Current and future storm surge and stormwater flood risk under climate change in Chelsea, Massachusetts

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Summary

Floods are some of the most devastating natural disasters and are expected to worsen under climate change due to intensification of extreme precipitation and sea level rise. In this study, present and future flood risk in Chelsea, MA are examined through changes in the 1% annual chance flood event. Future rainfall and storm surge are estimated for two time periods, 2041–2060 (2050) and 2071–2090 (2080) representing the mid and late 21st century, respectively, using a regional climate model and established sea level rise rates for the Boston area.

The output of these simulations show that the historical 1% annual chance rainfall event will be 3x and 3.5x as likely in 2050 and 2080, respectively. The historical 1% annual chance storm surge event will be 3.8x as likely in 2050 and occur at least once a year by 2080.

Using these estimates as inputs into a flood model reveals significant increases in flood risk across Chelsea. The percentage of land area in Chelsea inundated by the historical 1% annual storm surge event will increase from 14% in the present time period to 19% in 2050 and 34% in 2080. While storm surge events cause the greatest flood extents, the 1% annual chance rainfall event impacts the greatest number of buildings in the present time period and 2050. However, the 1% annual chance of joint rainfall and storm surge events impacts the greatest number of buildings in 2080. This finding underscores the need for including pluvial flood modeling in federal flood maps.

Introduction

The combustion of fossil fuels, deforestation, and other human activities release greenhouse gases (GHGs). These, in turn, have increased global average temperature at unprecedented rates. From 1901–2016, global average temperatures have already risen by 1°C (1.8°F;Hayhoe et al., 2018).The rate of warming is not attributable to natural variability, has no natural explanation, and is unequivocally the result of human influence (IPCC, 2021). The Paris Agreement aims to prevent the most catastrophic impacts of climate change by limiting global warming to 2°C (3.6°F). The response of Earth's natural systems to the rapidly warming climate and human disruption will impact our quality of life for generations to come. Understanding and preparing for these changes is critical.

The impacts climate change has on the frequency and severity of physical hazards will put many communities at risk. Physical hazards include extreme precipitation events, severe storms, extreme heat events, and flooding. Socioeconomic consequences include adverse public health outcomes, loss of critical infrastructure, and agricultural yield reduction among others.

Flooding is the costliest and deadliest natural disaster in the United States (Perry, 2000; Miller et al., 2008). Flooding comprises three main risks: hazard, exposure, and vulnerability. Hazard refers to a destructive event (i.e. flooding), exposure represents the local community elements (e.g. people, buildings, infrastructure) that could be impacted by flooding, and vulnerability is the susceptibility of those community elements to consequences of flooding (e.g. lack of resilience planning).

Due to climate change, much of the Northeastern United States is expected to see an intensification of extreme precipitation events, and, therefore, flood events (Dupigny-Giroux, 2018). Already, increased rainfall intensities in the Northeast are expected to outpace any other region in the United States. In addition, accelerating sea level rise will lead to an increase in sunny day flooding and storm surges. Much of the infrastructure, such as drainage and sewer systems, in the Northeast is nearing its planned life expectancy, and climate-related events will put further strain on these infrastructure systems.

This focuses on flooding in Chelsea, MA and will examine how flood events will be different in the future under climate change. The report also discusses building exposure and general exposure across the area of interest.

There are three different types of flooding: fluvial, pluvial, and coastal. Fluvial (also known as riverine) flooding occurs when rivers exceed the boundaries of the river channel. Pluvial flooding occurs as a result of extreme precipitation events and is not associated with riverine flooding. This usually occurs when a stormwater system or soils cannot effectively drain or infiltrate rainfall leading to standing water. Coastal flooding occurs during storm surge or high tide events. Chelsea is vulnerable to coastal flooding because of the city's significant coastline. Chelsea is vulnerable to pluvial flooding since rainfall can pond, so the city is largely reliant on the capacity of the stormwater system because 77% of the land area is impervious (OCM, 2018). The land cover present in Chelsea is shown in Figure 1. Areas of future development are also highlighted on the map, which will likely contain mixed use buildings and open space according to the proposed Chelsea Creek Municipal Harbor Plan and Designed Port Area Master Plan (City of Chelsea, 2021).

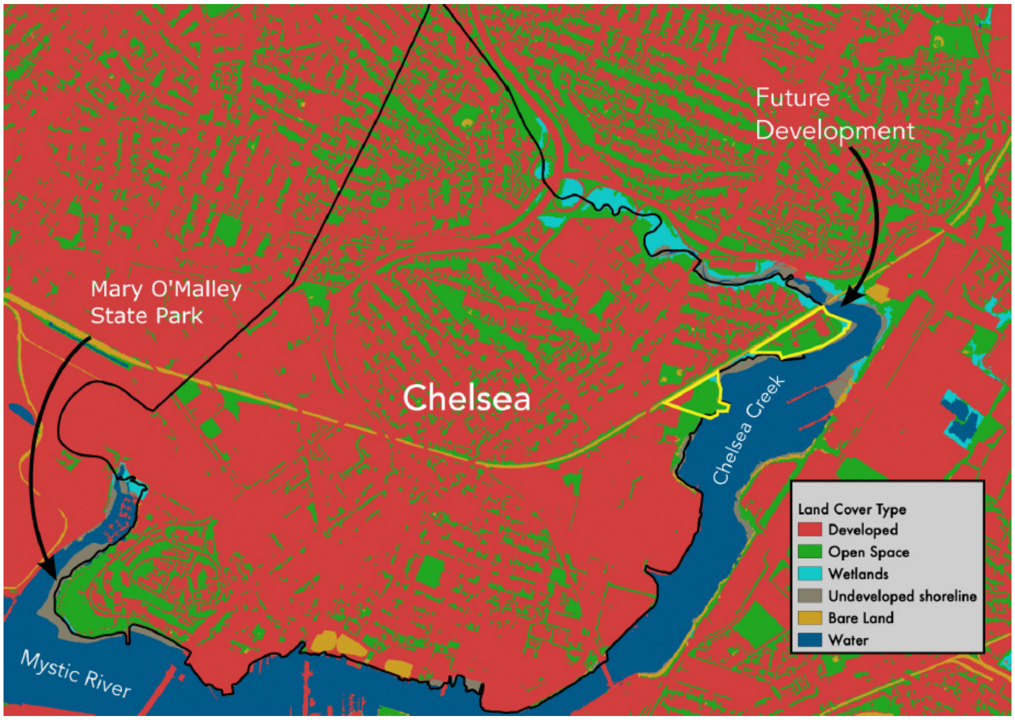

Figure 1. Land cover in Chelsea, MA.

Project Overview

This study first explores the present flood risk in Chelsea using historical (also referred to as present) rainfall and storm surge data. We focus on the 1-in-100 year (1% annual chance event) due to the importance of this particular flood event in policy and land-use decisions as well as its regulatory significance. The Federal Emergency Management Agency (FEMA) determines flood risk and properties required to purchase flood insurance mainly through delineating the extent of the 1% annual chance event. A comparison is made between the flood modeling results generated in this study to the currently effective FEMA flood maps, which showcases the deficiencies in the present federal flood mapping methodology. An additional comparison of results is made between the results of this study and the Boston Harbor Flood Risk Model (BH-FRM)—a federal and state climate risk study for the greater Boston region—for validation purposes.

While pluvial and coastal flood simulations are often modeled separately, both can occur simultaneously in real-world events. We draw on the work from Wahl et al. (2015), who showed a statistically significant Kendall's Tau rank correlation between storm surge and rainfall events in Boston of 0.34 using the past 30 years of data.[1] Moreover, it was shown that the correlation has been statistically significant since 1970 where it was calculated to be 0.2 and has increased since then. Based on this finding, the range of scenarios examined in this study were expanded to include a joint probability event. Joint events have the propensity to cause severe flooding as rainfall cannot flow out to sea through the stormwater system when storm surge flows into the outfalls. This leads to ponding at the surface near elevation depressions.

Here we zoom in on how this will impact Chelsea at a more local scale by using climate model simulations to calculate future rainfall in two future periods: the mid-21st century climate (2041–2060) and the late 21st century climate (2071–2090). To estimate future storm surge heights for the two future time periods, we draw on sea level rise estimates generated from the literature which uses the latest knowledge on local sea level processes, ice sheet dynamics, and ocean currents.

