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MIT Climate Resilience Planning: Flood Vulnerability Study

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MIT Joint Program on the Science and Policy of Global Change combines cutting-edge scientific research with independent policy analysis to provide a solid foundation for the public and private decisions needed to mitigate and adapt to unavoidable global environmental changes. Being data-driven, the Joint Program uses extensive Earth system and economic data and models to produce quantitative analysis and predictions of the risks of climate change and the challenges of limiting human influence on the environment—essential knowledge for the international dialogue toward a global response to climate change.

To this end, the Joint Program brings together an interdisciplinary group from two established MIT research centers: the **Center for Global Change Science (CGCS)** and the **Center for Energy and Environmental Policy Research (CEEPR)**. These two centers—along with collaborators from the Marine Biology Laboratory (MBL) at Woods Hole and short- and long-term visitors—provide the united vision needed to solve global challenges.

At the heart of much of the program's work lies MIT's Integrated Global System Model. Through this integrated model, the program seeks to discover new interactions among natural and human climate system components; objectively assess uncertainty in economic and climate projections; critically and quantitatively analyze environmental management and policy proposals; understand complex connections among the many forces that will shape our future; and improve methods to model, monitor and verify greenhouse gas emissions and climatic impacts.

This reprint is intended to communicate research results and improve public understanding of global environment and energy challenges, thereby contributing to informed debate about climate change and the economic and social implications of policy alternatives.

—***Ronald G. Prinn and John M. Reilly,***
Joint Program Co-Directors

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1. Background

The MIT Flood Vulnerability Study is one key part of a broader initiative led by the MIT Climate Resiliency Committee (CRC) and the MIT Office of Sustainability (MITOS) to understand and recommend how MIT can continue to fulfill its mission in the face of intensifying climate risks over the next 100 years and beyond; risks include precipitation flooding, sea level rise/storm surge and chronic heat stress. This study seeks to translate the science of current flooding risks and future campus-based flooding risk from climate change into operational and strategic guidance for informing campus planning and management.

Inspired by the MIT Plan for Action on Climate Change, one key research and academic objective of this study is to utilize the MIT campus as a test bed for climate innovations. This study engages MIT's global research expertise in downscaling global MIT climate models for application testing on MIT's campus, and also collaborates with expertise and tools advancing the MIT Sustainable Stormwater and Ecological Landscape Master Plan.

This research initiative is supported by the MIT Office of Sustainability in collaboration with the MIT Joint Program on the Science and Policy of Global Change.

Study implemented by:

Dr. Kenneth Strzepek, Joint Program on the Science and Policy of Global Change

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With oversight by:

Professor Kerry Emanuel, Cecil & Ida Green Professor of Atmospheric Science

Dr. Julie Newman, MIT Director of Sustainability

The MIT Flood Vulnerability Study includes the following phases:

Phase 1A – Evaluation of Precipitation Probabilities and Preliminary Campus Flood Risks

Phase 1B – Identification of Existing Critical Utilities and Infrastructure Equipment

Phase 1C – Pilot Build of a 2D Campus Drainage Model

Phase 1D – Analysis of Joint Probability of Precipitation + Sea Level Rise/Storm Surge

Phase 2 – Comprehensive Integration of Modelling and Mapping with City of Cambridge and Metro Region

Phase 1A: Evaluation of Precipitation Probabilities and Preliminary Campus Flood Risks

Phase 1A is complete with methods, results, key conclusions and recommendations described in this report. This report will be updated as findings from subsequent sub-phases are completed in FY'18. Campus flood risk maps will continue to be revised as greater accuracy and precision becomes available.

A variety of research methods and tools form the baseline of the MIT Flood Vulnerability Study, including:

- MIT Synthetic Tropical Cyclone Generator to evaluate precipitation from 5,000 storms that pass over Cambridge for historical and future modeling
- US EPA Stormwater Management Model developed for MIT Campus
- Cambridge Climate Vulnerability Assessment
- Phase 1 MIT Sustainable Stormwater and Landscape Ecology Plan process and baseline data collection

1.1 Study Purpose and Context

The primary purpose of Phase 1A is to quantify MIT Cambridge campus flood risks under current and future climate change conditions over a range of probabilities. Phase 1A goals include:

1. Determine probability of future precipitation amounts anticipated for the MIT campus (2080-2100) for extreme rainfall events
2. Understand campus flooding exposure from precipitation events (current and future climate conditions)
3. Understand campus flooding exposure from sea level rise (SLR)/storm surge (SS) propagation (Note that Phase 1D will evaluate campus exposure to the joint probability of combined storm surge and precipitation events. Phase 1D completion is anticipated in spring 2018.)
4. Identify next step planning recommendations and additional research needs

The City of Cambridge Climate Change Vulnerability Assessment (CCVA) provides a strong baseline for understanding climate change risks facing MIT. Specifically, the CCVA has provided an initial frame of precipitation-driven flooding risk for Cambridge. However, the CCVA precipitation-driven flood projections did not include analysis of the portion of the City containing MIT due to insufficient baseline data about MIT stormwater infrastructure. Therefore, further study is needed to fill in the MIT campus portion of the Cambridge precipitation-driven climate risk map (see **Figure 1**).

The MIT Office of Sustainability contracted Dr. Kenneth Strzepek of MIT and Shawn Dent and Dr. Len Wright of Carollo Engineers, Inc. to execute the MIT Flood Vulnerability Study. This study seeks to generate advanced findings about climate risks for the MIT portion of the Cambridge maps, enhancing the campus and City understanding of integrated flooding risks. It will utilize the outcomes of Professor Emanuel's research on climate change impacts on the intensity

