especially Long Beach, is most vulnerable to coastal flooding, where flood depths approach 6.5 feet (2 meters). Pluvial flooding adds a considerable amount of inundation extent, especially in North Plymouth making it the dominant source of inundation. Flooding from all sources is largely concentrated in North Plymouth, Long Beach, and the southern area of the domain in Figure 4.

Present-day 100-year flood

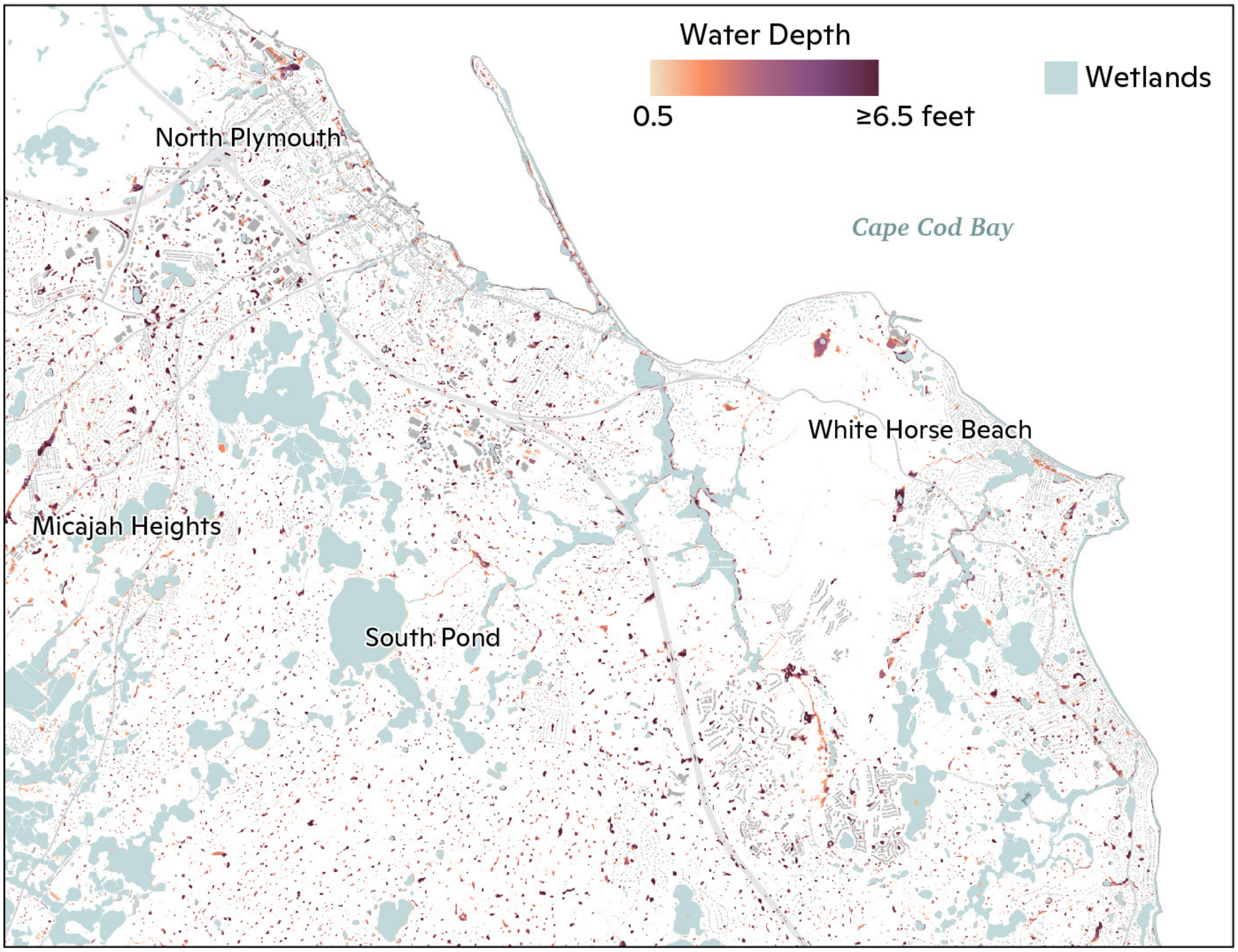


Figure 4: Present-Day 100-Year Flood. The flood depth for Plymouth, MA. The maximum depth between the 100-year pluvial/riverine and the 100-year coastal floods is shown. Darker hues indicate deeper flood waters. Brown polygons are buildings.