The results from the rainfall analysis and the sea level rise estimates are used as inputs into a flood model to simulate future flood events. We present results from the late 21st century as this is relevant for large infrastructure projects; the design life of many infrastructure systems such as rail tracks, bridges, transmission lines, generating plants, water treatment and wastewater treatment plants, and stormwater systems usually have a 50-year or longer design lifetime (Gibson, 2017). Furthermore, many of these installations are often used beyond their design period, which means it is likely that infrastructure built in 2020 will still be in use by the late 21st century. Presenting projected flood risks in the 2071–2090 time frame allows planners to incorporate information on future flood risks in policy choices and the chance to mitigate flood losses. The flood risk analysis extends to an assessment of how flood extents and the number of buildings impacted, including federally assisted rental units, changes across time periods and flood scenarios.

Finally, we include a brief analysis on the change in monthly flood insurance premiums due to FEMA's implementation of Risk Rating 2.0 on October 1, 2021. We analyze how many single-family home policies will increase or decrease in premium price as well as all policies in Chelsea.

Methodology

Flood risk in Chelsea is estimated using a coupled version of the LISFLOOD-FP flood model version 5.9 and the Environmental Protection Agency's (EPA) Stormwater Management Model (SWMM) (Bates et al., 2000; Rossman, 2015). LISFLOOD-FP has been tested extensively and produces comparable results to several localized and detailed flood studies conducted by the USGS that were calibrated using local data. Wing et al. (2017) compared the output of a non-calibrated continental United States LISFLOOD-FP model run at a 30-meter resolution to USGS flood risk estimates that utilized elevation data with resolutions between 1 and 10 meters. The LISFLOOD-FP model was able to achieve a consistent hit rate of at least 80%

[1] The Kendall rank correlation coefficient, or commonly known as Kendall's Tau, measures the strength and direction of a relationship between two variables.

across nine USGS flood studies that estimated the 1-in-100 year flood event.[2] The critical success index was between 60% and 90% for all but one USGS flood benchmark study. Another study that utilized LISFLOOD-FP to simulate coastal flooding in New Jersey also determined that the model achieved extreme accuracy (Seenath, 2018).Therefore, LISFLOOD-FP was chosen to model flood risk for the City of Chelsea because of its computational efficiency when run at high spatial resolutions and its ability to accurately estimate flood risk at large spatial scales. SWMM was chosen as the stormwater model due to its long history of development and frequent use in academia and stormwater system engineers. The two models are coupled using an approach similar to the one implemented by Wu et al., 2018. However, to reduce the runtime, the SWMM model is executed within the LISFLOOD-FP simulation rather than executing both from a third program. This modification only requires loading in the grid data into LISFLOOD-FP once rather than every time step as was done in Wu, et al. Further details on the coupling procedure can be found in the appendix.

Each flood simulation represents a one-day event, but the flood model was run for a total simulation time of two days to allow all the water that entered the domain to leave the system (or to remain ponded at the surface). Only grid cells with a water depth greater than or equal to 0.15 meters (6 inches) are shown in the final maps. We apply this threshold because water depths above this level have the potential to cause property damage (EA, 2019). Several inputs are required to run the model which are described in detail below:

1) Elevation data: Two Digital Terrain Models (DTMs) were merged to create a final DTM. Most of the study area was covered by a 3-foot resolution DTM created from LiDAR data shared by David Bedoya from Dewberry. The rest of the study area was filled in using data from the Coastal National Elevation Database (CoNED) project (Danielson and Tyler, 2016). The data was then reprojected to a 2-meter horizontal resolution grid. Bridges were taken out of the DTM and culverts were burned into the DTM for hydrographic reinforcement.

2) Floodplain friction values or Manning's n values: Each pixel in the model domain was assigned a friction value based on land cover from the NOAA Coastal Change Analysis Program Land Cover dataset (OCM, 2018). The friction values come from an analysis completed by the United States Department of Agriculture (NRCS, 2016).

3) Infiltration Rates: Soil infiltration rates were assigned as the saturated hydraulic conductivity rate from the SSURGO database using an area and depth weighted method (Wieczorek, 2014). Grid cells that are impervious according to the OCM land cover dataset were assigned an infiltration rate of zero.

4) Storm Surge:
    a. Historical storm surge: The historical 1% annual chance storm surge calculated in the "Summary Report of Coastal Engineering Analyses" prepared by STARR which informed the current effective FEMA flood map for Suffolk County (STARR, 2013). The tidal curve was created using Mean High Water and Mean Low Water for the NOAA Boston tide gauge. The tidal curve was also applied during the rainfall-only simulations to include backwater effects at outfalls.

    b. Future storm surge: To estimate future storm surge, sea level rise was added to the historical storm surge level. Sea level rise amounts for Boston from Kopp, et al. (2017) were used in this study because these estimates include highly relevant physical processes such as Antarctic ice-shelf hydrofracturing which leads to overall higher sea level rise estimates through 2100 compared to other sea level rise studies. Sea level rise was estimated to be 28 cm and 94 cm from 2020 to 2050 and 2020 to

[2] The hit rate measures how well the model predicted the number of wet cells in the benchmark data. Essentially, the hit rate gives an indication of how much the model underpredicted the validation data. The lower the hit rate, the greater the underprediction. The critical success index accounts for both underprediction and overprediction and so will usually be lower than the hit rate.

2080, respectively. Work by Edwards et al. (2019) has argued that because these ice-sheet dynamics are not well constrained in model simulations, estimates that do include them result in overestimating sea level rise. However, the values presented in Kopp, et al. (2017) are within the bounds expected by experts within the scientific community (Bamber et al., 2019). Additionally, since 1990, as studies continuously update sea level rise estimates through 2100, the predicted amount of sea level rise has steadily been increasing highlighting the need for utilizing higher-end estimates of sea level rise (Garner et al., 2018). Building infrastructure with slight overestimates of sea level rise can provide a buffer during extreme events. Changes in the climatology of nor'easters or hurricanes are not accounted for in this study. Sea level rise was also included during the future period rainfall-only simulations to properly account for future backwater effects at outfalls.

5) Precipitation: For this study, rainfall only occurs where the stormwater system is present in the model domain. This is due to the high area of impervious land cover present in Chelsea. The stormwater system is the main method for which rainfall leaves the surface in this municipality. Therefore, a small portion of the western model domain that is outside of the City of Chelsea boundary does not experience rainfall.

    a. Historical rainfall: Extreme precipitation amounts for the present climatological period were taken from the NOAA Atlas 14 (NA14) (Perica, 2019). The NA14 24-hour temporal distribution of rainfall was also used. The distribution representing 90% of all cases was used because of how likely a real-world event would be similar to this distribution. The distribution was not altered for modeling future rainfall events.

    b. Future rainfall: To estimate the change in probability of the 1% annual chance event in the 2041–2060 and 2071–2090 future periods in reference to the historical (2001–2020) under the Representative Concentration Pathway (RCP) 8.5 scenario. We use RCP8.5, the most aggressive emissions scenario, because it most closely matches historical emissions from 2005 to 2020 (within 1% for total carbon dioxide emissions) compared to other pathways (Schwalm et al., 2020). We use output from a regional 0.22° resolution climate model, REMO2015, which was forced by 3 general circulation models (GCMs) to calculate the change in probability (Remedio et al., 2019). A regional frequency analysis method was used to fit a generalized extreme value (GEV) distribution by the method of L-moments using the rainfall regions algorithm developed by Badr et al. (2016) (Hosking et al., 2005). Finally, the future return period of the historical 1% annual chance event is calculated by taking the average of the return period values of the surrounding 8 grid cells as well as the grid cell Chelsea is located in. This is done to estimate the regional trend in changes of extreme precipitation since climate model output for extreme precipitation can vary significantly between adjacent cells. To calculate the future rainfall amount, the return period is converted to a magnitude using the marginal distribution from NA14.

6) Stormwater system: The City of Chelsea's stormwater data provided by Dewberry required extensive modifications before being inputted into the SWMM model. Out of the 2,269 manholes provided, 2,262 were used but 10% were missing invert elevations. Out of the 2,070 catchment basins provided, 1,176 or 57% were used. Out of the 3,413 pipe segments used, 65% were missing invert elevations. Due to the missing data, invert elevation data was interpolated between valid features. First, invert data was shared between manholes, catchment basins, and conduits. Then, invert elevations were interpolated between upstream and downstream pipe segments. Finally, any remaining missing values were filled in by using the slope of the pipe segment and a valid

downstream invert elevation value. Some catchments were also moved to be attached to the stormwater system if they were extremely close to a nearby pipe segment. The Carter Street pump station was also included in the stormwater model using diagrams provided by Dewberry.