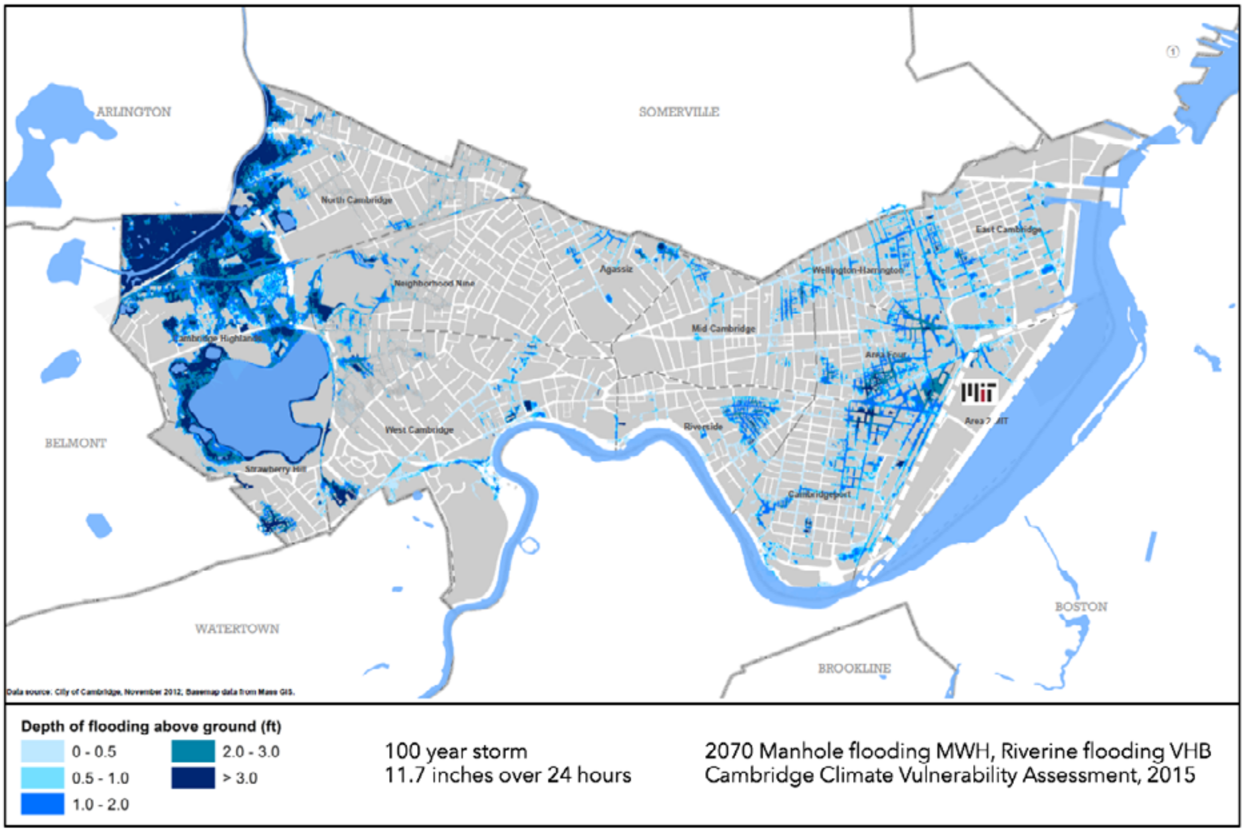

Figure 1. Cambridge CCVA Surface Flooding Depth 2070: This CCVA flood risk projection map illustrates the MIT campus portion (outlined in dashed white line) that will be filled in by the MIT Flood Vulnerability Study

and frequency of tropical storms, while at the same time harmonizing with the Cambridge CCVA flooding assessment.

2. Methods

The Flood Vulnerability Study Phase 1A involved developing methods for achieving three primary project goals:

1. Determine the probability of future precipitation amounts anticipated for MIT campus (2080–2100) for extreme rainfall events
2. Understand campus flooding exposure from precipitation events (current and future conditions)
3. Understand campus flooding exposure from sea level rise (SLR)/storm surge (SS) propagation

2.1 Determining the Probability of Future Precipitation

The Storm Water Management Model (SWMM) , first developed in 1969-71 by the U.S. Environmental Protection Agency, is a well-known and widely used dynamic rainfall-runoff quantity and quality simulation model for single event or long-term simulation, primarily designed for urban areas. A typical simulation starts with an estimation of runoff from climate parameters. The runoff is then routed through the system of pipes, channels, storage/treatment devices, pumps, and regulators, where quantity and quality are tracked. This allows for the determination of when and where flooding events inundate the system.[1] For the MIT Flood Vulnerability Study, we used a software tool called pcSWMM which adds many graphical and analytic enhancements to the basic USEPA SWMM.

While the MIT approach follows the same basic ratio approach used by the CCVA to adjust the design storm of modeled future precipitation to model historical precipitation, the climate change scaling ratios were developed using a unique and different approach. The MIT approach implements a high resolution tropical cyclone model driven by input from five climate models, and uses a Monte Carlo approach to estimate the modeled return period 24-hour storm amount and determine the ratio from the modeled 24-hour precipitation. We output precipitation on grid with node spacing of 5 km.

The MIT Synthetic Tropical Cyclone Generator (MIT-ST-CG) uses both thermodynamic and kinematic statistics to synthetically generate a large number of tropical cyclones under a given set of climate conditions. These climate con-

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[1] More detail on SWMM can be found online (https://www.epa.gov/water-research/storm-water-management-model-swmm).

ditions are specified by either reanalysis data (historical) or by General Circulation Models (GCMs). This process starts with a random seeding of potential storms, then uses a "track" model to predict each storm's horizontal path, and finally a model of the storm's intensity is used to estimate storm characteristics such as wind speed and precipitation. More detail on this method can be found in *Hurricanes and Global Warming: Results from Downscaled IPCC AR4 Simulations* (Emanuel *et al.*, 2008).

The MIT-STCG uses climate conditions from GCMs to produce the conditions in which the "seed storms" may or may not become harmful storm events. The GCMs used in this analysis are all sourced from the Climate Model Intercomparison Project Phase 5 (CMIP-5), the climate scenarios used in the latest Assessment Report (AR5) by the Intergovernmental Panel on Climate Change (IPCC). Since GCMs can produce varying results, multi-model assessments are usually conducted in order to understand the range (or uncertainty) associated with the projections. In this case, five GCMs were used: the NOAA GFDL (Geophysical Fluid Dynamics Laboratory) CM3, the UK Met Office Hadley Centre HADGEM2-ES, the Institute Pierre-Simon Laplace CM5A-LR, the University of Tokyo MIROC5 , and the Max Planck Institute for Meteorology MPI-ESM-MR.

For this study, only cyclones that effect the Boston metro area were considered. The model is run until there are 5000 storms that pass within 150 km of downtown Boston for a modeled historical climate (1981-2000) and for a modeled future climate (based on greenhouse gas emissions scenario RCP8.5) from 2081 to 2100. **Figure 2** shows the tracks of the 50 most intense hurricanes that affect Boston at the end of the 20th century, downscaled from the Max Planck model.

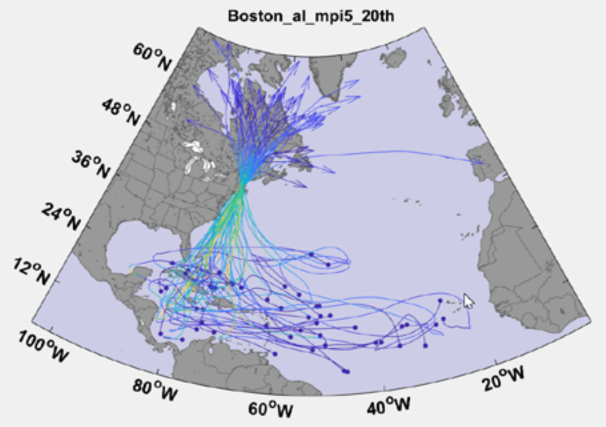

Figure 2. The tracks of the 50 most intense of 5,000 Storms generated with the MIT-STCG

The MIT Synthetic Tropical Cyclone Generator (MIT-STCG for informing rainfall probability distribution affecting Cambridge. The colors indicate storm intensity. There are two types of ensembles generated: one for current climate conditions and one for future climates projections for 2080 from a variety of climate models.

Probability distributions (PDFs) were developed from each model and for both time periods—1981 to 2000 and 2080 to 2100. An example of a PDF is shown in **Figure 3**. From these PDFs, estimates of maximum 24-hour precipitation events were obtained from each of the 5000 - 72 hours storms or a range of return periods can be calculated for each model and design storm time periods from 1 to 72 hours. Ratios are then determined for the appropriate return period by dividing the 2080 Return Period 24-hour precipitation by the historical Return Period 24-hour precipitation.

2.2 Understanding Campus Flooding Exposure from Precipitation Events (Current and Future Conditions)

This section describes the MIT approach to modeling urban drainage. The model simulates the conversion of precipitation events over the MIT campus to surface runoff and its flow to the drainage network. It then models the flow of storm water in the drainage network as it moves to the Charles River. If the flow to the drains exceeds the capacity of the system to discharge it to the outflow in the Charles River, the water will back up the manholes and spill out onto the campus as well as prevent stormwater runoff from entering the pipes. These combined impacts will lead to surface inundation of campus hard- and soft-scape and potential flooding of building basements, utility chambers and tunnels.

Using GIS and CAD data for the MIT drainage system provided by the MIT Working Group on Stormwater Management, a model of the campus stormwater drainage system was developed for both East and West Campus (see **Figure 4**). The next step in modeling the storm water system is to input the rainfall data.

