RESILIENTMASS ACTION TEAM (RMAT)

CLIMATE RESILIENCE DESIGN STANDARDS & GUIDANCE

SECTION 4: CLIMATE RESILIENCE DESIGN STANDARDS

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OWNER:
Massachusetts Executive Office of Energy and Environmental Affairs (EEA)
IN PARTNERSHIP WITH:
Massachusetts Emergency Management Agency (MEMA)
CONSULTANT TEAM:
Weston & Sampson, Woods Hole Group, Dr. Jennifer Jacobs,
BSC Group (EEA IT Vendor & Tool Developer)

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4. CLIMATE RESILIENCE DESIGN STANDARDS OUTPUTS

This section describes the Climate Resilience Design Standards Outputs provided by the Climate Resilience Design Standards Tool (“the Tool”), and the relationships that inform those outputs.

4.1 GOALS/OBJECTIVES

Many projects throughout the Commonwealth are currently using climate projections for design. The Standards provide a recommended uniform statewide methodology for consistent use of available climate projections.

The Standards also bridge the gap between the climate data that have been developed, and using that data for design, by translating it into design criteria.

The main objective of the Climate Resilience Design Standards (“Standards”) is to provide a consistent recommended basis-of-discussion across various projects in the Commonwealth considering the following climate parameters: sea level rise / storm surge, extreme precipitation, and extreme heat. The term “standards” has been used in many different ways in climate resilience literature, so the RMAT developed a working definition for this effort as follows: “***A Climate Resilience Design Standard is a scientifically based process or method that produces a consistent outcome, which uniformly guides users in the selection of planning horizons, return period, and flexible design criteria, by climate parameter***.”

The Standards for each climate parameter include the following: recommended planning horizon (intermediate and/or target), recommended return period (sea level rise/storm surge and precipitation) or percentile (heat), and a list of applicable design criteria that are likely to be affected by climate change.

Where statewide modeling has been performed with outputs for projected design criteria values, such as the Massachusetts Coast Flood Risk Model (MC-FRM) or EEA’s Massachusetts Climate and Hydrologic Risk Project, these projected values may be available through the Tool. As of Version 1.4 released in December 2024, the Tool will provide:

- projected design criteria values for several sea level rise/storm surge design criteria (projected tidal datums, projected water surface elevation, projected wave action water elevation, projected wave heights); projected total precipitation depth for 24-hr design storms; projected temperature statistics and/or
- tiered estimation methods with step-by-step instructions on how to generate projected values for design criteria based on the recommended planning horizon and return period or percentile using downscaled Global Climate Models (GCMs).

4.2 OUTPUT OVERVIEW

The Climate Resilience Design Standards are one of the two main outputs of the Tool (the other main output of the Tool is the Preliminary Climate Hazard Exposure and Climate Risk Screening Outputs, described in **Section 3**). Upon completing the necessary Project Inputs, users receive Climate Resilience Design Standards Output for their project's asset(s) from the Tool.

The recommended Standards are automated in the Tool for each asset entered and organized by climate parameter. They include the following as listed in Table 4.1.

Table 4.1. Standard Output Recommendations Provided by the Tool

Standards Output Recommendations	Example	Relationship Driving Recommendation
Planning Horizon[1]	2070	Useful Life
Return Period[2,8]	100-year (1% Annual Exceedance Probability)	Criticality[3], Asset Type, and Useful/Exposure Service Life[4]
Percentiles[5]	50th percentile	Criticality[3] and Construction Type
Design Criteria[6]	• Projected Total Precipitation Depth for 24-hr Design Storm • Projected Wave Action Water Elevation • Projected Cooling Degree Days, etc.	Asset Type and Location
Estimation Method Tier[7] **for projected design criteria values**	Tier 3 – High Level of Effort	Criticality[3] and Useful Life