An additional analysis was completed involving the joint probability distribution for rainfall and storm surge. Water elevation data from the Boston NOAA tide gauge (ID:8443970)[3] and rainfall from the NA1[4] annual maxima data for the Boston Logan Airport.4 The Generalized Extreme Value distribution was used to fit both the rainfall and storm surge data because it had the lowest AIC and BIC across several distributions that were tested (e.g. Gumbel, Pearson Type III). A Gumbel copula was then fitted to the data to determine the relationship between the two marginal distributions. Given the many possible combinations of storm surge and rainfall probabilities to form the 1% annual chance event, one scenario was chosen given the computational costs of running multiple scenarios. The 1% joint probability scenario used in this study was the 22-year storm surge and the 11-year rainfall events. While the annual maxima rainfall and storm surge data are from individual stations, we use the magnitudes from the marginal distributions of rainfall and storm surge calculated by NOAA and STARR, respectively, because they are the current estimates used in regulatory, local engineering, and policy spaces. Additionally, we assume copula relationship doesn't change in the future because it is difficult to estimate changes in the joint distribution using the available climate data with the degree of accuracy necessary for this study.

Finally, we note sources of uncertainty in this study that have not been previously mentioned. The first being that generally the uncertainty in climate model outputs will increase with spatial resolution since climate models are estimating some atmospheric processes that occur at spatial resolutions higher than the model resolution. Second, within a flood model, there is some uncertainty regarding antecedent moisture conditions as these can impact the ability of soils to infiltrate rainfall and thus flooding. Sensitivity tests regarding antecedent moisture conditions were not completed as part of this study; however, since most of the land cover in Chelsea is impervious, antecedent moisture is likely a small source of uncertainty. Third, there is uncertainty in pluvial flood estimates in urban areas where invert elevations and other attributes of the stormwater system are estimated. Fourth, wave action is not included in this study; however, wave action is likely quite minimal given how far upstream Chelsea is located within the harbor of Boston. Finally, estimating return intervals for extreme events in the future requires extrapolation of historical data which may not encompass the full range of possibilities resulting in uncertainty around the future probabilities.

Results and Discussion

A. Present Flood Risk and Comparisons to FEMA and BH-FRM Flood Maps

To validate the storm surge results of this analysis, we use the 2030 1% annual chance flood map generated from the BH-FRM. Since BH-FRM was calibrated and validated with previous extreme storm events and was shown to have a high degree of accuracy in predicting water surface elevations, the BH-FRM flood extents can be used as a proxy to ground-truth data. We also compare the FEMA 1% annual chance extent to the results from this study to determine if FEMA is under- or overestimating flood risk and subsequently, flood insurance requirements.

Figure 2 shows the BH-FRM 2030 1% annual chance flood extent and depth and Figure 3 shows the comparison between the rainfall and storm surge results from this study and the FEMA flood zone extent. There is a large discrepancy between FEMA and this study's results in the western part of Chelsea. The islands of flooding are from rainfall. The FEMA floodplain

[3] Data available at: https://tidesandcurrents.noaa.gov/stationhome.html?id=8443970

[4] Data available at: https://www.ncei.noaa.gov/maps/daily-summaries/

extends much further inland than the flood extents from this study or BH-FRM. On the other hand, the results from this study and BH-FRM are in close agreement over the entire coastline.

A possible reason for the large discrepancy is that a two-dimensional flood model was not used by FEMA, which instead uses an interpolation of coastline transects. While much of the area marked as within the 1% chance event by FEMA is lower than the 1% water elevation, there is a ridge between the low-lying area and the Island End River which prevents flood waters from reaching that far inland. It is unlikely that the FEMA transects would have picked up on this topographical feature because there are no transects within the City of Chelsea. However, this is a hypothesis and has not been verified with the authors of the FEMA flood maps. An additional discrepancy is that the water elevation values in the FEMA Flood Insurance Study (FIS) are lower than the values found in the STARR report even though the STARR report was used as a source for the FEMA FIS (STARR, 2013; FEMA, 2016). It is unclear why this discrepancy exists.

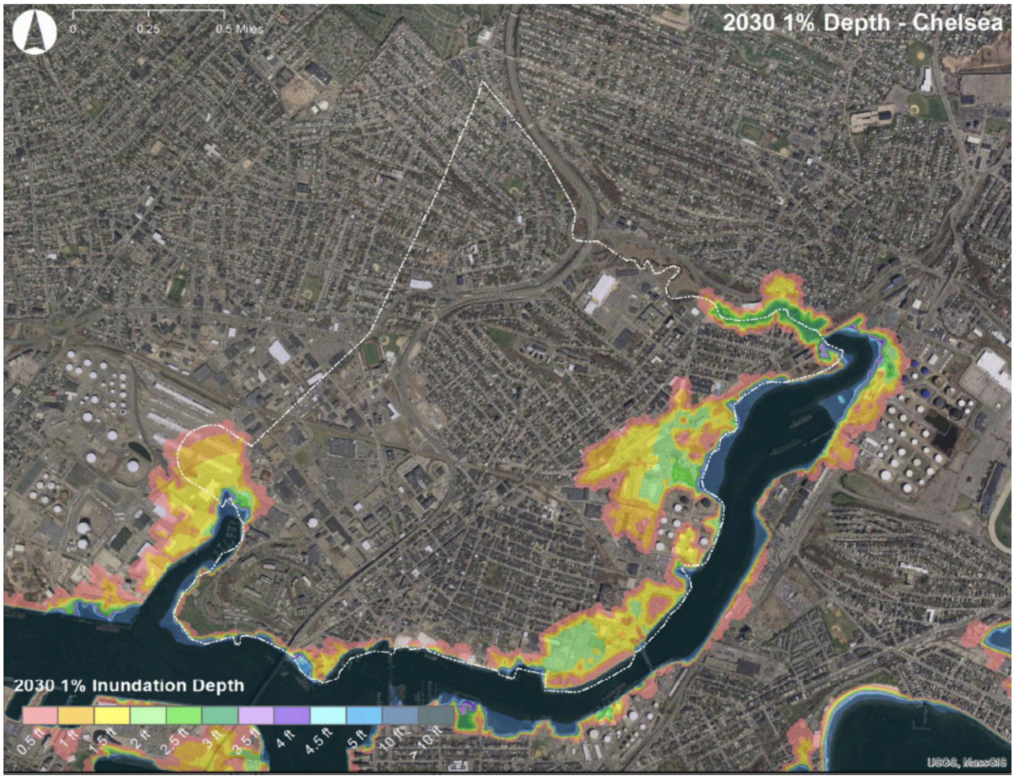

Figure 2.BH-FRM 2030 1% annual chance flood map.