The initial analysis aimed to assess MIT campus vulnerability to *current* flood risk. The pcSWMM model was run for current 10-, 25-, 50-, 100-, and 200-year Return-Period 24-hour design storms harmonized with City of Cambridge return-period rainfall total assumptions.

This next step involved capturing the future extreme rainfall probabilities described in Section 2.1 and inputting the rainfall probabilities into the campus stormwater system model described previously in this section.

The MIT Flood Vulnerability Study focused on manhole overflow as the key flood model output. Overflow occurs once the surface runoff exceeds the pipe capacity and the pipe discharges flow to the surface via manholes. Overflow is expressed by a number of parameters at each overloaded manhole: The total flood volume, catchment peak flows, maximum flow rate of pipelines and flooded hours of manholes. For this phase of the study, we used flooded hours as an initial indicator of flood risk. The MIT Flood

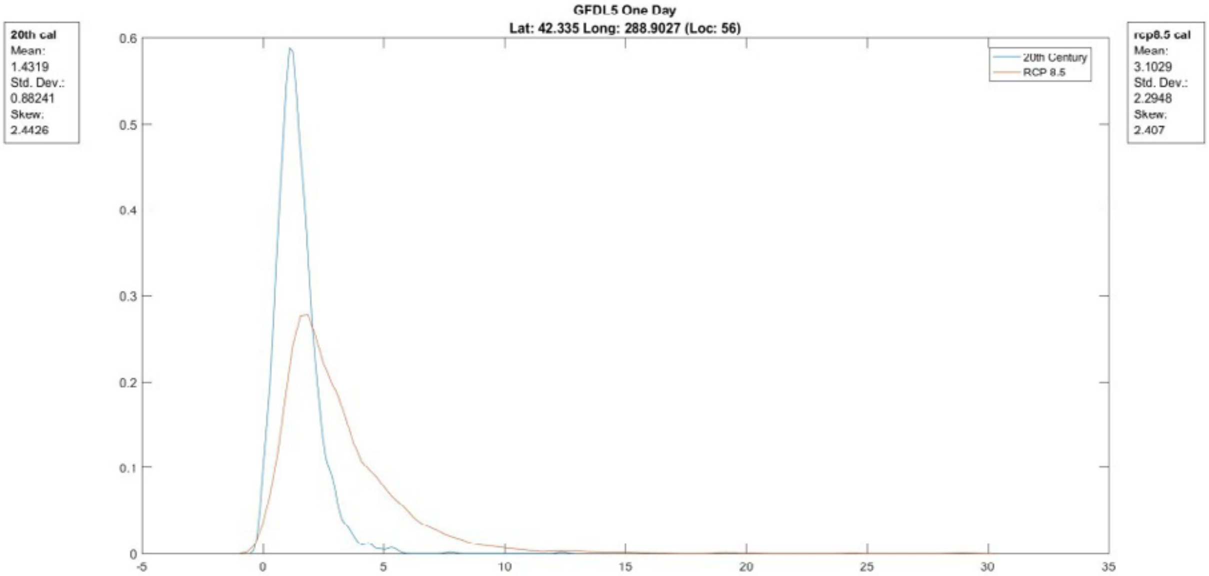

Figure 3. Probability distribution function (pdf) of 24 hour precipitation from the MIT Synthetic Tropical Cyclone Generator over Cambridge, Massachusetts

The blue pdf represents the distribution of rainfall over the model ensembles of current climate conditions while the red pdf represents the distribution over an ensemble of for a projected climate future from-restrained carbon emission greenhouse gas emissions (RCP 8.5) and as modeled by MIROC5 climate model.

Figure 4. Sample Schematic of MIT Campus Stormwater Infrastructure in PCSWMM

A schematic of the East Campus stormwater infrastructure for modeling flood capacity under current and future storms was developed, shown here as lines connecting catchments, drains and outfalls to the river (triangles).

Vulnerability Study anticipates preparing a preliminary version of this two-dimensional analysis in Phase 1C.

It should be noted that the Cambridge CCVA flood study undertook an extensive modeling effort that included the surface routing and flood depth estimations and produced the flood projection map (Figure 1). This type of analysis was beyond the scope, budget and data available for this study.

2.3 MIT Approach to Storm Surge and Sea Level Rise (SLR) Propagation Flooding Modeling

This analysis used the same data as the City of Cambridge regarding the Charles River Basin elevations under a 100 year flood Storm Surge in 2070 under climate change conditions using tropical cyclone data from Emanuel *et al.*, 2008. The elevations are determined by combining a deterministic sea level rise (SLR) projection by 2070 and tidal conditions for Boston Harbor Basin with the probability storm surge projections. Surface physical and topographical conditions were determined using a LIDAR digital elevation model along with GIS layers of campus infrastructure (roads, buildings and infrastructure) provided by MIT Office of Facilities Information Systems.

The modelled conditions recognize the following assumptions are aligned with CCVA projections:

- By 2070, sea level rise and episodic storm surge (SLR/SS) events will likely result in increases in Charles River water levels due to higher Boston Harbor waters by-passing the Charles River Dam.
- These increased water levels will then propagate flows upstream through existing drainage storm drainage outfalls and connected pipes to relief in low-lying areas within Cambridge via catch basins and manholes causing localized flooding even in days with no precipitation.
- For the Charles River basin, in particular, the piped infrastructure is very sensitive to river water level increases due to the low slope of pipes which limits the ability to drain stormwater.

3. Results

Findings of the Phase 1A study comprise 4 primary aspects:

1. Predicted precipitation probabilities (MIT STC Generator)
2. Campus flooding exposure from precipitation (current and future climate conditions)
3. Campus flooding exposure from sea level rise (SLR)/storm surge (SS) propagation
4. Testing of one potential flood mitigation solution

3.1 Predicted Precipitation Probabilities

The results for the 2080 100-, 200-, 300-, and 500-year return periods are presented in **Table 1** along with results from the CCVA 100-year return period. As shown in Table 1, the Cambridge CCVA estimate of the 100-year storm event of 12 inches is on the low-end of the results from the 5 Global Circulation Models (GCMs), which range from 12 inches to 30 inches.

3.2 Campus Flood Exposure: Current Climate Conditions

Table 2 presents a screenshot of model outputs for manholes that visually correspond to the Figure 5 map, illustrating MIT campus vulnerability to current flood risk. The pcSWMM model was run for current 10, 25-, 50-, 100-, and 200-year Return-Period 24-hour design storms. The Table 2 results are presented for all modeled manholes.

A map showing flooding (defined as hours of stormwater surcharge flooding from each manhole) of the MIT private storm water drains on Campus is presented in **Figure 5**. It shows considerable risk of flooding from rainfall in current climate conditions even at low return period storm events. Additionally, there is a spatial element to the risk as the mid-east campus is one concentrated area of risk. Flood risk is correlated with areas of impervious surfaces as the mid-east is highly impervious, while areas with more grass show the least risk, on both east and west campus. It should be noted that risk or exposure of campus buildings to flooding from rains is only an initial phase of understanding flood vulnerability. Additional analysis of each building and/or physical campus infrastructural assets is needed in order to determine the sensitivity or susceptibility of a building (i.e. via basement windows, low lying doorways and other building envelope penetration points) to disruption from flooding.

