Agent-Based Model for Adaptation to Sea Level Rise in Boston Harbor

Model Documentation and Supplemental Information

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# Overview, Design Concepts, and Details Model Documentation

## 1.1 Purpose

The purpose of the model is to explore under what conditions different adaptation governance regimes are successful in reaching specific adaptation metrics in Boston Harbor. We set up the model to quantitatively compare scenarios of no cooperation, voluntary coalitions, and regional authorities to improve coastal adaptation. The model allows for a quantitative assessment of when cooperation or regionalization is beneficial and to whom. The model is built in NetLogo with extensions for python and GIS [1].

## 1.2 Entities, state variables, and scales

### Entities:

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Agent Type | Names | Count | Adaptation Options | Presence in Adaptation Regimes |
| Municipal Agents | Boston, Quincy, Winthrop | 3 | Seawalls (evaluation for 9 segments in Boston, and one in each other municipality) | All |
| Massachusetts Bay Transportation Authority Subway (MBTA) | -- | 1 | On-site barriers | All |
| Regional Assets | Boston Logan Airport, Food Distribution Center | 2 | On-site barriers | All |
| Property Owners | 3 Commercial per municipality  3 Homeowners per municipality | 18 | On-site barriers  Aquafence  Flood insurance | All |
| Regional Flood Authority | -- | 1 | Seawalls | Regional Authority |

### State variables:

|  |  |
| --- | --- |
| Agent | Variable |
| Property owners and regional assets | Elevation |
| Property owner | Flood insurance |
| All | Damage Functions |
| All | Adaptations |
| All | Geographic location |
| All | Sea Level Rise Projections |
| All | Potential Seawall Heights |
| All | Adaptation Costs |
| All | Foresight for damage projections |
| System | External Financing Percent |
| System | Storm Multiplier |
| System | Maintenance Fee |
| System | Reduction of funding access |
| System | Planning Delay |
| System | Permitting Cost |
| System | Prioritization Method |
| System | Discount Rate |
| System | Sea Level Rise |

### Scales:

* The model captures a significant portion of the inner Boston Harbor.
* Agents may be located as point sources (property owners), be spread throughout the model area (MBTA), or cover sub-regions (municipalities).

A map of the united states

AI-generated content may be incorrect.

Figure S1: Map of geographic area covered by the model with key agents incorporated.

## 1.3 Process overview and scheduling

The model begins with the user selecting key parameter values for a single model run. The user must select the sea-level rise to be generated (0,1,3 or 5 feet), any storm intensity modifier (increases the mean of the storm distribution every year by the chosen parameter, but with a constant CV), the discount rate (0.03, 0.07), the agent sea-level rise projection (0,1,3,5) and the adaptation regime (no cooperation, no cooperation with a behavioral damage modifier, voluntary cooperation, or regional authority).

Additionally, the user will select the storm surge generation method (random, no extreme floods, one extreme flood, two extreme floods), whether or not flood reactive behavior occurs, the planning horizon delay (0-10 years), the permitting delay (0-10 years), the presence of the insurance module, the amount of external financing available (0 – 100%), any reduction in funding availability to property owners, the cooperative maintenance fee, the cost of permitting, the cost of operations and maintenance on an adaptation, and the foresight that agents use to project cumulative damages and benefits over time (0 – 30 years).

In each time step, representing one year, the simulation begins with the generation of a stochastic annual maximum flood. This flood elevation is then used to calculate damages for each agent, taking into account any adaptations that an agent may be protected by. This damage modifier is calculated by comparing the experienced damage to the expected annual damage calculated by the agent according to their projection of sea level rise and the method suggested by Kirshen, et al. [2].

Following this process, agents proceed with adaptation decision-making. This is represented differently according to the adaptation regime (closely tied to governance strategy) selected and will be broken up as such below.

A diagram of a step-by-step process

Description automatically generated

Figure S2: Diagram of the major steps in the model process.

#### No Adaptation

In this version of the model, we assume a counterfactual where agents are not permitted to adapt. In this regime, agents experience damages but do not adapt in any way. This provides a useful baseline to calculate the Net Benefits of adaptation. In these simulations, there are never adaptation costs, but flood damages are tracked.

#### No Cooperation

In this adaptation regime, each agent is assumed to operate independently. While they are aware of and benefit from other adaptations (for example, a sea wall in front of them), they operate independently in their decision-making process. Each agent estimates the damage they will experience in the future (set by the *foresight* parameter) without an adaptation against the damage for the future with an adaptation.

If the benefit-cost ratio is greater than one, the adaptation will be adopted. In the case of two adaptations being beneficial, the one with the larger ratio of benefit to cost will be constructed. This is implemented in the following way:

Equation 1:

Where benefit is calculated by:

Equation 2:

#### Role of the behavioral modifier

The behavior calculation accounts for irrational behavior and reactivity of agents to the floods they experience. The benefit-cost ratio is modified according to an agent’s most recent flood experience using this process. This supports the observation of rapid adaptation implementation following a large storm (such as the response to Hurricane Sandy). If the benefit (with the additional cost of construction) is less than the expected damages, the adaptation will be implemented. In the case of two adaptations being beneficial, the one with the larger ratio of benefit to cost will be constructed.

The equations representing this are shown below.

Equation 3:

Where α represents the behavioral modifier, is the damage that an agent experiences in the year, and is the damage an agent expected to have in a year given their projected scenario of sea level rise and their probability-damage curve.