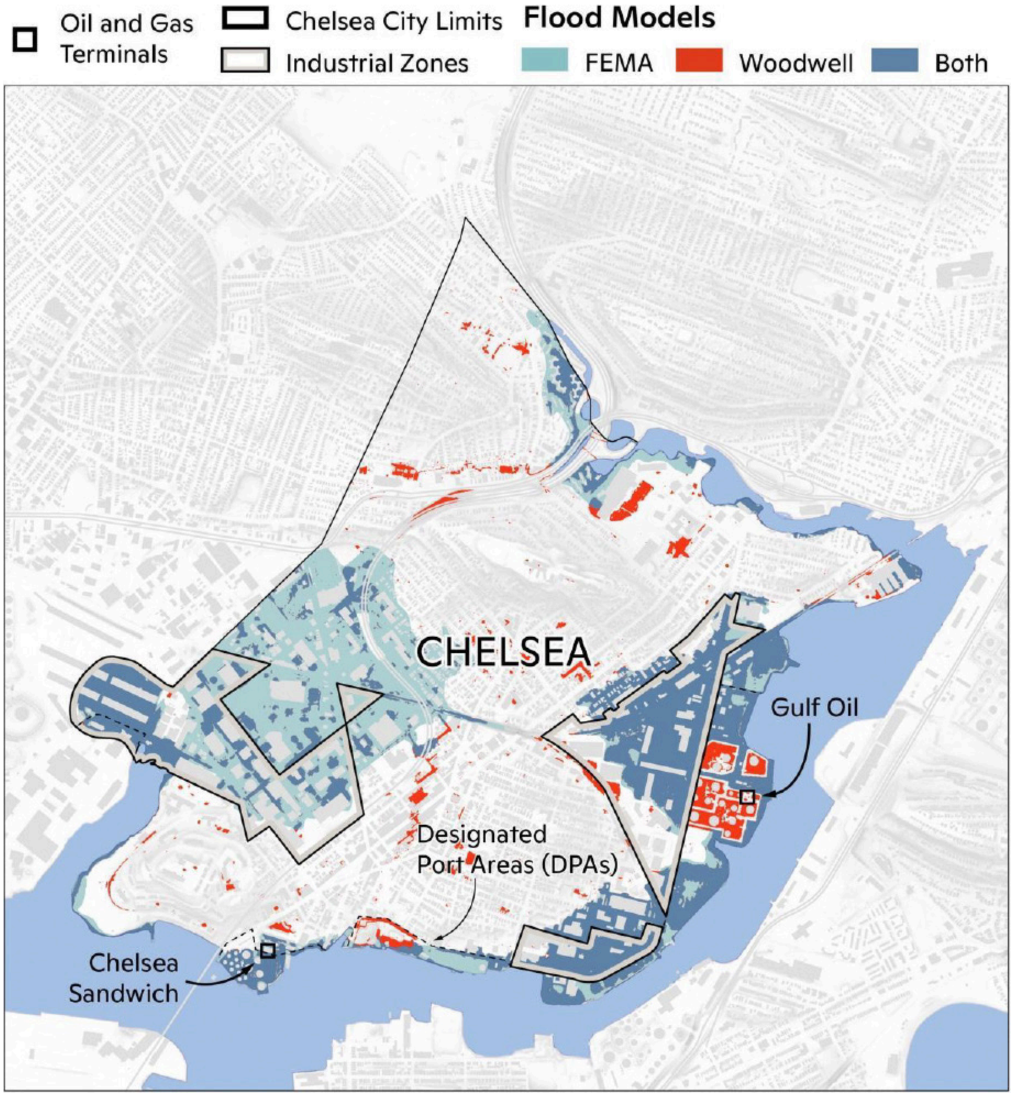

Figure 3. FEMA 1% annual chance vs Woodwell 1% annual chance.

B. Shifting Return Periods for Extreme Rainfall and Storm Surge

The future return period and probabilities of occurrence each year of the 1% annual chance rainfall and storm surge events are shown in Table 1. By 2050, the historical 1% annual chance rainfall event will be 3x as likely and almost 4x as likely by 2080. The historical 1% storm surge event will however experience even greater intensification; it will be 3.5x as likely in 2050 and **will likely occur every year by 2080**. The changes in the magnitudes for rainfall and storm surge are shown in Table 2. The changes in the marginal distributions that comprise the joint 1% chance event are shown in Table 3. Similar to the 1% chance event, the historical 9% annual chance rainfall event and the historical 4.5% annual chance storm surge event will become much more frequent by the mid and late 21st century. The changes in the magnitudes for the joint event of rainfall and storm surge are shown in Table 4.

	Present		2041–2060 (2050)		2071–2090 (2080)	
	Return Period	Probability	Return period	Probability	Return Period	Probability
Rainfall	1-in-100 year	1%	1-in-34 year	2.9%	1-in-26 year	3.8%
Storm Surge	1-in-100 year	1%	1-in-28 year	3.6%	1-in-12 months	100%

Table 1. Future return periods and probabilities of the historical 1% annual chance rainfall and storm surge events.

	Present (NA14)	2041-2060 (2050)	2071–2090 (2080)
Rainfall (inches)	7.99	10.63	12.42
Storm Surge (feet)	10.04	10.96	14.04

Table 2. Rainfall and storm surge magnitude of the present and future 1% annual chance event.

	Present		2041–2060 (2050)		2071–2090 (2080)	
	Return Period	Probability	Return period	Probability	Return Period	Probability
Rainfall	1-in-11 year	9.1%	1-in-6 year	17%	1-in-5 year	20%
Storm Surge	1-in-22 year	4.5%	1-in-7 year	14%	1-in-2 months	100%

Table 3. Future return periods and probabilities of the historical joint distribution 1% annual chance rainfall (9% annual chance) and storm surge (4.5% annual chance) events.

	Present (NA14)	2041-2060 (2050)	2071–2090 (2080)
Rainfall (inches)	7.99	10.63	12.42
Storm Surge (feet)	10.04	10.96	14.04

Table 4. Rainfall (9% annual chance) and storm surge (4.5% annual chance) magnitude of the present and future joint 1% annual chance event.

C. Future Flood Extents and Risk

The rainfall and storm surge values in Tables 2 and 4 are used as inputs into the flood model to generate flood extents which are shown in Figures 4, 6, and 7. As storm surge elevations increase with time, so too will flood extents. The western portion of Chelsea will see the greatest changes in flood extent as the floodwaters move into the previously tidal area of the Island End River.

Since the industrial portions of the city are generally located closest to the shoreline, they will face the greatest risk. This includes the oil and gas terminals, a road salt distribution facility, the New England Produce Center and Boston Market Terminal. Additionally, the Mary C. Burke Elementary Complex is within the 1% flood extent. Residential areas along the Chelsea Creek will also be increasingly affected by floodwaters. As sea levels rise, storm surge will be able to move further inland through the culverts along Chelsea Creek which will impact residents on either side of the waterway. Figure 5 shows the flood extent for the 1% annual chance event in 2070 as predicted by BH-FRM. The Woodwell Climate results show greater flooding along Chelsea Creek likely due to the inclusion of culverts in the simulations while BH-FRM does not incorporate stormwater system infrastructure. Other possible reasons for differences between the two maps are that this study used the most recent LiDAR survey of Chelsea, BH-FRM utilized a different storm surge climatology, and this study assumed a static storm track and intensity climatology while BH-FRM estimated changes in tropical cyclones and nor'easter distributions for the future.[5]

The 1% annual chance rainfall event in the present time frame causes significant flooding in the eastern and western lowlands. The stormwater system is overwhelmed in these areas which results in severe ponding. The bund walls (berms surrounding oil tanks) in the Gulf Oil terminal are completely inundated and it is unclear how such a large volume of water would affect the structural integrity of the oil tanks or the bund walls. By 2050 we generally see slight increases in the flood extent in the eastern portions of Chelsea but some reductions in the extent in the western half of Chelsea. It is unclear as to why this occurs but likely due to the parameterization of water flowing into catchment basins within the LISFLOOD-FP and SWMM coupling. Due to increased pressure from more rainfall, the parameterization may be forcing more water into the sewer system than in the historical simulation. By 2080, the flood extent will increase throughout Chelsea.

The present joint 1% annual chance event causes flooding mainly in the industrial areas on the eastern and western edges of Chelsea. The low-lying areas pool water while some coastal flooding prevents rainfall from properly draining to the ocean. By 2050, in addition to increased pluvial flooding, coastal flooding resembles the historical 1% annual chance storm surge event. In 2080, the coastal flooding extent is only slightly smaller than the 2080 1% annual chance storm surge event plus the increased pluvial flood risk.

[5] Woodwell Climate reached out to the Massachusetts Department of Transportation (MDOT) for access to the BH-FRM storm surge climatology but no response was received.