3.3 Campus Flood Exposure: Future Climate Conditions

The pcSWMM model was also run for the CCVA 2070 100-year design storm and for two of the MIT 100-year return period 2090 24-hour design storms. Two GCMs from the MIT storms were selected from the 5-climate change models used in the MIT-STCG. These two GCMs represent the 20th and 80th percentiles, which were deter-

Table 1. Comparison of projected 24-hour storm depths (inches) between the Cambridge CCVA and the five MIT-STCG Results

Model	100-yr	200-yr	300-yr	500-yr
Cambridge CCVA	12	--	--	--
GFDL	20	22	27	31
HadGEM	30	33	41	47
IPSL	14	15	19	22
MPI	14	15	19	21
MIROC	12	13	16	19

Table 2. PcSWMM model results for current 10, 25, 50, and 100 year return period 24-hour design storms for all 22 manholes in MIT model J1 – J22. This shows conditions of significant flooding at manholes (J1-J22) across campus.

Rainfall (inches)	5.5	6.3	7.24	8.7	9.54
Return Period (yrs)	**10**	**25**	**50**	**100**	**200**
J1	0.0	0.0	0.0	0.0	0.0
J3	0.7	0.8	0.8	0.9	1.0
J4	0.9	0.9	1.1	1.4	1.8
J5	0.0	0.0	0.2	0.3	0.7
J7	0.0	0.0	0.0	0.0	0.0
J9	1.1	1.2	1.8	2.1	3.0
J11	0.0	0.0	0.0	0.0	0.0
J13	0.0	0.0	0.2	0.7	0.7
J14	0.0	0.0	0.2	0.7	0.7
J17	0.0	0.0	0.0	0.0	0.0
J18	0.0	0.0	0.0	0.0	0.0
J20	0.0	0.0	0.0	0.0	0.0
J21	0.0	0.1	0.7	0.8	0.9
J22	0.0	0.0	0.0	0.0	0.5
J2	1.3	1.5	1.7	2.0	2.3
J6	0.0	0.6	0.7	0.9	1.0
J8	0.0	0.3	0.7	0.8	1.0
J10	0.0	0.0	0.0	0.0	0.7
J12	0.2	0.7	0.7	0.8	1.0
J15	0.0	0.0	0.0	0.0	0.2

Figure 5. Current flood risk: Hours of Flooding at a sample of manhole locations on campus.

These results show portions of the campus are under flood risk from the 1 in 10 year storm event (10% per year probability of occurrence) and that most of campus is impacted by the 1 in 50 year (2%) and 100 year (1%) storms.

mined based on exceedance likelihoods. These results are shown in **Table 3**, which compares the results from Cambridge CCVA to the MIT-STCG 20th and 80th percentile scenarios.

A map showing the future projected 100 year design storm flooding risk under climate change is presented in **Figure 6**. It shows considerable risk of flooding even at low return period storm events. Additionally, there is a spatial element to the risk with mid-East Campus with extensive impervious surfaces showing the greatest risk, while areas with more grass cover showing the least both on east and west campus.

The results show there are significant flooding risks even under high frequency current climate events. They also show that CCVA and MIT 100-year climate change impact suggest that the 200 year historic event will become the future 100 year event. Additionally, the 20 percent likely MIT 100-year event will present extreme flood risk.

3.4 Storm Surge and SLR Propagation Flooding Modeling

Figure 7 presents the City of Cambridge's analysis of sea-level rise/storm surge risk (SLR/SS) with more detailed analysis needed in future study phases for understanding MIT Cambridge campus risks to SLR/SS.

The MIT Flood Vulnerability Study examined the impact of SLR/SS water levels to the MIT campus. **Figure 8** provides

Table 3. Future flood risk: Hours of Manhole Flooding. Comparison of the CCVA 2070 to the 2090 MIT-80th and MIT-20th for the 100-year, 24-hour storm event for all 22 manholes in MIT model J1 – J22.

Modelled 1% (100 yr) Storm Event	CCVA	MIT-80th	MIT-20th
Rainfall (inches)	**11.7**	**14**	**20**
J1	0.1	0.5	0.8
J3	1.0	1.2	1.7
J4	2.0	2.5	3.9
J5	0.7	0.8	0.8
J7	0.0	0.0	0.0
J9	3.1	4.0	7.5
J11	0.0	0.0	0.0
J13	0.8	0.8	0.9
J14	0.8	0.8	0.9
J17	0.0	0.0	0.0
J18	0.0	0.0	0.0
J20	0.0	0.0	0.0
J21	1.0	1.1	1.5
J22	0.6	0.8	1.0
J2	2.5	2.9	4.4
J6	1.1	1.3	1.7
J8	1.0	1.2	1.6
J10	0.7	0.8	1.0
J12	1.0	1.1	1.6
J15	0.2	0.2	0.3

This table shows conditions of significant flooding at hot spots on both east and west campus. Also included in the columns are the predicted rainfall surcharge hours at each manhole for the three flooding events: Cambridge 100 year (2070); 80% likely and 20% likely 100 year (2080) rainfalls from the MIT models.

Figure 6. Future projected change in 100-year flood and resulting hours of flooding at key manholes on campus.

These results show portions of the campus that are under flood risk from current 100 year (1%) storms. These risks will increase modestly under the Cambridge projected storm and significantly under the low probability MIT projected storm.

the key modeled Charles River Basin Levels at Massachusetts Ave bridge for the high tide cycle on the 24-hour 100 year Storm surge. This figure shows that from 9 am to 1 pm over 4 hours the level is above 20 feet Cambridge Datum. For our analysis, we assumed that a static hydraulic head on the drainage system that would impact all drains in the MIT system would be 20.5 feet Cambridge Datum. It is assumed that water would propagate to a level of 20.5 ft within the campus. A map of localized flood areas showing vulnerable buildings for the SLR/SS was produced. **Figure 9** shows peak flood levels and locations resulting from the propagation of Charles River water through existing drainage storm drainage outfalls, connected pipes, catch basins and manholes.

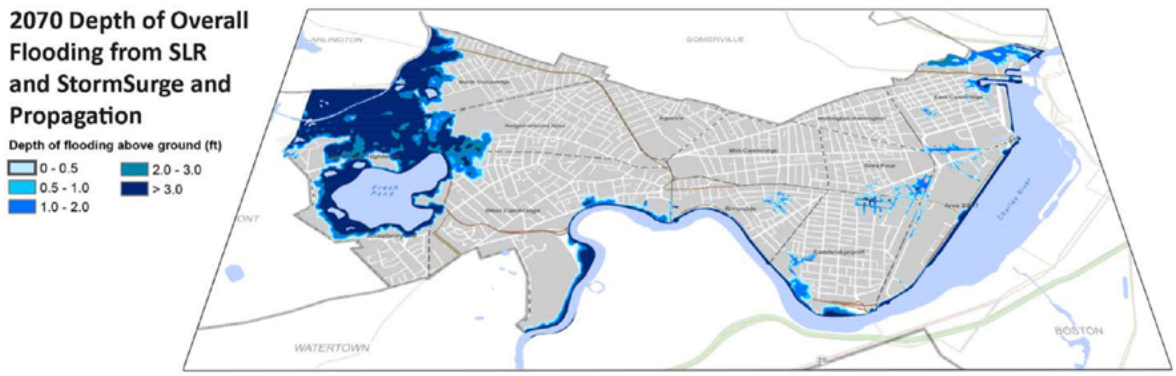

Figure 7. 2070 Depth of Overall flooding from the 100 year SLR/Storm Surge Event (CCVA 2070)

This event is informed by the MIT STCG ensembles of future tropical storms but also includes the risk of Extratropical storms (Nor´easters). This 100-year event does not correspond with the 100-year precipitation events discussed above.