Future flood risk is most notably seen in North Plymouth, Long Beach, and White Horse Beach as shown in Figure 5 and zoomed in on in Figure 6. While some communities see increased pluvial and riverine flooding in the future, such as North Plymouth, most of the increased flood risk is along the shoreline as a result of increased storm surge. Even though future rainfall is projected to increase between 2–5.5 inches (50–140 mm), as shown in Table 1, the flood extent is impacted more by the increase in sea level of 1.31 feet (0.4 meters) by 2050 and 2.66 feet (0.81 meters) by 2080. This increase in extent can be seen on Long Beach where more of the peninsula is at risk of flooding. We also present several flood risk metrics in Table 2. Presently, 9% of the structures in Plymouth are vulnerable to the 100-year flood. That number increases to 11% by mid-century and then 13% by late century. The average flood depth in Plymouth increases by 1.31 feet (0.4 meters) through the 21st century while the area flooded increases from 26% in the present-day to 38% by late century.

Present and Future 100-year flood

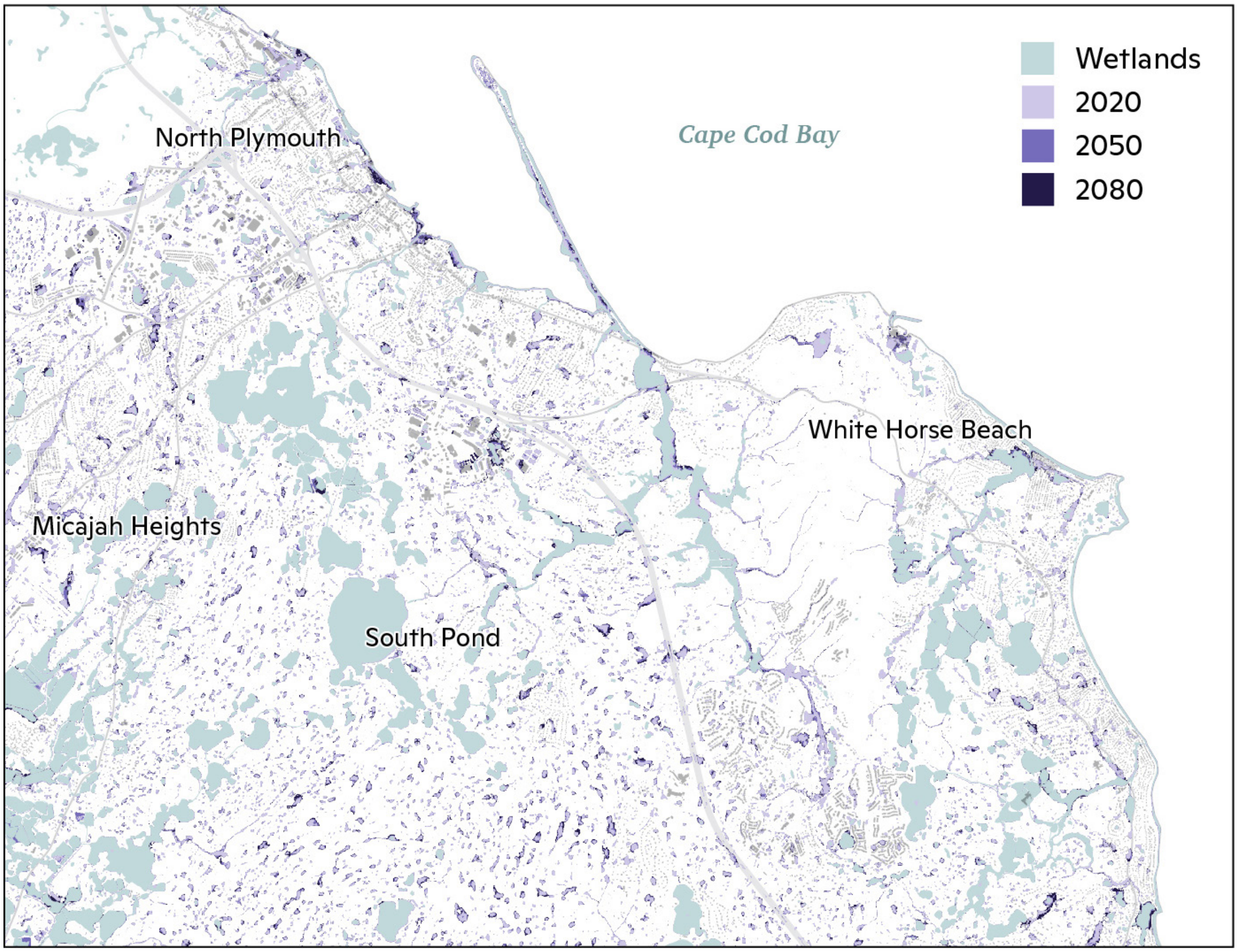


Figure 5: Present-Day and Future 100-Year Flood Plymouth, MA. The flood extent, quantified as having a depth of at least 0.5 ft (0.15 m), for Plymouth, MA. The maximum extent between the 100-year pluvial/riverine and the 100-year coastal floods is shown. Brown polygons are buildings.

	Present	2040-2060	2070-2090
Area Flooded (%)	26%	32%	38%
Average Depth (m)	3.35 ft (1.02 m)	4 ft (1.22 m)	4.63 ft (1.41 m)
Structures Flooded	1,561 (9%)	1,888 (11%)	2,310 (13%)

Table 2: Flood Risk Metrics for Mid and Late 21st Century in Plymouth. The percent of land area (excluding wetlands) flooded, average flood depth in meters and feet, and the number of buildings (and percent of total structures) flooded for Plymouth of the present day, 2040–2060, and 2070–2090 100-year rainfall events.