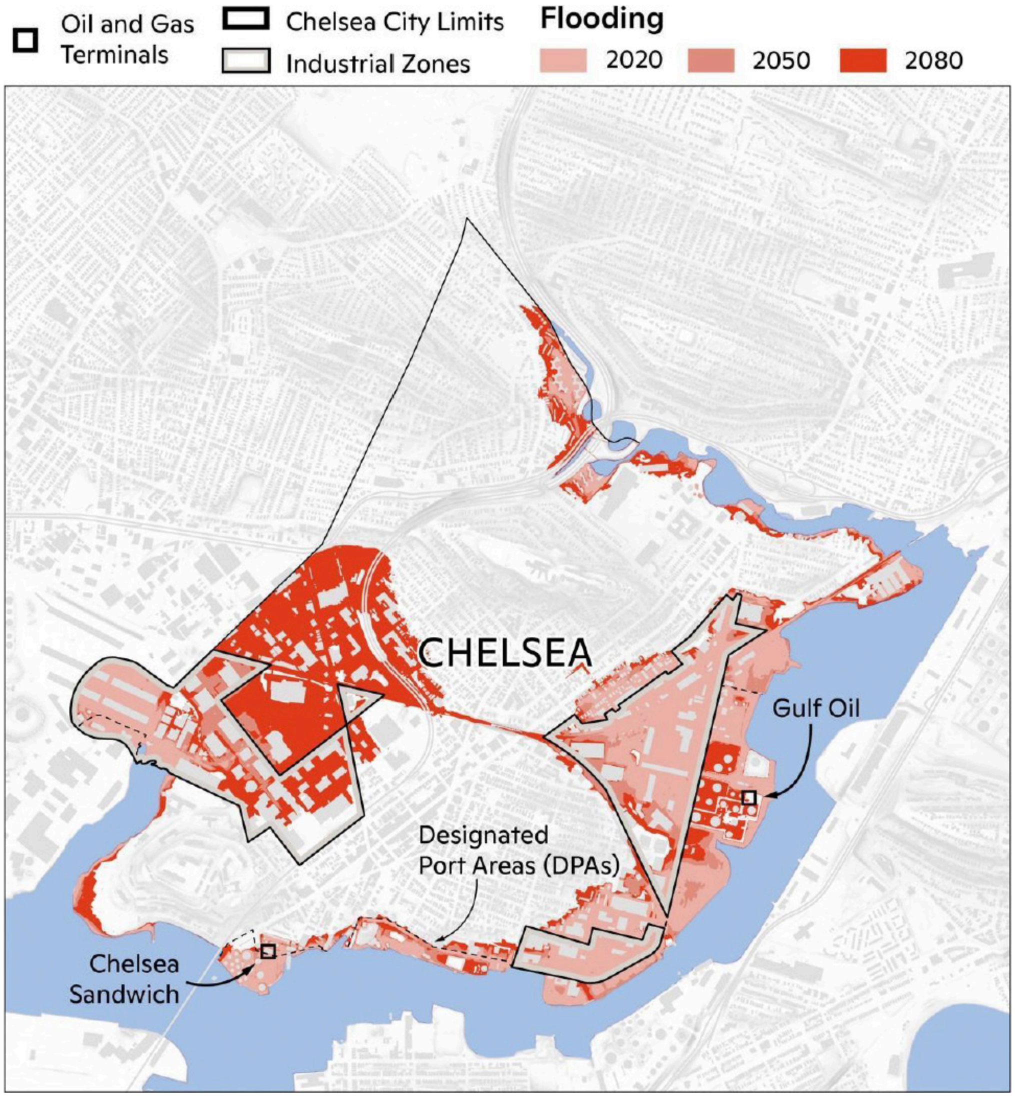

Figure 4. Woodwell Climate present, 2050, 2080 1% annual chance storm surge flood map.

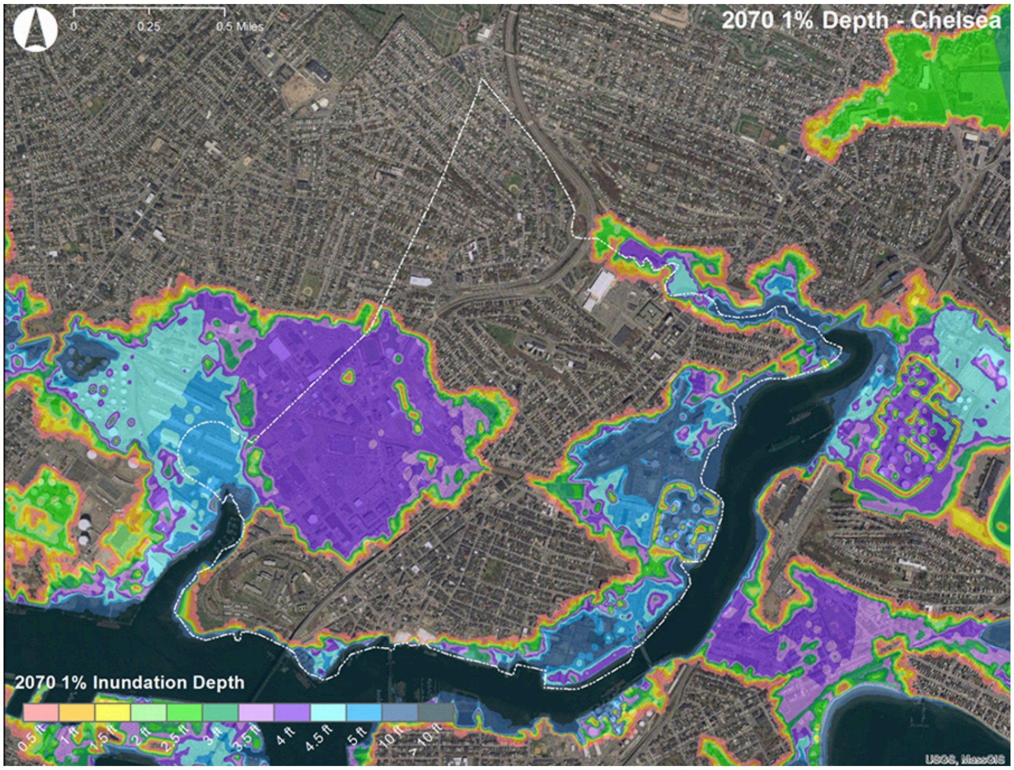

Figure 5. BH-FRM 2070 1% annual chance flood map.

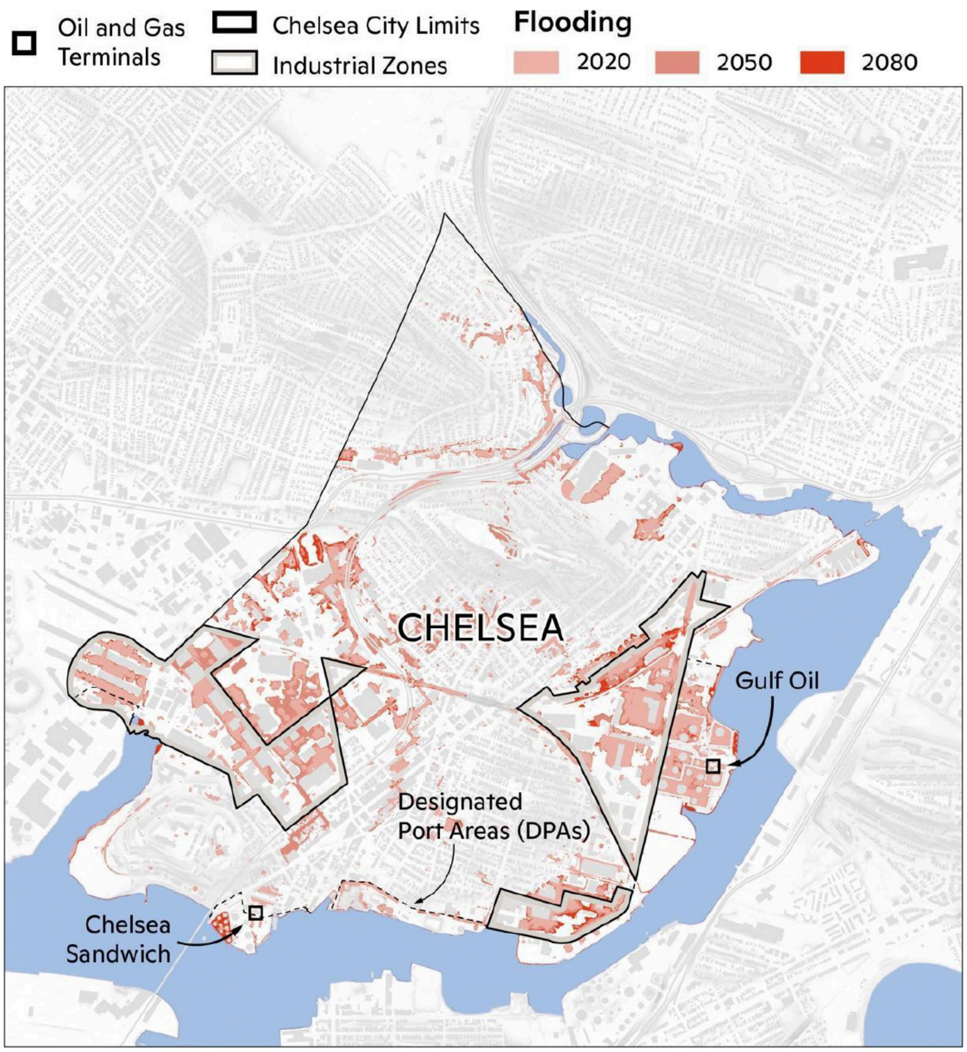

Figure 6. Woodwell Climate present, 2050, 2080 1% annual chance rainfall flood map.