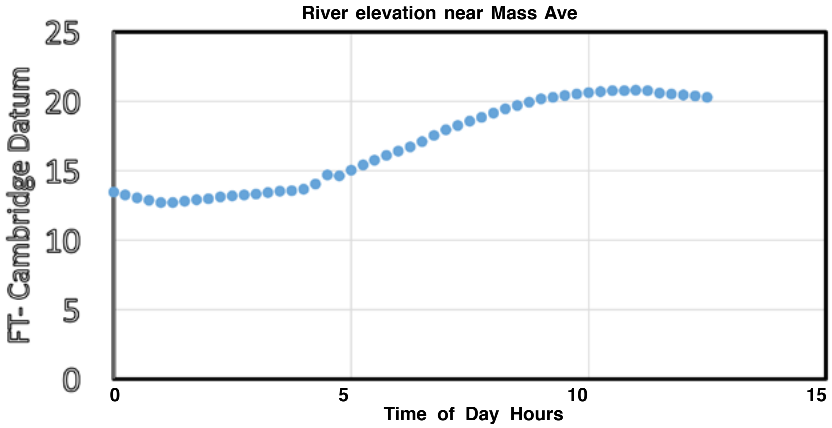

Figure 8. Charles River Water Levels under the CCVA SS-SLR 100 year event (Cambridge Datum).

The impact of storm surge is not from water from the Boston Harbor or Charles river pouring over the campus as a wave but rather it felt by the water of the Charles River coming through the drainage system and flooding campus at low points from manholes and catch basins. It is impacted by tides and assumed Sea Level Rise.

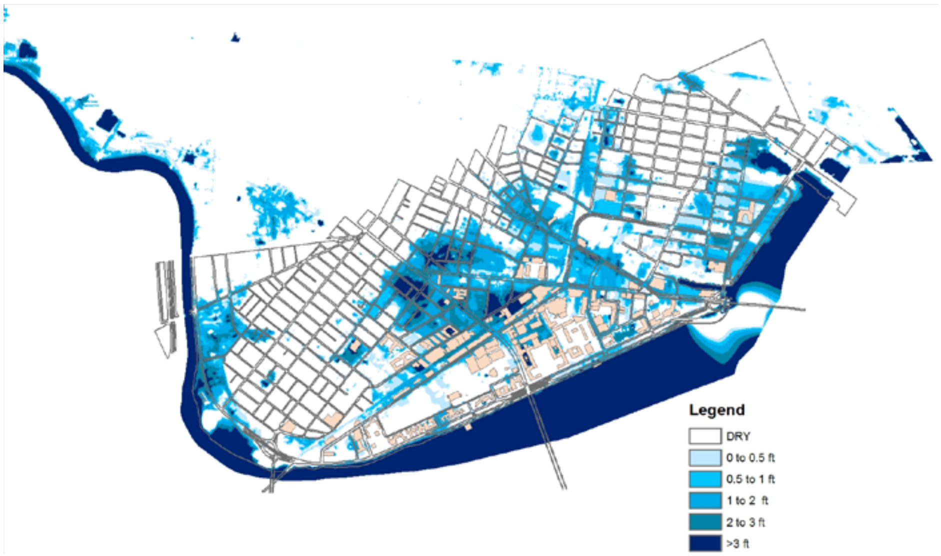

Figure 9. 2070 Depth of Overall flooding from the 100 year SLR/Storm Surge Event for MIT Campus.

This is the MIT portion of the conditions reported in Figure 7. This peak extent of flooding could remain up to four hours and could include brackish water with the mixture of flood water from the Charles and Boston Harbor.

The map presented in Figure 9 shows that a significant portion of the campus is exposed to flooding risks, particularly those buildings adjacent to Vassar, Albany and Main Streets. One reason for this flood exposure is historic, as this part of the campus was primarily built on land reclaimed from the original Charles River Estuary, and likely still retains estuarine drainage and flow characteristics (**Figure 10**). It should be noted that additional analysis of each building is needed in order to determine the sensitivity or susceptibility of a building to disruption from flood water. The portion of campus near the north bank of the Charles River appears to be much less vulnerable and exposed to SLR/SS flooding.

3.5 Testing of Potential Solutions

A detailed pilot analysis has been presented for a key campus location, the manhole located on west campus between the Koch Childcare Center and the current West Garage (**Figure 11**), scheduled to become an undergraduate dormitory.

The results are shown in **Figure 12**. There are two sets of results shown in the graph. Set one is for 10 to 200 year storms for current risk and the CCVA 2070 100-year design storm and for two of the MIT 100-year return period 2090 24-hour design storms for current landscape conditions. A second set of runs were made for the same input but with a 6-foot-deep underground stormwater capture and storage (see Figure 12).

The results show that, for this one manhole, an underground storage facility can remove the risk of all design storms except the 20 percent likely MIT 100-year event and in this case reduces the flooding by 75 percent. The underground stormwater storage facility is designed to accommodate 180,000 cubic feet or 1.35 million gallons of stormwater and has been sized as 100 feet wide by 6 feet deep and 300 feet long.

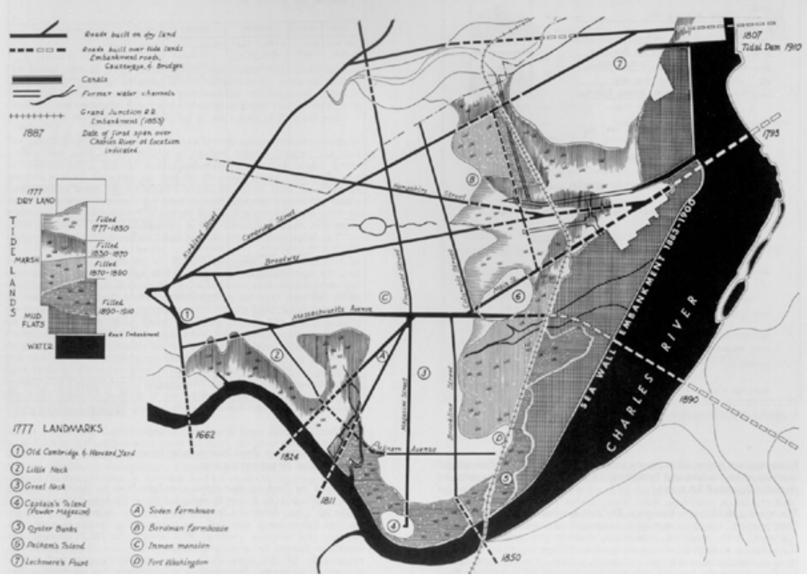

Figure 10. Shoreline and Filled Land Areas of Cambridge

Figure 11. Location for Detailed Flooding Analysis near the Koch Childcare Center

The results presented in Figure 12 are for the manhole in the center of the red rectangle and the black shaded rectangle represents the spatial extent of a 6 foot deep underground storm retention facility shown in the analysis to greatly reduce flood risk at the manhole.