Equation 4:

Where benefit is calculated again as:

Equation 5:

This means that when damage is more than an agent expects, alpha is greater than 1. If the benefit-cost ratio is close to 1, this adjustment may result in the total modified ratio being greater than 1 and spurring adaptation. If the damage modifier is less than 1, the opposite may occur, disincentivizing adaptation processes.

#### Voluntary Cooperation

In this version of the model, we explore how coalitions may form if multiple agents desire adaptation at the same time. It is assumed that if multiple agents in the same municipality are planning adaptations independently and can reduce the costs of adaptation through cooperation, then they will cooperate to reduce potential costs. This process occurs according to the following steps:

1. Municipalities indicate whether or not they plan to construct a seawall. We assume that if the municipality is not interested in adaptation, it is unlikely that a cooperative structure will be able to obtain permits for and construct a seawall.
2. All other agent types (property owners, MBTA, private assets) assess whether or not they would also like to implement an adaptation.
3. For agents to behave cooperatively, agents must:
   1. Want an adaptation
   2. Exist within a municipality that wants an adaptation
   3. Pay less than what they would have paid for their desired adaptation (adaptation cost may be reduced due to access of municipalities to external financing, but base costs may be elevated due to the maintenance fee, which is a multiplier on the adaptation cost).
4. Agents willing to cooperate re-calculate their benefit-cost ratio according to their updated access to funding and maintenance fee if they cooperate to determine if they are better off cooperating or not
5. Agents then either implement their adaptation as a coalition or independently.

#### Regional Authority

For the regional authority, the only adaptations being considered are seawalls in 11 potential locations: the nine neighborhoods of Boston, and seawalls along Winthrop and Quincy. The decision-making process is similar to the decision-making process in the *no cooperation* adaptation regime without the regional modifier, except costs and benefits are calculated differently. Here, the benefit and cost of each seawall is calculated based on all agents that would be protected by the seawall. For example, the seawall in East Boston also protects Boston Logan Airport, downtown Boston protects the property owners and a portion of the MBTA, etc. Estimates for the ratio of financial protection for the MBTA based on each sea wall were made to reflect where MBTA lines are critical infrastructure are located.

#### Implementation

Agents experience a gap between determining adaptations to be implemented (the adaptation decision process) and the implementation process. This gap is due to both a permitting delay and the time necessary to raise funds to finance an adaptation. Agents must be able to currently have budget allocations available for 10% of the project, and can pay the remaining 90% over time (representing the effects of bonds or loans). This separation between intention and implementation means that even if downtown Boston decides to construct a seawall, other agents are not impacted by this knowledge until subsequent time steps.

## 1.4 Design Concepts

### Basic Principles

Every time step, a stochastic annual maximum flood is generated, which causes damages to agents. Agents use their projections of sea level rise to complete a benefit-cost analysis on the efficacy of adaptations and then implement their selected adaptation. Each adaptation regime reflects a slightly different process of decision-making.

### Emergence

Adaptation implementation patterns emerge over time under each adaptation regime.

### Adaptation

Adaptation is represented in the model as agents construct physical adaptations to increasing sea level rise. Each agent has a subset of possible adaptations that they may pursue. While we use a seawall as representative of a large scale adaptation, we imagine that other large infrastructure based adaptations (either nature-based or not) could replace this adaptation option.

### Objectives

The objective of all agents is to minimize future damages from sea level rise and coastal flooding through coastal adaptation.

### Learning

Agents currently do not learn in the model. However, agents are reactive in each year to the differences between their expected and experienced damages. In this sense, they are responsive for predicting sea level rise correctly or incorrectly in a given year.

### Prediction

Agents ‘predict’ the level of sea level rise that will happen in Boston Harbor. This prediction is set by the perceived SLR parameter. This is not a dynamic process in the model.

### Sensing

There are no instances of sensing in the model.

### Interaction

The nature and degree of interactions between agents varies between the three major adaptation regimes. In the Regional Authority regime, there is no interaction, as there is only one decision-maker who acts as an optimizer.

In the no cooperation regime, agents do not interact with other agents. However, as agents construct seawalls, they shift the risk profile of agents behind them geographically. Agents recognize and utilize their adjusted risk profile to make decisions.

In the voluntary cooperation regime, agents also interact through the environmental modifications of seawall construction. However, they may also choose to form coalitions to jointly finance seawall construction with other geographically-connected agents.

### Stochasticity

Stochasticity is incorporated through the generation of annual maximum flood elevations in each time step. Due to the effect of the behavioral modifier, this means that both damages and adaptation time incorporates elements of stochasticity. Because of the interactions between agents, this means that multiple adaptation patterns may emerge due to the stochastic nature of the runs.

### Collectives

In the voluntary cooperation formulation of the model, agents may form coalitions to adapt collectively and contribute to shared seawall costs.

### Observation

Agents currently do not update their beliefs, but they observe the construction of adaptations nearby and the damages caused by flooding.