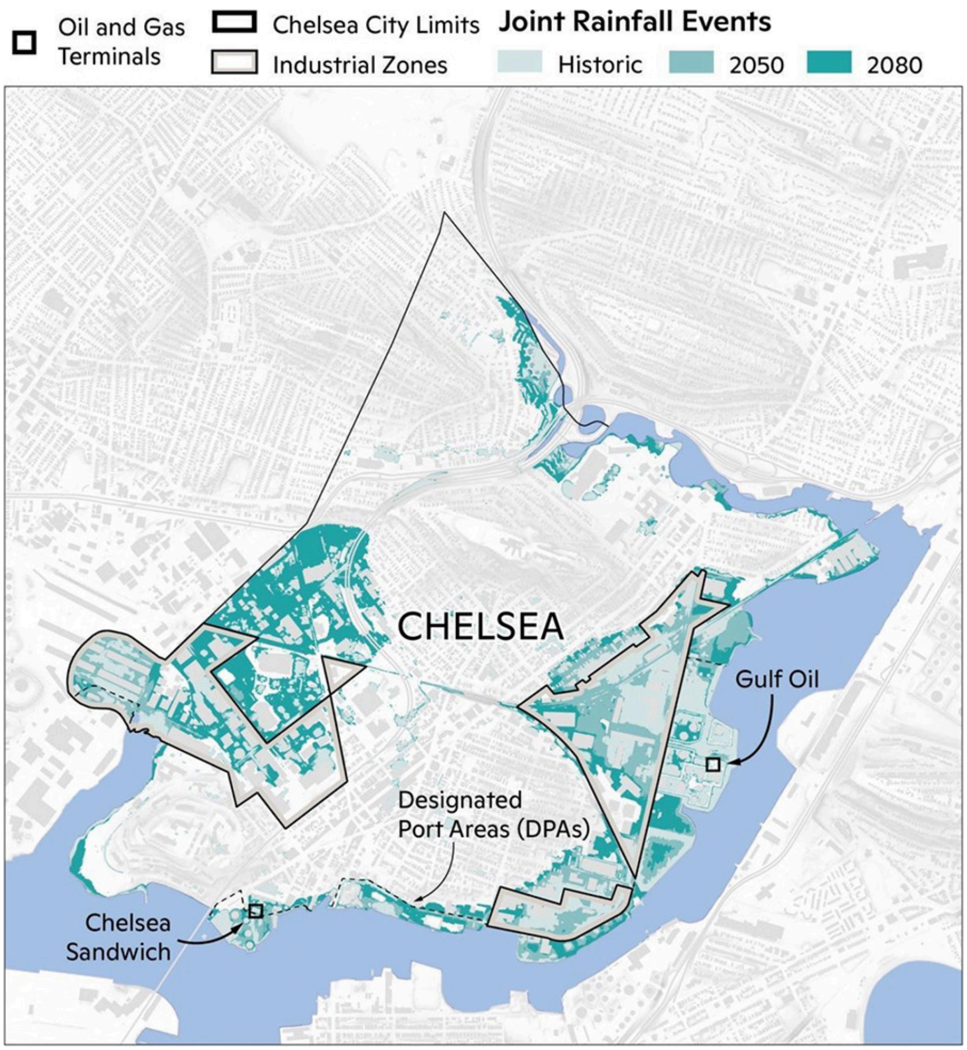

Figure 7. Woodwell Climate present, 2050, 2080 1% annual chance joint event flood map.

Storm surge is often characterized as the most devastating of flood types due to the large-scale flooding that occurs. While storm surge often produces greater flooded areas compared to joint events or rainfall events, as shown in Figure 8, this metric does not fully incorporate the impact on structures and people. Figure 9 shows the zoning districts of the City of Chelsea and Figure 10 shows the building outlines within the city. The building data is sourced from MassGIS. Industrial activity dominates the waterfront and the western part of the city while residential neighborhoods are located in the central and northern parts of the city. Because residential areas are not directly on the shoreline, heavy rainfall events would likely present a greater threat than storm surge. Many buildings in the residential zones, R1 and R2, are impacted by pluvial flooding while the storm surge cannot reach that far inland. As shown in Figures 11, 12, and 13, the 1% annual chance rainfall event impacts more buildings than the joint event or the storm surge event despite impacting the least amount of total area. This holds true through all time periods except for 2080 where the joint event affects the greatest number of buildings. The joint event impacts approximately 200 more buildings than the storm surge event across time periods. The joint event affects significantly more residential and business retail structures than the storm surge event. These findings demonstrate the often underestimated and underappreciated risk associated with pluvial events as well as joint events (Wing et al., 2018). While storm surge can produce greater flood depths, the inland propagation of coastal flood waters is limited. Pluvial flooding is not restricted in the same way.

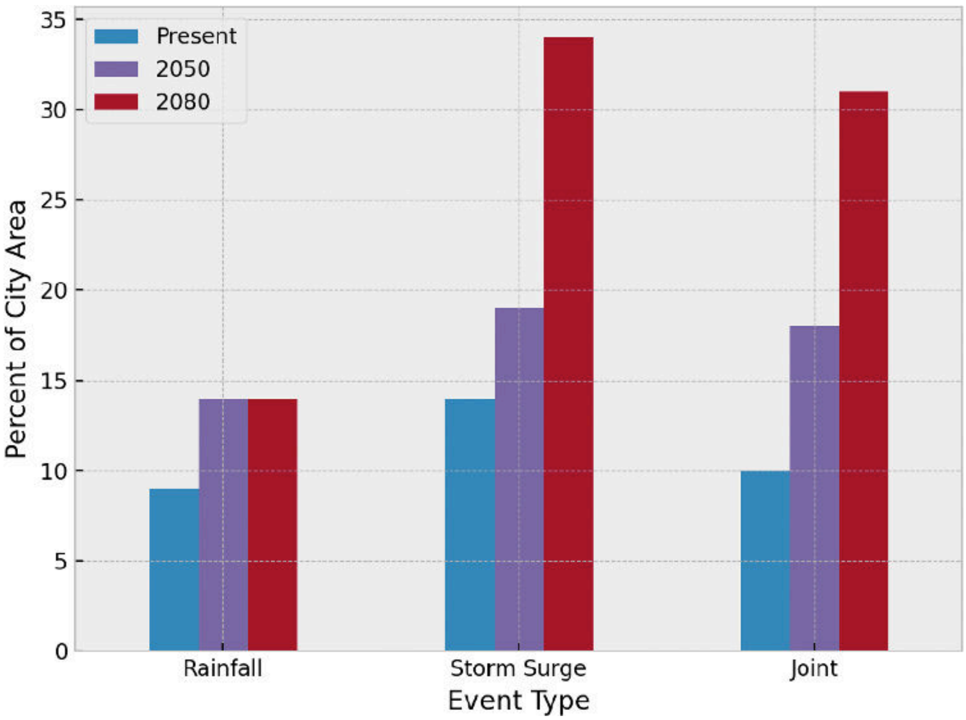

Figure 8. Percentage of Chelsea area within the flood extent for various flood events and time periods. Exact numbers are shown in the appendix Table A.1.

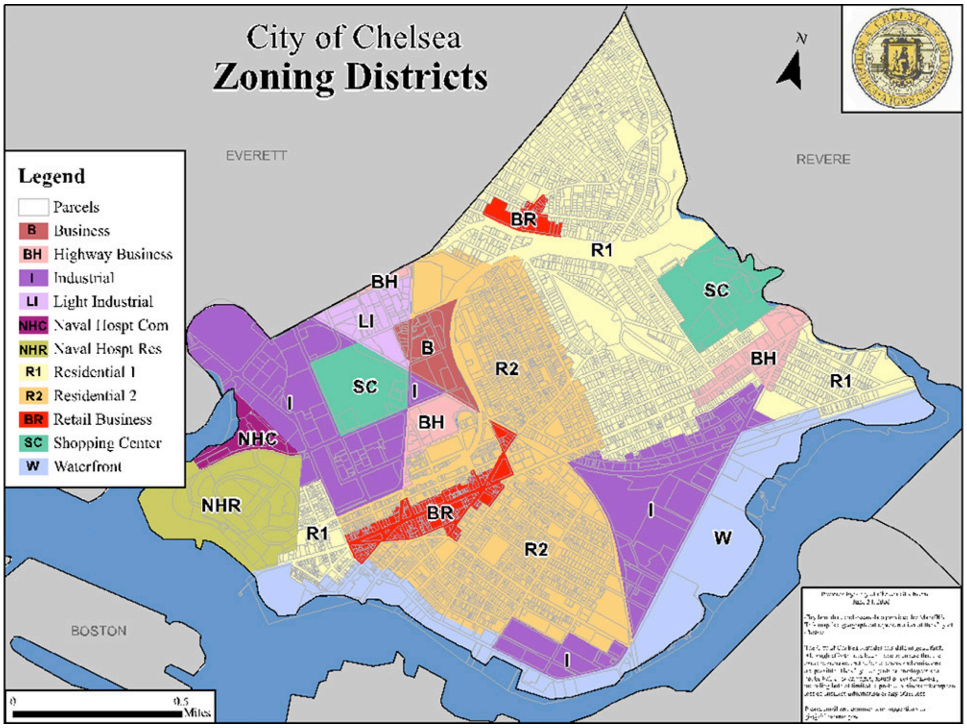

Figure 9. Zoning Districts for Chelsea, MA; source: City of Chelsea.