Present and Future 100-year flood

Figure 6: Present-Day and Future 100-Year Flood North Plymouth and Long Beach. The flood extent, quantified as having a depth of at least 0.5 ft (0.15 m), for North Plymouth and Long Beach. The maximum extent between the 100-year pluvial/riverine and the 100-year coastal floods is shown. Brown polygons are buildings.

Stormwater System Vulnerability

In addition to flood extents, an analysis of the flood model results for Plymouth stormwater system was conducted to identify bottlenecks in the system. Any manholes or catch basins (sometimes referred to drainage basins) that overflowed during the simulation were considered flooded. Conduits (pipes) that are capacity limited (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 under-sloped. 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.

Plymouth's stormwater system has several 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 7, 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, almost 50% of all conduits in Plymouth's stormwater system are capacity-limited. By the mid 21st century, that number increases to 54% and then almost 60% by the late 21st century. The percentage of manholes and catch basins flooded is smaller compared to the conduits but a similar upward trend is expected with 25% of the catch basins and 21% of the manholes flooded by the late 21st century. We identified several hotspots of stormwater flooding throughout Plymouth. Taylor Avenue in White Horse Beach, The Grove at Plymouth shopping mall, the Plymouth harbor area, and the Cordage Park area in North Plymouth all show a high concentration of flooded manholes and catch basins.

	Present	**2040-2060**	**2070-2090**
Manholes	387 (11%)	533 (16%)	715 (21%)
Catch Basins	749 (13%)	1,054 (19%)	1,400 (25%)
Conduits	4,642 (49%)	5,123 (54%)	5,618 (59%)

Table 3: Plymouth 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.