## 1.5 Initialization

|  |  |  |  |
| --- | --- | --- | --- |
| Name | Variable Name | Values | Practical Meaning |
| Sea Level Rise Scenario | Sea-level-rise | 0,1,3,5 ft | Scenario used to generate annual maximum floods as they occur |
| Intensity multiplier | Multiplier\_storms\_annual\_mean | 0-1 (limited in NetLogo interface) | Increases the coefficient of variation (mean and variance) of the flood distribution annually by this much |
| Sea level projection | Mun-slr-proj | 0,1,3,5 | SLR scenario that agent’s expect to occur |
| Damage Modifier | Flood-reaction-[] | On/off for each agent type | Agents are flood reactive or not (affects benefit-cost calculations) |
| Discount Rate | discount | 0.03, 0.07, 0.0 | Value agent’s place on current vs future damages |
| Adaptation Type | Model-version | No cooperation, voluntary cooperation, regional authority | Governance regime used in the simulation |
| Storm-surge method | Storm-surge-method | Random, 1 storm, 2 storms, no storms | Controls how the annual maximum floods are generated |
| Insurance-module | Insurance-module | True/False | Turns insurance options on/off |
| Delay for the planning horizon | Planning-horizon-delay | 0-10 | Adjust benefit-cost calculations to begin at a year in the future, rather than the present year |
| Permitting delay | Permitting-delay | 0-10 | Once agents decide to build an adaptation, delay is assumed for permits (building up financing can also occur in these stages) |
| Foresight | Foresight-mun-pas-mbta  Foresight-property-owners | 0-30 | How many years are used to project forward for the benefit-cost calculations |
| External Financing Percent | External-financing-percent | 0 - 1 | The percentage of assumed external financing available to agents |
| Funding cap | Funding-cap | True/False | Limits funding in the simulation (against an assumption of unlimited funding) |
| Storm Surge Pattern | Flood-pattern | 0-200 | Draws a series of storm surges from pre-generated distributions for replicability |
| MBTA- cost-2020 | Mbta-cost-2020 | 6.6B/3.3B | Allows the user to set the 2020 price of adaptation |
| Method | method | Normal/Behavior Space | Indicates whether or not the model is run through the interface or through Behavior Space |
| Permitting-cost-proportion | Permitting-cost-proportion | 0-1 | Indicates the proportion of adaptation cost that is spent on permitting |
| Maintenance-fee | Maintenance-fee | 0-1 | Indicates the proportion of adaptation cost that is required to coordinate a collaborative adaptation structure |
| Reduction-funding-access | Reduction-funding-acces | 0-1 | Reduction in external funding available to all agents except municipalities to reflect some of the current adaptation funding mechanisms |
| Operation and Maintenance Cost | O\_M\_proportion | 0-1 | Annual % of adaptation cost that is an OM cost |
| Prioritization Method for when limited money | Prioritization-method | Normal/EJ | Specifies id adaptation priority is given to top benefit-cost ratios or to benefit-cost ratios that are weighted with inverse income |
| MBTA Adaptation Method | Mbta-adaptation-method | All-at-once/Segments | MBTA either implements all adaptation at once or with the same neighborhood segments as before |

## 1.6 Input data

|  |  |
| --- | --- |
| Data | Source |
| Boston Harbor Annual Max Flood Elevation | NOAA |
| Damage Estimates Municipalities | [Feasibility of Harbor-wide Barrier Systems Preliminary Analysis for Boston Harbor](https://www.greenribboncommission.org/wp-content/uploads/2018/05/Feasibility-of-Harbor-wide-Barriers-Report.pdf) [3] |
| Flood elevation per AEP | Woods Hole MC-FRM (private communication) |
| Scenarios of Sea Level Rise | Taken from Feasibility Study above [3] |
| Damage Estimate MBTA | [Martello Dissertation (2023)](https://dspace.mit.edu/handle/1721.1/151212?show=full) [4] |
| Depth-damage Curves | [Army Corps of Engineers](https://www.iwr.usace.army.mil/Portals/70/docs/iwrreports/85-R5.pdf) [5] |
| Adaptation Costs (Aquafence, sea wall cost) | NACCS [6] |
| GIS Shapefiles | [7], [8] |
| Income Data | [9], [10] |

## 1.7 Sub-models

### Flood generation

The model can run in two versions: either step-by-step, or with pre-generated flood sequences to use in the Behavior Space Experiments. In the first, where “*method*” = “normal,” a new flood is randomly generated in each time step. If “*method*” instead is set to “behavior space,” then the model will run using up to 200 pre-generated storm surge patterns corresponding to each sea level rise and a storm intensity of 1. This allows for the same pattern of storms to be tested again and again against different governance strategies or parameters.

In order to generate the floods, I fit a Gumbel distribution to the record of approximately 100 years of the annual maximum flood elevation, de-trended for sea level rise that occurred throughout the existing record. The data for historical annual maximum flood height and its fit to a Gumbel distribution is shown below.

A graph with blue dots

Description automatically generatedA graph with red dots

Description automatically generated

Figure S3: Plot of the annual maximum flood in Boston Habor and Q-Q plot of these transformed to Boston Harbor.

Alternative distributions, including a GEV distribution and lognormal distribution were considered, but the two parameter Gumbel distribution fit our historic data as well or better than other 2-or-3-parameter distributions. All flood elevations use the NAV88 datum.