Figure 10. Outlines of the 4,347 structures in Chelsea.

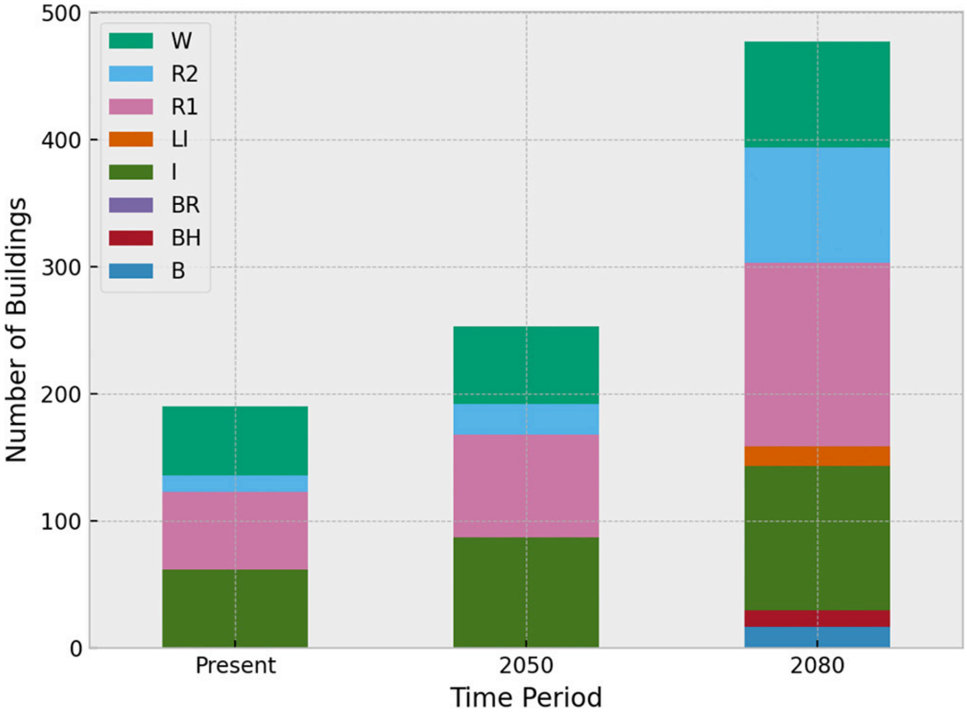

Figure 11. Number of buildings in flood extent by zoning district for the 1% annual chance storm surge event. Exact numbers are shown in the appendix Table A.2.

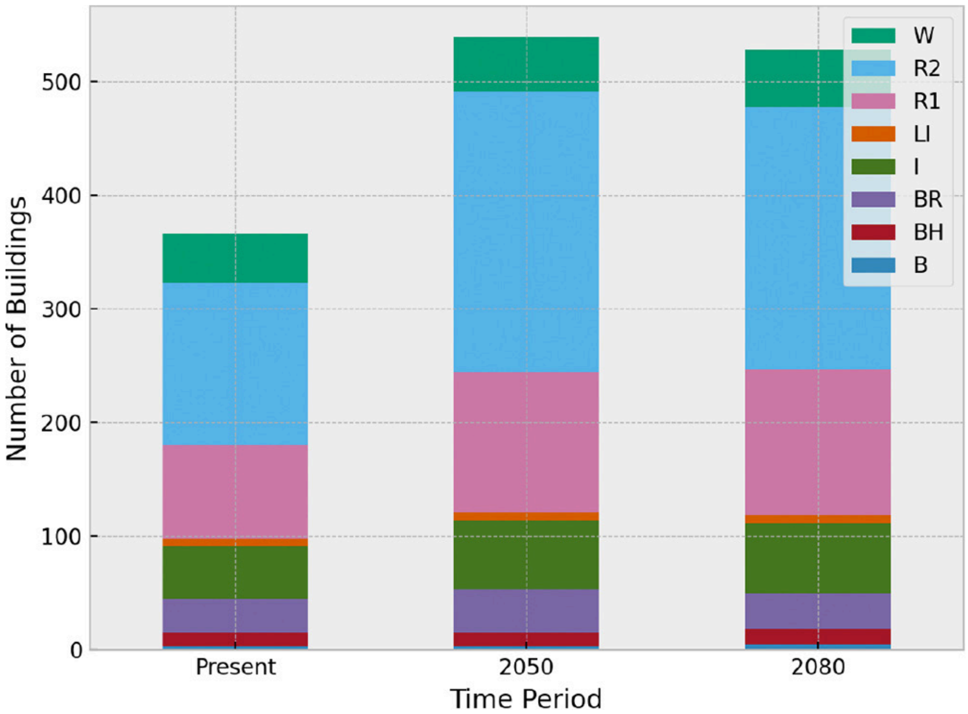

Figure 12. Number of buildings in flood extent by zoning district for the 1% annual chance rainfall event. Exact numbers are shown in the appendix Table A.3.

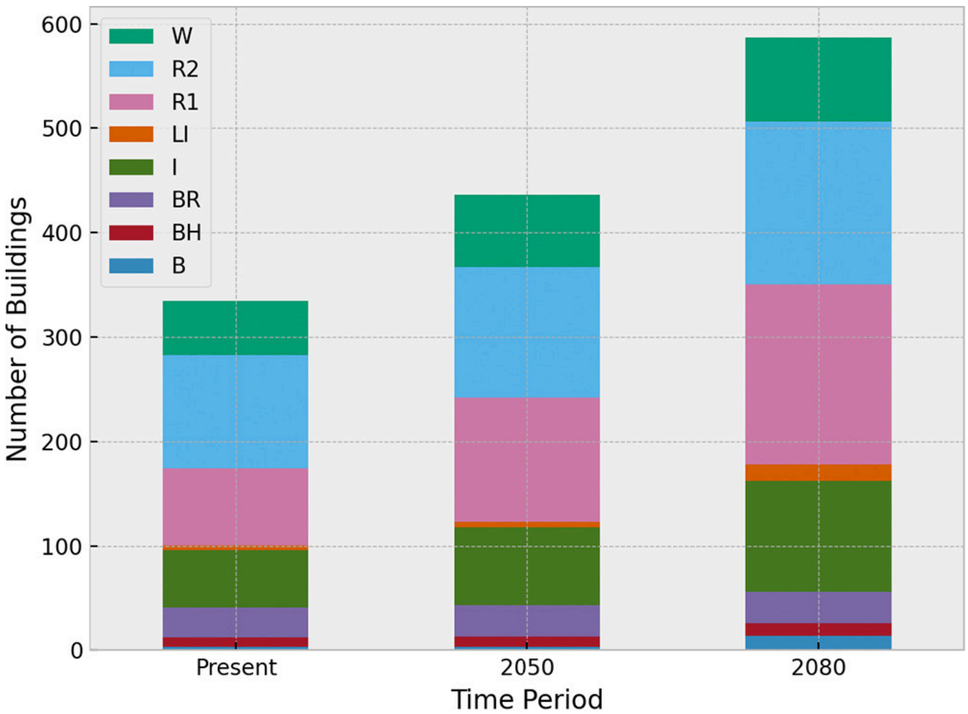

Figure 13. Number of buildings in flood extent by zoning district for the joint 1% annual chance rainfall and storm surge event. Exact numbers are shown in the appendix Table A.4.