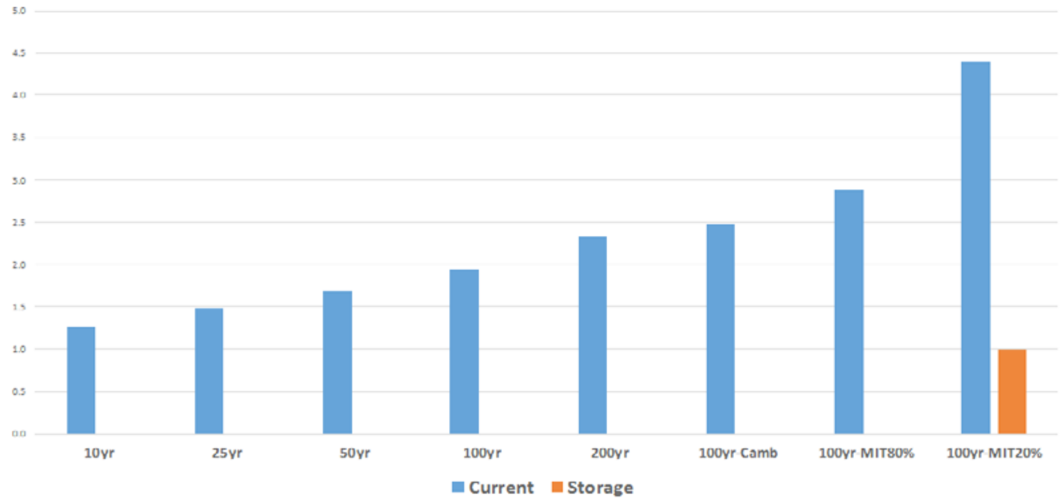

Figure 12. Results for Manhole on West Campus near Koch Child Care center and West Garage

The location for these results are shown in Figure 11. Installing a 1.35-million-gallon underground storage facility would remove the risk for the current 100 year event and most future projected 100 year events.

4. MIT Campus Flood Vulnerability Study Phase 1A Conclusions and Recommendations

4.1 Conclusions

1) Future rainfall for MIT campus and Cambridge

Conclusion: Extreme rainfall events in 2080–2100 with a 1% probability of annual occurrence (i.e. 100 year return period 24 hour storms), are projected to yield approximately 60% more rain in a 24 hour period (totaling 14 or more inches in 24 hours) compared to the current 1% probability rain event (8.7 inches).

2) MIT campus flood risk

Conclusion: The MIT campus is vulnerable to four types of flooding risk in the present climate with greater flooding risk under future climate conditions. Four primary sources of current and future flood risk are:

1. Precipitation falling on campus that exceeds MIT private drainage system capacity
2. Precipitation falling in Central and Kendall Square that exceeds City of Cambridge stormwater drainage system capacity and flows onto campus and/or fills sub surface pipes reducing campus drainage capacity
3. In-land flooding from propagation of storm surge via on-campus pipes
4. In-land flooding from propagation of storm surge via pipes in Central and Kendall Square areas

3) MIT Campus flood capacity and exposure to rainfall

Conclusion: The existing capacity of the MIT campus stormwater pipe infrastructure and site flood retention function is limited in its ability to absorb and convey stormwater from both current and future rain events.

3a) Moderate frequency, rain events (10, 25 and 50 year 24 hour storms)

Conclusion: Current flooding risk from moderate frequency events exposes areas of campus to flooding via surcharge from stormwater manholes (see Figure 5 showing the current climate stormwater pipe surcharge map).

- Areas of concern for frequent flood exposure include buildings located along the northern half of the mid-east zone of campus framed by Ames St, Main St, Vassar St and Mass Ave.

3b) Low frequency, extreme rainfall events (100 year, 24 hr storm)

Conclusion: Significant areas of campus are exposed to flood waters from the current climate's 1% probability extreme rain event (100 year, 24 hr storm), with even greater flood water exposure (via manhole surcharge) under future 1% probability extreme rain events impacted by climate change (2080–2100) (see Figure 5 for current and Figure 6 for future flood conditions).

- Areas of concern include buildings located along Vassar St west of Mass Ave as well as buildings located in the northern half of the mid-east zone of campus framed by Ames St, Main St, Vassar St and Mass Ave.

4) Flood exposure from sea level rise / storm surge propagation (SLR/SS)

Conclusion: Campus flooding due to sea level rise and coastal storm surge propagation of the drainage pipes from a 100 year recurrence storm in the Charles River basin could raise floodwater levels on campus to approximately 21ft elevation (Cambridge Datum), flooding sub-surface and surface assets as shown in Figure 9. Notably, areas along Vassar St, would be directly impacted by storm surge propagation of stormwater, along with other areas along Ames St.

5) Vassar St. and Main St. elevation and boundary conditions

Conclusion: Significant floodwaters (current and future climate conditions) are projected along Vassar St and Main St., according to both the MIT campus flood model (Figure 5 and Figure 6) and the City of Cambridge flood models (see Figure 1). An integration of these flood models is essential for understanding extent of probable floodwater pathways across this boundary condition. These flood volumes reflect the lower elevations of these areas, historic sub-surface factors and boundary condition limitations of each model and require integrated modelling to determine extent of inundation across these boundaries.

6) East Campus vs West Campus

Conclusion: High amounts of impervious surfaces on east campus is a driver of flooding risks. West campus flood risks are largely due to low elevation areas along Vassar that are vulnerability to stormwater pipe capacity limitations.

7) Regional model coordination

Conclusion: The current climate change flood models for urban drainage throughout the region are not sufficiently integrated for projecting a comprehensive understanding of MIT campus flood risks. Coordination and integration of climate change flood projections for urban drainage models of the Charles and Mystic Rivers as well as Boston Harbor is needed to enable a more comprehensive understanding of upstream and downstream conditions for informing future flooding risks for the MIT campus.

8) Campus living lab-ready learning

Conclusion: Data generated through the MIT Flood Vulnerability study can enable broadening awareness of campus flood risks throughout the MIT community, especially students, in order to grow campus capacity to adapt to future risks.

4.2 Recommendations and Next Steps

4.2.1 Campus Planning and Campus Construction

1. Each large-scale new building and major renovation project to schedule a resiliency workshop to utilize existing findings from the Cambridge Climate Vulnerability Assessment and the MIT Flood Vulnerability Study (Phase 1a) to integrate flood risk planning by evaluating:
    - How does a campus building, site and infrastructure project contribute to enhancing overall campus stormwater capacity?
    - How is a project impacted by the four primary sources of current and future flood risk? How might flooding impact interdependent services and infrastructure?
2. MIT to consider adopting current practices recommended by the Cambridge Department of Public Works for new construction to:
    - Ensure protection of structures and critical systems from 10% or 10 year rain event (2070 projections)
    - Enable recovery from 1% or 100 year rain event (2070)
3. Continue the current practice of using the MIT design elevation of 26’ (Cambridge Datum) for critical equipment in order to minimize flood exposure from extreme sea level rise/storm surge events as follows:
    - Critical equipment and assets located below 26’ (Cambridge Datum) have a higher risk of flooding exposure and should be incrementally modified to be adapted to floodwater over time
    - Integrate critical equipment elevation layer into updated 2D inundation mapping (Phase 1C)
4. Review and implement findings of MIT Campus Sustainable Stormwater and Landscape Ecology Plan (Phase 1 – to be released Sept 2017) regarding gaps and needs for enhancing current capacity of campus site and stormwater infrastructure systems to capture, absorb, retain, reuse and convey extreme rain-induced flood events.

4.2.2 MIT Climate Resiliency Sub-Groups

1. Conduct vulnerability assessments of campus physical assets including operational, life safety and community wellness perspectives:
    - Identify individual building and infrastructure assets that are “sensitive” or structurally or functionally-disrupted by flood waters (i.e. via low lying window wells, gaps in the building envelope, electrical manholes that can fill with water and cause electrical equipment shortages etc.) (Activity underway by Resiliency Sub-Groups on Buildings and Infrastructure/Utilities)
        - » Estimate time needed to plan for recovery and restoration of impacted assets and services
        - » Identify actions to protect or prevent impacts to critical services and assets.
    - Identify those physical assets that are essential to campus life safety, community health and wellness as well as business/research continuity requiring planning for protection and/or adaptation to flood

exposure (Activity underway by OEMBC and Resiliency Sub-Group on Community Resiliency).