There are two inputs to then determine the projected floods: the *sea-level rise scenario* and the *storm intensity multiplier*. If the *storm intensity multiplier* equals 1, a random maximum flood is generated from the fitted Gumbel distribution. Sea level rise is assumed to be a linear increase from 2020 to 2100 according to the scenarios of 0, 1, 3, and 5 feet of sea level rise. Sea level rise is added back into the generated flood according to the year of the simulation and assumed sea level rise. For example, if the simulation is in the year 2100, our scenario of sea-level rise is 3 ft, and the randomly generated flood elevation is 9.2 feet NAV88, then with sea level rise, we would have a flood elevation of 12.2 feet. Additionally, the model can be run to continue the linear trend derived from historic annual maximum (approximately an increase of 0.0123 feet per year). This annual increase was determined with an ordinary least square (OLS) regression with an r-squared value of 0.3, indicating that a linear sea level rise trend only accounts for 30% of the variance in annual maximum flood elevation.

If the *storm intensity multiplier* does not equal 1, the mean and variance of the fitted distribution are changed every time step. This multiplier represents the possibility that in addition to sea level rise increasing, we may see more extreme storms every year. The multiplier affects the coefficient of variation (CV) of the fitted Gumbel distribution and is used to change the mean at each time step. The new mean is the value of the old mean multiplied by the modifier. The variance is adjusted to hold the CV constant from the original distribution (note that if the multiplier is set to 0, variance of the Gumbel distribution does not change over time, as sea level rise is added after the random flood generation). Then, the annual maximum flood is randomly generated from the new distribution and sea level rise is added back in the same method. The entire process is illustrated in the flow chart below.

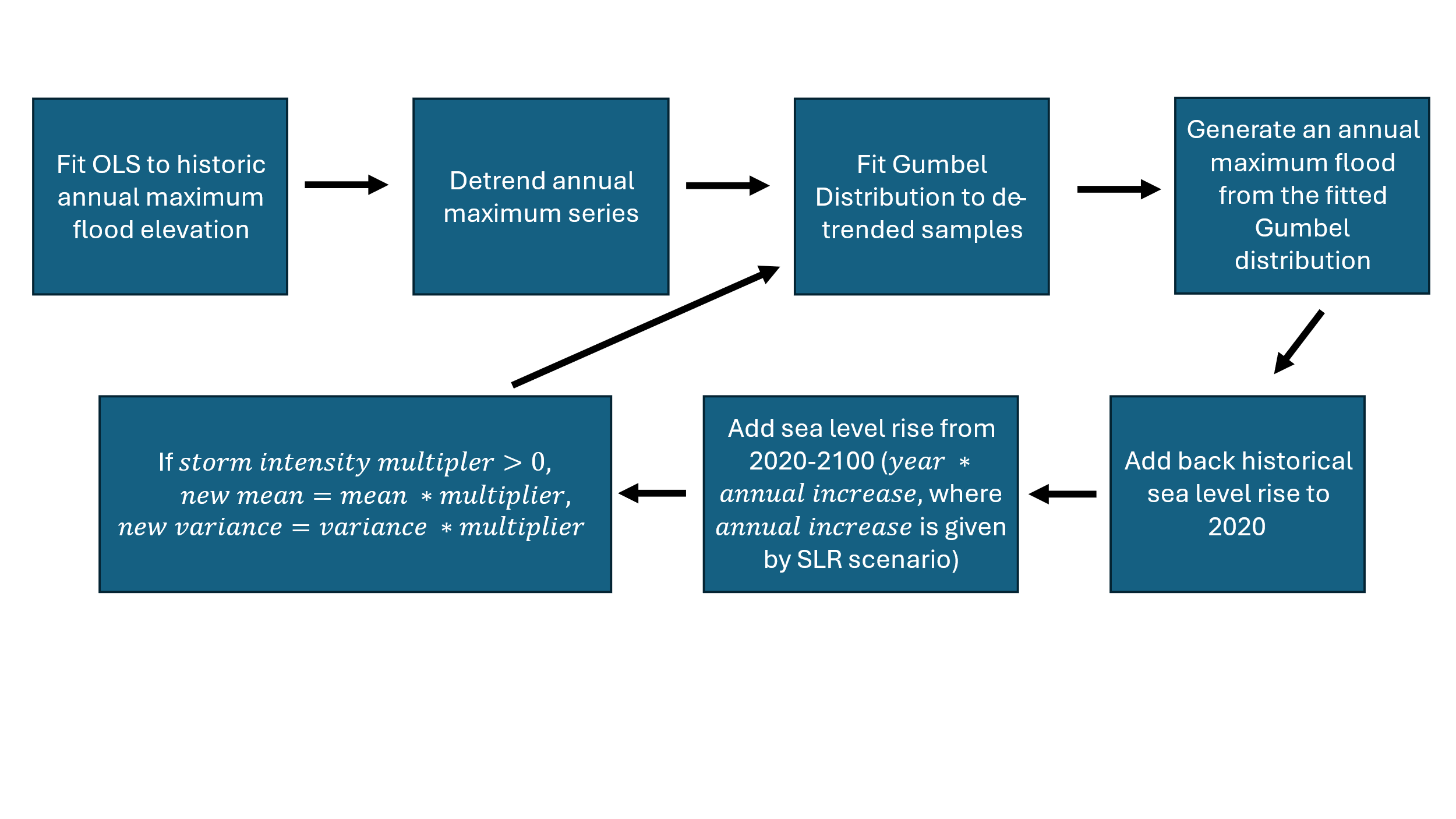


Figure S4: Process for generating an annual maximum flood elevation in each year of simulation.

The model also includes the possibility of incorporating known flood patterns as tests. These include a scenario where an artificially low flood occurs in every year except 2050, a scenario where a flood occurs in 2025 and 2075, and a scenario where there are no floods. The 1000-year storm surge is used as the extreme flood in these scenarios. These are built into the NetLogo model and were used as sanity checks when testing model behavior.