To complete an analysis of the federally assisted rental housing units vulnerable to flooding in Chelsea, data from the National Housing Preservation Database (NHPD) was used.[6] The NHPD combines data from different federal agencies and programs that provide funding for housing assistance. There are 45 buildings in Chelsea that currently receive federal funding for housing assistance. Of those 45, none are vulnerable to the present day 1% annual chance storm surge and only one, the Spencer Green apartment building on the east side of Chelsea, is vulnerable to storm surge in 2050 and 2080. By 2050 approximately 30 cm (11.8 in) of water will impact the building and by 2080 the water level will jump to one meter (3.3 ft). The 1% annual chance rainfall event will also only impact one building, The Greenhouse, in southern central Chelsea. It is estimated that the present day 1% annual chance event will flood the structure with bring 40 cm (1.3 ft) of water. By 2050 and 2080, the water level will increase to 43 cm (1.4 ft) and 45 cm (1.5 ft), respectively. The current 1% annual chance joint event will also affect The Greenhouse but with 35 cm (1.1 ft) of water. By 2050 and 2080, the water level will increase to 37 cm (1.2 ft) and 39 cm (1.3 ft). Additionally, the 2080 1% annual chance joint event will impact the Spencer Green building with 74 cm (2.4 ft) of flooding.

D. Risk Rating 2.0 in Chelsea

On October 1, 2021, a new flood insurance premium pricing system for FEMA went into effect for all policies up for renewal if the policyholder wishes to participate. This program, Risk Rating 2.0, will be applied to all policies starting on April 1, 2022. The purpose of this new system is to provide more equitable pricing for flood insurance premiums and price flood risk at the individual house level. Many critics of the program worry that the new prices will be unaffordable to many current policyholders. Here we provide a brief analysis on the changes to monthly flood insurance premiums for the City of Chelsea. The highest resolution of the data provided by FEMA on the projected changes to premiums is at the zip code level and since the zip code 02150 only covers Chelsea, we can provide an analysis that only considers Chelsea.

Table 5 shows the percentage of policies that will experience different levels of adjustments to their monthly premiums. A separate row also shows those changes for single family homes only. Within Chelsea, a quarter of single-family home policies will see a decrease in the premiums while 75% will see a slight increase of no more than $10 per month. If all policies are considered, approximately a quarter will see a decrease, $50 will see an increase of no more than $10, and another quarter will see an increase greater than $20.

However, because 70% of households in Chelsea rent, this analysis is somewhat limited in assessing the impact of Risk Rating 2.0 on the residents of Chelsea (Ambrosino, 2017). Since renters are not required to purchase flood insurance, even if they live in the 100-year floodplain, it is unlikely that the 196 policies (that are not single-family homes) are renters' policies. There are 461 buildings (after removing oil tanks and small structures on industrial properties) within the FEMA 100-year flood extent. It is possible that several buildings are under the same policy but it is unlikely that all buildings within the 100-year floodplain currently have mandatory flood insurance given that there are twice the number buildings as policies. Therefore, there is likely a large proportion of households that are or will be vulnerable to flooding and do not carry flood insurance. Flood risk in Chelsea is exacerbated by the fact that 50% of all housing units are in small buildings with 2 to 4 units and 65% of all units were built before 1939 (Ambrosino, 2017). With more units at or below the ground elevation and aging building structures, flood waters would affect a large number of households.

[6] Data available at: https://preservationdatabase.org/

Lower income groups and minorities are impacted disproportionately by natural disasters and part of the reason is that insurance uptake is greater among more privileged communities (Kousky and Wiley, 2021). Low income communities lose a greater proportion of their net worth during a flood than communities with greater resources. Flood insurance would safeguard against such a loss. Flood insurance uptake is an affordability issue since the average monthly rent of $2,202 for a multifamily residence is $1,000 more than what the average employee in Chelsea can afford to spend (Ambrosino, 2017). Additionally, low flood insurance uptake among renters is partly due to many renters believing a standard renter's insurance covers weather related floods when it does not. A 2011 survey by Allstate reported that 30% of respondents thought they had flood insurance when they did not (Dixon et al., 2013). Since renter's insurance is considerably less common than homeowner's insurance, it is likely that a sizable majority of renters in Chelsea do not carry flood insurance. This is problematic because without flood insurance, it is substantially harder to recover after a flood when many possessions are lost.

	Number of Policies	Decrease	$0 to $10	$10 to $20	Greater than $20
Single-Family Homes	45	26.7%	73.3%	0%	0%
All Policies	241	21.9%	53.1%	2.1%	24.9%

Table 5. Monthly Premium Changes for FEMA policies in Chelsea.

Appendix

	Present	2050	2080
Rainfall 1% Event	9%	14%	14%
Storm Surge 1% Event	14%	19%	34%
Joint 1% Event	10%	18%	31%

Table A1. Percentage of Chelsea area within the flood extent for different flood events and time periods.

	All	B	BH	BR	I	LI	NHC	NHR	R1	R2	SC	W
Present	**191**	0	1	0	61	0	0	1	61	13	0	54
2050	**256**	0	1	0	86	0	1	1	81	24	1	61
2080	**487**	17	13	0	113	16	1	1	144	91	8	83

Table A2. Number of buildings in flood extent by zoning district for the 1% annual chance storm surge event.

	All	B	BH	BR	I	LI	NHC	NHR	R1	R2	SC	W
Present	**383**	3	12	30	46	6	0	10	83	143	7	43
2050	**558**	3	12	38	61	7	0	100	123	247	9	48
2080	**545**	5	13	32	61	8	0	10	128	230	7	51

Table A3. Number of buildings in flood extent by zoning district for the 1% annual chance rainfall event.

	All	B	BH	BR	I	LI	NHC	NHR	R1	R2	SC	W
Present	**348**	3	9	29	55	5	0	7	73	108	6	53
2050	**452**	3	10	30	75	5	0	9	119	125	7	69
2080	**606**	14	12	30	106	16	1	9	173	155	9	81

Table A4. Number of buildings in flood extent by zoning district for the joint 1% annual chance rainfall and storm surge event.

LISFLOOD-FP and SWMM Coupling Methodology

LISFLOOD-FP (LFP) and SWMM are coupled by taking the output from one model and using it as the input for the other model over one time step. For each time step, exchanges of water volume occur at three connecting features: manholes, catchbasins, and outfalls. When water flows into a catchbasin, a volume is subtracted from the LFP grid cell and enters the SWMM model domain. If a manhole begins to flood in SWMM and begins to pond at the surface, a water volume is removed from SWMM and added to an LFP grid cell. Finally, as water flows out of an outfall in SWMM it is removed from both the SWMM and LFP model domains. The ocean is treated as an infinite reservoir so no water from outfalls is added to the LFP domain. Several assumptions are required to complete this model coupling:

1) We assume all manholes are not sealed. The additional head pressure of a sealed manhole is not accounted for and is only applied for manholes along a force main.

2) Flow into catchment basins is not inhibited by debris. We also do not consider the lowered efficiency of clogged catchment basins.

3) Estimation of inlet capacity of catchment basins is based on highly localized features such as street slope, size of grate, curb opening, type of grate, type of curb opening, etc. (UDFCD, 2016). To reduce the complexity required for hundreds of catchment basins, flow into catchment basins is governed by the orifice equation which only relies on the size of the grate opening, the pressure head from the ponded water, and an orifice coefficient to estimate flow (Rubinato et al., 2017; Mustaffa et al., 2006). The orifice coefficient was estimated using a regression analysis by Rubinato et al. (2018). The orifice area, or size of the grate opening, was assumed to be the same for all catchbasins. This assumption is reasonable due to a visual survey of catchbasins in Chelsea. Based on the survey, most catchbasins in Chelsea are of the same size and type. The orifice equation is a simplification of water flow into the stormwater system. It is likely that the flow into the stormwater system due to the orifice equation is an overestimate because there is no upper limit on flow and not all the water in the cell would be available to flow into the catchbasin. Some water would travel further downhill.

About Woodwell Climate Research Center

Woodwell Climate Research Center ("Woodwell") is an organization of researchers who work with a worldwide network of partners to understand and combat climate change. We bring together hands-on experience and 35 years of policy impact to find societal-scale solutions that can be put into immediate action, including with municipalities that are so often on the front lines of the climate crisis.

We were founded in 1985 as the Woods Hole Research Center by George Woodwell, a visionary ecologist. Today, we work around the globe, conducting research in collaboration with policymakers and decision makers in more than 20 countries. We conduct research on a range of strategies to immediately address climate change, from carbon sequestration solutions using Earth's forests and soils, to climate risk assessments that seek to shift public perception and corporate behavior. Our scientists are widely published in leading scientific journals, testify to lawmakers around the world, and are regularly quoted in media outlets from the *New York Times* to *CBS Evening News*. They have contributed to every Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), and shared the 2007 Nobel Prize awarded to the IPCC.

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