- Develop refined mapping and graphics that can illustrate levels of inundation at key locations throughout campus. Action requires preparation of:
  - a detailed geo-database of campus stormwater utility infrastructure including manhole locations and depths (MIT Flood Vulnerability Study Phase 1B)
  - a two-dimensional (2D) campus drainage model (MIT Flood Vulnerability Study Phase 1C)
  - illustration of street level photos for key campus locations with different flood elevation levels (i.e. 10 year, 100 year precipitation; 100 year storm surge) (Phase 1C)

2. Develop the MIT campus flood vulnerability outputs into a living laboratory-ready platform to engage students and other faculty in using the campus as a test bed. The following elements should be considered:
   - Data Collections and Computational Modeling
   - Risk Analysis and Economic Impact Analysis
   - Institutional Assessments
   - UROP, Graduate Students - Research Opportunities
   - Integration with undergraduate classes such as Terrascope
   - Faculty across campus bringing research to practice at MIT

4.2.3 Coordination with City of Cambridge and Metro Region

1. A comprehensive understanding of how in-land flooding from beyond the edges of campus would influence MIT campus and vice versa is essential for informing campus flood risk planning—particularly for Vassar St building and campus infrastructure projects. Planning steps to integrate this boundary include:
   - MIT should meet with the City to provide a formal update on key findings and explore how the city's existing flood drainage model and mapping can be updated to "fill in the East Cambridge gaps" in the city's flood risk maps.
   - Comprehensive integration with City models will require MIT to complete the updated 2D campus flood risk model which is anticipated for completion as part of MIT Flood Vulnerability Study Phase 1C.
   - Based on results of the integrated modelling, MIT's physical assets should be re-evaluated for flooding exposure.
   - Vassar St projects should be comprehensively evaluated for exposure and sensitivity to potential flood scenarios.
2. Convene a regional climate modelling summit. Engage with key modelling entities in the region to integrate flood projections across risk types, models and political boundaries. Consider exchanging approaches and existing models with academic entities already engaged in campus and regional resiliency planning such as Boston University and UMASS Boston as well as Woods Hole Group/Mass DOT modelling team.

4.2.4 Research Next Steps

The MIT Flood Vulnerability Study will continue in FY'18 as follows:

Phase 1B: Identification of Existing Critical Utilities and Infrastructure Equipment

The Flood Vulnerability team is coordinating with MIT Facilities Information Systems (FIS) to digitize existing stormwater utility infrastructure for enhancing the modelling capability necessary for Phase 1C and 1D.

Phase 1C: Pilot Build of a 2D Campus Drainage Model

The MIT Flood Vulnerability Study (Phase 1c) will develop and evaluate two-dimension (2D) modelling of campus surface and stormwater capacity. This will enable a basic understanding of flood inundation levels for campus locations as well as flow pathways from different storm frequencies under current and future climate scenarios.

Phase 1D: Analysis of Joint Probability of Precipitation + Sea Level Rise/Storm Surge

The probabilities for heavy precipitation events and sea level rise/storm surge (SLR/SS) events occurring in rapid succession or simultaneously has not yet been studied. The next phase of the MIT study (Phase 1D) will explore this joint probability to determine campus risk exposure and to frame risk planning that might be needed.

Phase 2: Comprehensive Integration of Modelling and Mapping with City of Cambridge and Metro Region

The goal of phase 2 is to undertake a full flooding risk assessment for MIT and the other riparian stakeholders of the Charles River basin by integrating modeling used across the basin and its stakeholders. Considerations include using the same assumptions and being driven by the same climate scenarios e.g. precipitation and storm surge. This will provide all parties with a much more accurate assessment of future flooding risks on the region's assets.

Since the MIT campus sits on the shores of the Charles River, it is vulnerable to precipitation-based stormwater coming from the city of Cambridge in addition to precipitation over the campus. The ability to drain this water is a function of the elevation of the Charles River basin. The elevation of the Charles River basin is a complex combination of the flow from the upper Charles River entering the basin downstream of the Watertown dam, the urban stormwater runoff from the riparian cities of the basin, (e.g. Cambridge, Boston, Newton) and the potential storm surge that may come from Boston Harbor. Additionally, the level of the basin is controlled by six pumps at the Charles River dam which separates Boston Harbor from the Charles River basin.

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Appendix A: Purpose and Context

A1. MIT Climate Action Plan 2015

Before adaptation can take place, people, firms, communities, institutions and governments must assess how vulnerable they are to the impacts of a changing future climate. In October 2015, MIT released the Plan for Action on Climate Change. The goal of the plan was "to minimize emission of carbon dioxide, methane and other global warming agents into the atmosphere, and to devise pathways for adaptation to climate change, through the active involvement of the MIT community, proactively engaged with industry, government, academia, foundations, philanthropists and the public."

The Plan for Action is a five-year plan, which commenced upon its release and runs through October 2020. The plan includes a number of specific action items, contained in five pillars:

Pillar A: Improve our understanding of climate change and advance novel, targeted mitigation and adaptation solutions

Pillar B: Accelerate progress towards low- and zero-carbon energy technologies

Pillar C: Educate a new generation of climate, energy, and environmental innovators

Pillar D: Share what we know and learn from others around the world

Pillar E: Use our community as a test bed for change

This has generated many activities at MIT to address this crucial issue, spanning academics, research, facilities, and operations.

A2. Cambridge Climate Change Vulnerability Assessment (CCVA)

The City of Cambridge released a municipal climate change vulnerability assessment in late 2015. The Climate Change Vulnerability Assessment (CCVA) was designed: "to address the concerns expressed by the Cambridge community about the local implications of global climate change." The City feels" it is their responsibility to account for climate change in its planning and decision-making in order to sustain this vibrant City and its people."

"The CCVA Report Part 1 makes clear that there will be real and significant risks to Cambridge over time – especially from increasing heat and precipitation- driven flooding – that will threaten public health and safety, our economy, and the City's quality of life if we do not act."

While much of the CCVA findings directly include the MIT campus the MIT campus is not included in the CCVA flooding analysis because the analysis only modelled publicly-owned stormwater infrastructure, while much of MIT's stormwater drainage system is privately owned.

The Cambridge CCVA report presented an opportunity for MIT to apply CCVA results to the campus to study its unique needs and priorities.

A3. MIT Campus Sustainability and Resilience

The MIT Climate Resilience Committee (CRC) was launched in Fall 2015 under the MIT Campus Sustainability Task Force with the goal of providing an assessment of campus vulnerabilities to emerging climate risks and identification of proposed actions to help mitigate risks. CRC facilitated the process of adapting publicly available data from the City of Cambridge and other regional data to create a climate change vulnerability assessment of the campus, in order to inform decision makers about the short and long term risks facing the MIT community.

CRC membership includes key faculty and staff and has been co-chaired by Prof. Kerry Emanuel, Department of

Earth, Atmospheric and Planetary Sciences and Brian Goldberg, Office of Sustainability.

MIT's Office of Sustainability (MITOS) has taken a leading role in helping to translate climate science into strategic and operational decision-making by leveraging MIT's research and operational expertise. In 2014, MITOS created campus sustainability working groups charged with identifying challenges and recommending solutions in four areas of focus. The MIT Stormwater and Landscape Management working group—a collaboration of MITOS, the Office of Campus Planning (OCP), and the Office of Environment, Health, and Safety (EHS)—has undertaken the development of a **Sustainable Campus Stormwater and Landscape Ecology Plan**.