### Damage Calculations Details

Once the stochastic annual maximum flood elevation is generated, agents calculate the damage that they experience. The process for damage calculation varies based on agent type.

*Municipalities:*

Damages are calculated for each separate municipality. Damages in Boston are broken down into 9 regions, corresponding to seawall segments that may be constructed. These segments are: Allston, Back Bay, Charlestown, Downtown, East Boston, Fenway, North Dorchester, South Boston, and South Dorchester. Benefits to inland neighborhoods were allocated to the neighborhood where the seawall would prevent flood pathways reaching inland areas. To calculate damage for each neighborhood in Boston and the municipalities of the North Shore and the South Shore, we used data from the Sustainable Solutions Lab Analysis of the Feasibility Study on an Outer Harbor Barrier [3], and data from NOAA and Woods Hole Group’s MC-FRM model on flood elevations corresponding to specific AEPs. The data from the MC-FRM estimate was provided to us in private communication from an individual at the Woods Hole Group and is shown below. We use the 2008 MC-FRM estimates of flood elevations for this model.

A screenshot of a table

Description automatically generated

Figure S5: Exceedance probabilities of storm surges complied from the Woods Hole MC-FRM model.

The data from [3] provides estimates of single-event damages avoided by the construction of an outer harbor barrier (assuming for the purposes of this model that there is full damage protection). These estimates were provided for 12 neighborhoods of Boston and municipalities along the North and South shores of the Harbor. The damages are separated by both scenario of sea level rise (0, 1, 3 and 5 ft) and flood frequency. A brief snapshot of the data is provided below.

A close-up of a table

Description automatically generated

The first data transformation was to change the damage estimates from the Outer Harbor Barrier Feasibility Study to be dependent only on flood elevation, rather than frequency and sea level rise scenario. This was accomplished by assigning the MC-FRM flood elevation to each return period, effectively replacing the ‘Frequency’ column with a base elevation established in 2008 (note: this will introduce some error). In order to then account for the effect of sea level rise, the value of sea level rise was added to the base elevation corresponding to the frequency. For example, given a 1000-year flood elevation of 10.95 feet, the flood elevation corresponding to the damages shown in the first three rows of the figure above would be replaced with 15.95 ft NAV-88. This provides a reference of expected flood damages given a flood elevation in NAV88.

Once this was completed, we were left with datasets for each neighborhood in Boston and for each municipality that provided flood damages according to various flood elevations. Because these are rough transformations, an equation was fit to each neighborhood or municipality to represent the relationship between flood elevation and damages to smooth the damage curve, leaving us with a specific relationship between flood elevation and damage for each geographic area. For datasets that experienced little or no damage until the flood elevation reached a specific height, the near-zero damages were removed prior to fitting a curve and assumed that any damages below said height would be negligible, and represented by zero damages in the model. The figures below demonstrate how the different municipalities may have different damage curve shapes.

A graph of a flood elevation

Description automatically generated with medium confidence

Figure S6: Fitted curve of estimated Damage compared to flood elevation in ft NAV88 for the East Boston neighborhood.

A graph of a diagram

Description automatically generated with medium confidence

Figure S7: Fitted Damage curves for Allston. The top figure demonstrates that damages to Allston are negligible with floods less than approximately 12 ft NAV88, so the fitted damage curve is only applied to flood elevations above that elevation.

When a municipality constructs a seawall, our model assumes that the seawall protects up to 15 ft NAV88. Any flood elevation below this level results in no damage, and damage above this level is calculated according to the previous elevation-damage relationships established. Boston cumulatively calculates damages by summing the damages according to each of the 9 neighborhoods we were able to establish an elevation-damage relationship for based on the data from [3].

*Property Owners:*

Property owners experience damage based on their elevation and a depth-damage curve provided by the Army Corps of Engineers [5]. Inundation value is calculated if the flood elevation is greater than the elevation of the property owner, which is a variable assigned at initialization.

Equation 6:

Using the inundation value, damage percent is assigned based on the depth-damage curve and then the percent is used to calculate total damage to a structure based on the structure’s total assumed value.

If a property owner has constructed an aquafence, it is assumed that there is no damage with an inundation less than 3 ft above the structure’s elevation. If the property owner has constructed an on-site barrier or seawall, it is assumed no damage when the flood elevation is less than 15 ft NAV-88. Property Owners also experience no damage when floods are less than 15 ft NAV-88 if their municipality has constructed seawalls that protect them.

*MBTA:*

Damage for the MBTA is calculated similarly to the methodology used with the municipalities, although our input data for damages based on scenarios of sea level rise and exceedance probability is from Martello (2023) [4]. The same data transformations are completed and a curve is fit to create a relationship between flood elevation and damages for the MBTA.

Despite the similarities to the methodology for the municipalities, the impact of adaptations is calculated differently. The MBTA can decide to protect all vulnerable assets for a cost of $6.6 billion for floods up to 15 ft NAV-88. Additionally, municipal seawalls may protect components of the MBTA system. For example, a seawall in South Boston that protects vital storage facilities for the MBTA would reduce damage by a significant amount, while a seawall in Quincy may only be assumed to reduce damage by 5% due to the lack of assets in Quincy. When the MBTA is allowed to adapt with segments corresponding to the same neighborhoods, the degree of damage attributed to each segment is estimated according to the amount of exposed assets within that segment. For example, segments that protect rail yards or tunnel entrances are considered to contribute more to damages. The costs are estimated according to the length of the segment and the complexity of the project (for example, East Boston tunnel is assumed to be both expensive and complex). These estimates are stored as an array of damage percentage and cost percentage that can be adjusted by the model user.