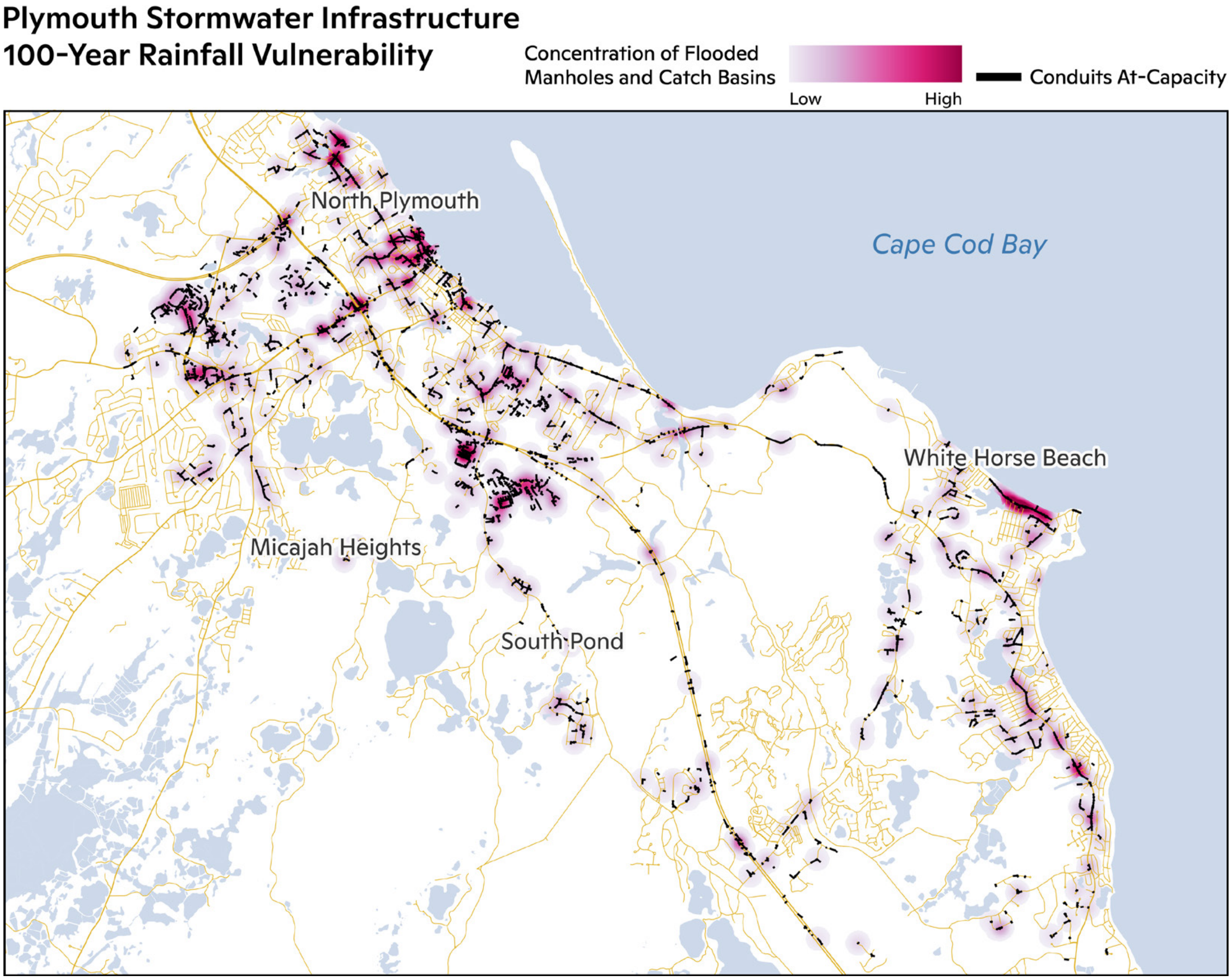


Figure 7: Plymouth Stormwater System Flooding Heat Map. The concentration of flooded manholes and catch basins shown as a heat map for the present-day 100-year rainfall event. Areas with no flooded manholes or catch basins are shown in white. Capacity-limited conduits are shown in black.