The Plan will create **an integrated hydrology and landscape ecosystem framework** to aid campus development by identifying project and campus-wide opportunities, locations, and strategies for sustainable stormwater management that will support the health and well-being of the MIT community and other living systems. It will also make recommendations and provide guidance for future projects that collectively work to slow and reduce stormwater runoff, reduce impervious surfaces and mitigate urban heat island effects. The Plan aims to improve water quality, decrease thermal pollution of waterways, prevent or alleviate localized flooding, increase campus green space and grow a vigorous urban forest, build healthy soils, enhance biodiversity, and contribute to improving the ecological health of the campus and the lower Charles River watershed.

Appendix B: Methods

B.1 Storm Water Management Model

The Storm Water Management Model (SWMM), first developed in 1969-71 by the U.S. Environmental Protection Agency, is a well-known and widely used dynamic rainfall-runoff quantity and quality simulation model for single event or long-term simulation, primarily designed for urban areas. A typical simulation starts with an estimation of runoff from climate parameters. The runoff is then routed through the system of pipes, channels, storage/treatment devices, pumps, and regulators, where quantity and quality are tracked. This allows for the determination of when and where flooding events inundate the system.[2] For this project, we used a software tool called pcSWMM which adds many graphical and analytic enhancements to the basic USEPA SWMM.

B.2 CCVA Modelling Approach

CCVA Approach: Current 24-Hour Design Storm

For Cambridge, the 24-hour storm event was chosen as the design rainfall event for urban drainage. Historical precipitation data was collected and statistical techniques used to determine varying amounts of 24 hour-rainfall that correspond to different probability of occurrence or return periods. The historical 24-hour storm amount for different level of risk or return period is listed in **Table B1**.

The population, assets, and criticality of the infrastructure at risk together with a community's ability to invest in flood protection determines the level of risk that a certain type flood protection is designed to provide. Finally, the temporal pattern of the rainfall over the storm event is also a feature of a design storm.

The City of Cambridge has selected the Soil Conservation Service (SCS) Type III for its design storm distribution. The 100-year 24-hour design precipitation rate is illustrated in **Figure B1**.

CCVA Approach: Climate Change Impact on The Design Storm

The climate projections for the Cambridge CCVA were developed using a statistical approach called the Asynchronous Regional Regression Model (ARRM). ARRM established a statistical relationship between climate model outputs and weather station data from in and around Cambridge over a long historical period (30 to 40 years). This historic relationship was then applied to future climate projections to produce a local distribution of temperature and precipitation that changes over time. Based on the ratios of modeled future precipitation to model historical precipitation, the historical design storm precipitation amounts are scaled by the climate model results.

The CCVA used only one climate ratio but developed ratios for 2030, 2050, and 2070 for the 10 year, 25 year and 100 year return period 24 hour storm. These are presented in **Figure B2**.

Design storm precipitation frequency analysis

Due to the uncertain nature of precipitation, flood protection infrastructure is designed to protect against a certain level of flood risk. This flood risk is expressed as the probability of a flood each year or converted to a frequency or return period given in years as presented in **Table B2**. A critical rainfall event or duration is chosen based on the spatial scale of the flood protection being considered and the hydrologic conditions.

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[2] More detail on SWMM can be found online (https://www.epa.gov/water-research/storm-water-management-model-swmm).

Table B1. City of Cambridge 24 hour rainfall events (2015 Climate Conditions)

Return Period (years)	10	25	100
24 hour Rainfall (inches)	4.9	6.2	8.9

Table B2. Mapping of return periods in years to the probability of annual occurrence

Statistical Design Events	
Return Period (years)	Probability of Occurrence (in any one year)
1	99%
2	50%
5	20%
10	10%
20	5%
50	2%
100	1%

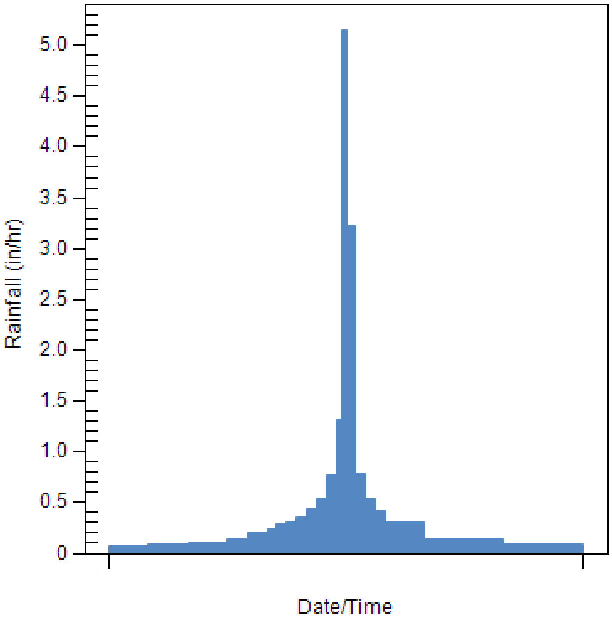

Figure B1. Temporal distribution of the City of CAMBRIDGE 100-year 24-hour design event: 8.9 inches with SCS Type III.

This figure demonstrates a key assumption involved in all urban drainage analysis. The distribution over time of the 24 our precipitation event can greatly impact the flooding. In this SCS Type III, the current choice of the city of Cambridge, most of the rainfall occurs in the middle of the storm. detailed analysis of the true historical nature of extreme precipitation events for the campus needs to be analyze and current practice by urban drainage institutions is allowing for more flexibility in the choice of design storms and their spatial distribution.

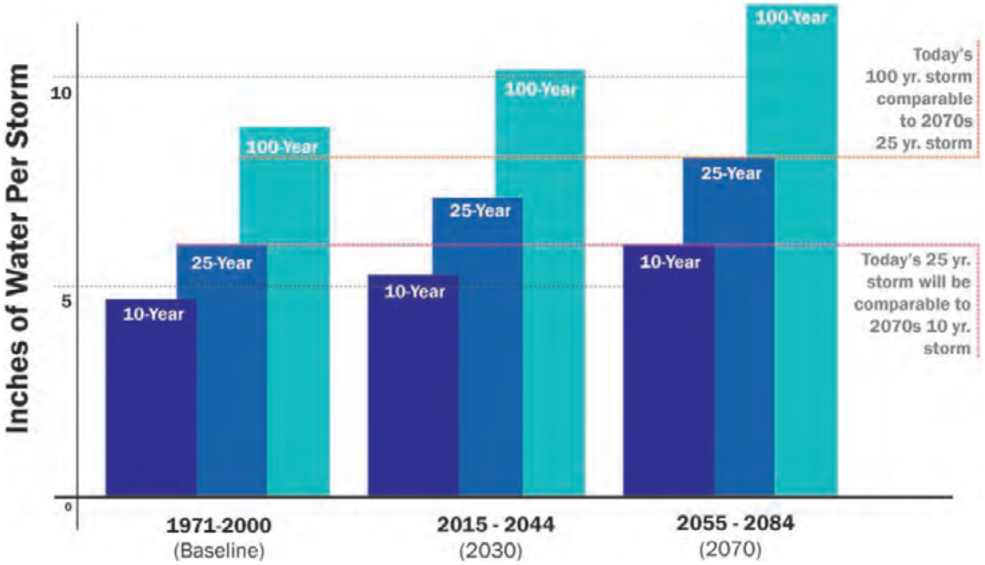

Figure B2. The CCVA 10 year, 25 year and 100 year return period 24 hour storm. for 2030, 2050, and 2070 (Source: The CCVA report, 2015)

This demonstrates two key points: 1) The 2070 25-years events will become equivalent to the current 100 year event (meaning the current 100 year event will be four times as likely in 2070) and 2) Both higher frequency 10 year storms and lower 100 year storms will change significantly under future climates.

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