*Regional Assets:*

Damages for regional assets are calculated differently. It is assumed that these assets can tolerate up to three feet of inundation, after which damage is assumed to be catastrophic ($1 Billion of damages). These assets can similarly be protected by on-site barriers up to 15 ft NAV-88 and will be protected by the construction of municipal seawalls if a municipality decides to construct sea walls along their flood pathways.

### Expected Costs and Benefits Details

Expected benefits for all adaptations are calculated for the length of the time corresponding to the value selected for the *foresight* parameters. We use 30 years as our selected value. We assume that there is a delay equivalent to the length of the *permitting delay* parameter to construct the adaptation, and therefore account for the cumulative benefits with an adaptation as the sum of expected damages without adaptation for the first years (length of the delay) and expected damages with the adaptation for the remaining time. The year in which agents begin their assessment of future damages is set by the planning-horizon-delay. All adaptation costs and benefits are discounted according to the selected discount rate. Additionally, the final cost of an adaptation is determined by the selected values for the *maintenance fee* for cooperative adaptation, *permitting-cost-proportion,* *external-financing-percent,* and any *reduction-funding-access* that may be selected.

*Municipalities:*

The method for municipalities to assess annual expected damages is established in the work of Kirshen, et al. [2], where the area below the damage-flooding depth probability exceedance curves represents an estimated annual expected damage value. These curves are taken from [3], and shown graphically below for Boston.

A graph of damage on sea level rise scenes

Description automatically generated

Figure S8: Example curves for Boston connecting flood annual exceedance probability to damages under different sea level rise scenarios.

In our experiments, municipalities use 30 years of discounted annual estimates to estimate the cost of future storms. The damage-flooding depth probability exceedance curves are linearly interpolated from the curves assembled previously (corresponding to 0, 1, 3, and 5 feet of sea level rise) to correspond to the agent’s believed sea level in each year of the simulation. This process can be represented by the equation below:

Equation 7:

,

where *d* is the discount rate and *i* is the year of calculation from the present simulation year. The damage curve shifts with each iteration of the iterative process to reflect sea level rise expectations. The is approximated through a trapezoidal integration of the damages and exceedance probabilities present from our input data source [2], [3].

The cost of municipal seawalls is assumed to be 7500/ft. Assessments of the length of the seawall needed are based on GIS files using QGIS software.

In order to assess the efficacy of seawall construction, the exceedance curves were altered so that any flood corresponding to a level of less than 15 feet NAV-88 corresponded to a damage of 0 (representing a seawall height of 15 ft NAV-88). 30-years of these altered discounted damages were summed, allowing agents to determine the benefit of constructing a seawall.

This process was done once per municipality, with the exception of Boston, which maintained the division of nine potential seawall segments determined in the damage calculations.

*Property Owners:*

In order to be able to calculate annual expected damages for property owners, damage curves had to be developed for each agent in order to be able to complete the same process as for the municipalities. Using the flood heights for various exceedance probabilities, under 0 feet of SLR, the elevation of the structure, and the depth-damage curves used to calculate flood damage, I was able to assign certain inundation depths to each exceedance probability. Sea level rise adjustments were added in each predicted year linearly for each of the projections up to 30-years out, as it was assumed that an increase in MSL affected the depth of the expected floods equally. The depth-damage curve then was used to estimate damages from the new inundation heights, resulting in the same style curve: expected damages for floods corresponding to various exceedance probabilities. Once again, using the method in [2], the area under this curve was taken to estimate annual expected damages. The same equation to calculate 30-year expected damages for the municipalities could then be used for the developer agents.

The aquafence costs property owners $500,000 to install and $40,000 to deploy. Property owners currently assume a worst-case rate of one deployment per year. On-site barriers are assumed to cost #3.2 million per building, which assumes $5300 construction cost per foot and a perimeter of 600 feet. We assume that the aquafence protects structures up to 3 feet of inundation, while the on-site barriers protect for floods up to 15-ft NAV-88.

*MBTA:*

The MBTA process for assessing risk mimics that of the municipalities in the case where no seawalls are constructed throughout the Harbor. When municipalities choose to construct seawalls, annual damage estimates are altered to reflect the reduction in damage that the seawalls would provide according to their specific location. This allows the agent to update expected damages as seawalls are constructed. However, the MBTA does not have information about future planned municipal seawalls or speculate on their construction.

Reductions in risk from seawall construction or on-site barriers is completed in the same manner as the municipal assessments. Cost estimates for on-site barriers is taken from Martello (2023) [4].

*Regional Assets:*

Damage estimates for regional assets was completed similarly to the procedure for property owners. Assuming catastrophic damages ($1B) at inundation depths of more than 3 feet, a curve was created plotting exceedance probabilities against damages. This curve is shifted with each projected year of sea level rise according to the agent’s projection. Thirty years of these projections are discounted and summed to get the 30-year estimate of potential damage.

Costs of on-site barriers are expected to be similar to on-site barriers for property owners ($5300/ft). I used GIS to estimate the perimeter of these assets and estimate construction costs. It is assumed that these barriers protect agents up to 15 ft NAV-88. The damages coming from flood exceedance probabilities that correspond to an elevation less that 15 ft NAV-88 are assumed to cause no damage in the case of an on-site barrier.