Conclusion

Plymouth is currently at high risk from flooding, 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. The results of this research indicate an expected increase in the frequency and intensity of heavy rainfall with the probability of the present-day 100-year rainfall event likely to quadruple by the mid 21st century and be ten times more likely by the end of the century. Sea level rise is also an important contributor to changing flood risk for coastal areas of Plymouth. The projections from IPCC AR6 indicate significant sea level rise by 2050 (1.31 feet; 0.40 meters) and 2080 (2.66 feet; 0.81 meters) leading to larger flood extents. This report provides insight into the vulnerability of coastal and relatively inland areas, such as North Plymouth, Long Beach, and White Horse Beach where an increasing number of buildings and areas will be exposed to flood water by the end of the century. To alleviate some of the flooding, capacity limited conduits could be a good starting point for upgrades to the stormwater system for Plymouth.

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 Environmental Protection Agency's (EPA) Stormwater Management Model (SWMM). LISFLOOD-FP is a two-dimensional raster hydraulic model that solves an approximation 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 USA Environmental Protection Agency and has been developed since then. 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 (DDL). 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. The time step of LISFLOOD-FP is set as SWMM's time step which keeps the two models aligned during the simulation. Flow from LISFLOOD-FP to SWMM through manholes and catch basins are 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 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 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/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.

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 Plymouth, MA (Bonnin et al., 2006). 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. Precipitation annual maxima were then extracted for three time periods, 2000–2020, 2040–2060, and 2070–2090 using the SSP5-8.5 scenario from the downscaled data. The Akaike Information Criteria (AIC) was used to determine the best Generalized Extreme Value (GEV) distribution between the L-moments method (Hosking, 1990) and the Maximum Likelihood Estimation (MLE) (Prescott and Walden, 1980). The annual maxima data for each pixel across all models were fitted to a GEV distribution using the L-moments method as it was the best fit for Plymouth. The future return period of the historical (2000–2020) 1-in-100 year event is determined by finding the percentile in the future GEV distribution that corresponds with the historical rainfall amount. Rainfall amounts for the future 1-in-100 year events were estimated by determining what percentile in the historical period corresponds to the future 100-year amount, according to the future GEV. The percentile (analogous to a return period) was then converted to a rainfall amount using the rainfall distributions from the NOAA NA14 dataset.

2 | Digital Elevation Model

The USGS CoNED Topobathy DEM (Compiled 2016): New England was used to create the Plymouth, 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.

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 Massachuettes 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 | Tide

Tidal data was retrieved from the NOAA Tides and Currents. For Plymouth, the mean higher high water, 1.45m and the mean lower low water, -1.76m were used. These values are relative to the vertical datum NAVD88.

6 | Storm Surge

The FEMA flood insurance study reports were used to obtain 1-in-100 year storm surge values for points along the coast of Plymouth. We do not account for shifting tropical cyclone distributions as this is beyond the scope of this study.

7 | Sea Level Rise

Sea level rise data for Plymouth, MA was taken from the IPCC AR6 Sea Level Projection Tool. We use the SSP5-8.5 Low Confidence scenario in order to maintain consistency with the future rainfall analysis. We use the low confidence scenario (which refers to greater Antarctica and Greenland ice sheet melting) because global sea level rise projections continue to increase as new data comes to light (Garner et al., 2018). Moreover, the scientific community's understanding of Antarctica's contribution to sea level rise is not strong enough to meaningfully differentiate between SSP5-8.5 and other scenarios except for SSP1-2.6 (van de Wal et al., 2022). However, there is only a 0.1% chance that society will experience the SSP1-2.6 scenario (Zeppetello et al., 2022). Additionally, the SSP5-8.5 Low Confidence scenario is roughly equivalent to the NOAA Intermediate scenario presented in the Interagency Sea Level Rise Scenario Tool.

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Gallows Pond, Plymouth Massachusetts / photo by John Phelan (CC BY-SA 4.0)

WOODWELL CLIMATE RESEARCH CENTER conducts science for solutions at the nexus of climate, people and nature. We partner with leaders and communities for just, meaningful impact to address the climate crisis. Our scientists helped to launch the United Nations Framework Convention on Climate Change in 1992, and in 2007, Woodwell scientists shared the Nobel Prize awarded to the Intergovernmental Panel on Climate Change. For over 35 years, Woodwell has combined hands-on experience and policy impact to identify and support societal-scale solutions that can be put into immediate action. This includes working with communities on the frontlines of the climate crisis.

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