*Flood Authority*

The flood authority uses calculations from all agents above. However, instead of considering individual adaptations for each agent, the agent only considers constructing seawalls across 11 locations: the nine neighborhoods in Boston, Qunicy, and Winthrop. 30-year damage estimates from all other agents are summed based on their locations to estimate the cumulative damages that could be avoided from the construction of each segment of seawall.

*Additional cost considerations*

The cost of an adaptation is not only the costs specified in the section above. Adaptation costs are also affected by a few user selected parameters: discount rate, operations and maintenance percent, permitting cost, and maintenance fee. The operations and maintenance costs and permitting costs are both represented as percentages of the total adaptation cost that are added to the cost estimate. The maintenance fee is also represented by a percentage, assumed to represent the additional transaction costs due to cooperation for both voluntary coalitions or the regional flood authority. The discount rate is applied according to the following equation:

Equation 8:

### Insurance Module

Some property owners are required to have insurance. We model our insurance market off of the NFIP flood insurance process. Any household in the 100-year flood plain with a mortgage is often required to by NFIP insurance by their lender. De Ruig, et al estimate the percentage of households in the flood plain that are required to comply to be around 55%, with around 78% of those actually purchasing the insurance [11]. Although there will be discrepancies between these values and large scale property owners, we use this as an approximation of how many agents are required to purchase NFIP insurance. Out of agents within the 100-year flood plain, we assume 43% of these agents must purchase flood insurance. It is assumed that these agents will always purchase this insurance regardless of the cost of the insurance. We distinguish insurance options between homeowners and commercial properties both for price and coverage. Although not all properties may be eligible for NFIP insurance, we do consider this to be representative of all insurance in the Harbor and do not model private insurance markets.

In each time step, property owners have the option to purchase flood insurance. Prior to the year 2022, the insurance premium is assumed to be $1482, the average value in Massachusetts, following the procedure used by [11]. For commercial properties, we set this to $4,224. In 2022, we begin to price the premiums to better reflect NFIP’s Risk Rating 2.0, which has been updated to better reflect an accurate assessment of property risk [12]. Insurance is then priced according to the following procedure:

1. For each property owner, the annual expected damage is assessed according to the same area methodology as the benefit-cost ratio.
2. The premium is set to either an 18% increase from the current premium or the expected annual damage, whichever is smaller.
3. Premium minimums are set at $100 so no household would pay less than $100 for coverage.

If property owners purchase insurance, they are assumed to be eligible for the maximum NFIP coverage in a given storm (350,000 for homeowners and 1,000,000 for commercial structures), subject to a 10% deductible. While this does not reduce the damage, it does alter who pays for the damage that occurs to a property owner.

Property owners may purchase flood insurance in addition to other adaptations or may purchase flood adaptation on their own.

We estimate the role of the CRS system on insurance premiums by reducing the cost of a premium by 30% for any agent protected by a seawall [13].

### Funding and Budgeting

The model can be run with or without budget constraints. Without budget constraints, we assume that financing is not an obstacle for adaptation. In this case, adaptation implementation would be limited only by a permitting delay.

With a budget constraint, some available funds are required to allow an agent to­­ adapt. We assume a 10% down payment for adaptation implementation. Assumed annual budgets are based on published capital improvement plans, municipal plans, and percentages of structure value.

Adaptation prioritization for the MBTA, Boston Harbor, and Regional Authority can be completed in one of two ways. In the first, prioritization of particular segments is completed in order of the highest benefit to cost ratio (*prioritization-method = normal)*. The second methodology (*prioritization-method = EJ*) utilizes the method proposed by [14], where potential benefits of adaptation are weighted by:

Equation 9:



Where epsilon is 1.35.

Rather than calculating these at the census tract level, we identified weights at the scale of the model: neighborhoods or towns in 2017. This resulted in the following weights for each neighborhood and municipality considered in the model:

|  |  |
| --- | --- |
| ***Municipality/Neighborhood*** | ***Income Weight*** |
| Allston | 1.454823548 |
| Backbay | 0.510401236 |
| Charlestown | 0.502590867 |
| Downtown | 0.666944919 |
| East Boston | 1.238426983 |
| Fenway | 1.835616468 |
| North Dorchester | 1.4452918 |
| South Boston | 1.109159906 |
| South Dorchester | 1.349865209 |
| Quincy | 0.911733669 |
| Winthrop | 1.002224514 |

### Permitting

Permitting manifests through two variables in our model: *permitting\_cost\_proportion* and the *permitting\_delay* parameter. These work together to account for the direct costs on permitting on adaptation decision-making and the time that it may take to permit large adaptation projects, during which storm damages will still occur. For example, the total cost of an adaptation is calculated as follows:

Equation 10:

Where is the *permitting\_cost\_proportion,* represents any cooperation maintenance fee, and represents any reduction in funding due to external grant accessibility.

In addition to increasing the number of years that an agent is exposed to damaging floods while awaiting adaptation, the *permitting\_delay* parameter is also taken into account directly when calculating benefits of an adaptation into the future. In this way, large *permitting\_delays* both reduce the calculated benefits of an adaptation (because it is a longer time before the benefits can be realized) and increase damages that an agent experiences before the adaptation is in place. Expected benefits of an adaptation, which drive the adaptation decision-making are calculated as below:

Equation 11:

Where indicates the year of calculation, is the *foresight* parameter, which controls how far into the future agents project their calculated benefits, is the *permitting\_delay* and the terms and correspond to the expected damages with and without an adaptation in the calculated year. All agents experience the same permitting delay and permitting cost proportion within a single simulation.

### Adaptation Metrics

Metrics in the paper are reported in 6 different ways that can be separated into two categories: using a baseline of no adaptation and using a baseline of no cooperation. The first is useful to understand the relative behavior of each form of adaptation governance independently. However, using the scenario of no cooperation as a baseline provides insights on the benefits of cooperation in direct contrast to a scenario that is likely reflective of a business-as-usual adaptation strategy (we consider it to be unlikely that no adaptation will occur in the absence of cooperation, which provides a strong case for the second set of metrics. Regardless of the baseline, we directly quantify three metrics: flood damages, adaptation costs, and net benefits. These are calculated in the following ways for use in analysis:

***Flood damages (no adaptation baseline):***

Equation 12:

***Flood damages (no cooperation baseline):***

Equation 13:

***Adaptation costs (no adaptation baseline):***

Equation 14:

***Adaptation costs (no cooperation baseline):***

Equation 15:

***Net benefits (no adaptation baseline):***

Equation 16:

***Net benefits (no cooperation baseline):***

Equation 17:

### GIS

The map in NetLogo is generated using GIS files of the Boston Harbor Area. These files were also used to estimate seawall length needed for each municipality (and in the case of Boston, each neighborhood). These files are use to generate a map and demonstrate where seawalls are constructed, but the patches in NetLogo do not directly interact with the agents. The following table displays both the estimated seawall length required for each designated segment and the neighborhoods that it protects.

|  |  |  |
| --- | --- | --- |
| Seawall Segment | Length (ft) | Additional Neighborhoods? |
| Allston | 14505 |  |
| Backbay | 4146 |  |
| Charlestown | 16676 |  |
| Downtown | 13842 |  |
| East Boston | 73993 |  |
| Fenway | 5428 |  |
| North Dorchester | 20811 | Jamaica Plain, Roxbury |
| South Boston | 44647 | Roxbury, South End |
| South Dorchester | 20811 |  |
| North-Shore | 54530 | Assumed to be Winthrop |
| South-shore | 105324 | Assumed to be Quincy |

### Python Extension

The NetLogo model is run with the python extension. Python is utilized to complete some of the more complicated benefit-cost calculations. Model users will need to have python and a corresponding environment to run the model. The packages of Scipy and Sys must be downloaded.

# Example Dashboard

A screenshot of a computer

AI-generated content may be incorrect.

Figure S9: Snapshot of the GUI for the model in NetLogo.

A screenshot of a computer screen

AI-generated content may be incorrect.

Figure S10: Close-up on graphs from a single simulation on the NetLogo interface.

# Key Assumption List

|  |  |
| --- | --- |
| Assumption | Details |
| Max Storm Surge Distribution | Captured with Gumbel distribution based on historical data |
| Flood Heights corresponding to AEPs | For AEPs of [.001, 0.002, 0.01, 0.02, 0.05, 0.1, 0.2, 0.25], we use flood heights of [10.95, 10.54, 9.99, 9.58, 9.17, 8.61, 8.17, 7.7, 7.75] determined from the MC-FRM with linear interpolation |
| Assumed damages municipalities | Values calculated in Outer-harbor feasibility study |
| Annual Adaptation Budget of Airport | $50M |
| Annual Adaptation Budget of Food Distribution | $50M |
| MBTA Cost per Neighborhood Adaptation | In order of: North Shore, South Shore, Allston, Back Bay, Charlestown, Downtown, East Boston, Fenway, North Dorchester, South Boston, South Dorchester;  [2.5, 2.5, 5, 5, 10, 25, 25, 5, 2.5, 15, 2.5] |
| Annual MBTA Adaptation Budget | $40M |
| Annual municipality adaptation budget | Calculated as the same ratio that Boston has allocated to climate out of tax income; Boston has a budget of 20000000, NS of 560000, and Quincy 2720000 |
| Property Owners annual budget | 10% of property value |
| Property Value of property owners | Homeowners: 1000000  Commercial: 8000000 |
| Property owners with mandatory NFIP insurance | 43% if elevation < 9.58 ft NAV88 |
| Minimum NFIP premium | 100 |
| Aquafence Protection | Structure elevation + 3 ft |
| Seawall protection | 15 ft NAV88 (~5ft above 100-year flood) |
| Insurance Coverage Caps | Homeowners: 250,000  Commercial: 500,000 |
| Insurance deductible | 10% damages |
| MBTA Exposure | In order of: North Shore, South Shore, Allston, Back Bay, Charlestown, Downtown, East Boston, Fenway, North Dorchester, South Boston, South Dorchester;  [2, 2, 2, 10, 15, 2, 5, 40, 2] |
| Cost of municipal seawall | 7500/ft |
| CRS Discount with municipal seawall in place | 30% |
| Aquafence cost | 500,000 |
| Modifier value in case of no expected damage | 0.5 |
| Prioritization of adaptation in case of limited budget | Maximum benefit-cost ratio |
| Voluntary cooperation requirements | Agents are already willing to adapt  Agents pay less than current adaptation plans |
| Adaptation down payments | 10% |

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