1. Intermediate planning horizon provided for sea level rise / storm surge climate parameter only.
2. For sea level rise / storm surge and extreme precipitation climate parameters only.
3. Not applicable for natural resource assets. For a description of Criticality, please refer to the **Glossary of Terminology** and **Section 2.5.7**.
4. Return period recommendations for extreme precipitation are based on the useful life of the asset. Return period recommendations for sea level rise / storm surge are based on the exposure service life of the asset, which is defined as the number of years from when an asset is first exposed to coastal flooding to the end of its service/useful life (estimated using probability of flooding maps from the MC-FRM). Please refer to **Section 4.7.4** for a description of exposure service life.
5. For extreme heat climate parameter only.
6. Design criteria are accompanied by guidance in the Tool, including definitions; how to estimate the projected value or the projected value (if available); how to consider for planning, early design, and project evaluation; and limitations.
7. Several design criteria provide projected numerical values associated with the recommended return period and planning horizon, while others provide tiered estimation methods with step-by-step instructions on how to generate projected values given the other recommended Standards.
8. Return period recommendations are not provided by the Tool for natural resource assets. For projected total precipitation depth for the 24-hr design storm, natural resources assets receive projected values associated with the 25-yr (4%) return period. For applicable sea level rise /storm surge design criteria, natural resources assets received projected values associated with the 20-yr (5%) return period.

4.3 TIERED ESTIMATION METHODS

The Standards utilize existing available climate change data and provide a consistent, repeatable method for generating projected design criteria values from the data. The Tool will directly provide projected design criteria values for several sea level rise/storm surge design criteria (projected tidal datums, projected water surface elevation, projected wave action water elevation, projected wave heights), projected total precipitation depth for 24-hr design storms, and most temperature design criteria (projected annual/summer/winter average temperatures, projected number of high heat days, projected number of heat waves, projected growing degree days, and projected cooling/heating degree days) —see **Section 4.7** and **Section 4.8**.

Users may need to follow these step-by-step methods to calculate projected design criteria values associated with the recommended planning horizon, return period, and/or percentile for some extreme heat design criteria (projected heat index), several sea level rise/storm surge design criteria (projected duration of flooding, projected scour & erosion, projected design flood velocity), and several extreme precipitation design criteria (projected peak intensity for 24-hr design storms, special cases for projected total precipitation depth for 24-hr design storms, projected riverine peak discharge & peak flood elevation). The step-by-step calculation methods are structured in tiers which reflect the level of effort associated with generating the projected design criteria values. The tiered calculation method instructions are available as downloadable PDFs for each design criteria used in the Tool.

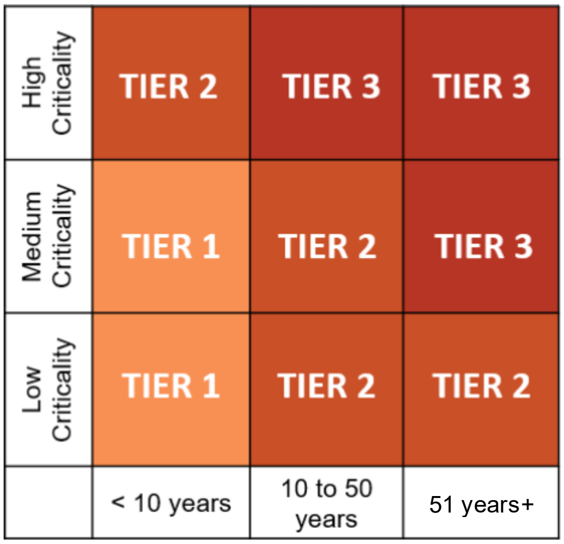
- **Tier 1** is the lowest level of effort to determine design criteria values and is only recommended for assets which have a useful life of less than 10 years and/or infrastructure and building assets which have been rated low and medium criticality. These projects should incorporate Tier 2 estimation methods where feasible, but if not, should design for today and plan for resilience reinvestment in the future.
- **Tier 2** is a moderate level of effort and utilizes existing established relationships between current and future climate scenarios and current design criteria to generate future climate design criteria values. These relationships are referenced often in climate studies, such as the present-day 100-year rainfall event is similar to the 2070 25-year rainfall event. In cases where those relationships are not yet established for design criteria, such as the case for heat waves, Tier 3 or Tier 1 estimation methods are recommended.
- **Tier 3** is the greatest level of effort and the most site-specific method to calculate design criteria values. The Tier 3 estimation methods generally utilizes downscaled global climate model projections of meteorological variables (GCMs) either as design criteria values directly or as a basis for calculating design criteria values which are not meteorological variables (e.g., flood elevation).

Existing Available Projections for Design Criteria

Some communities have also developed or are in the process of developing local site-specific extreme precipitation and extreme heat data and models for planning and design, such as Cambridge, Somerville, and Boston. If this information has previously been generated for the necessary design criteria, it may be used instead of following the recommended methodology. Where statewide modeling has been performed with outputs for projected design criteria values, such as the Massachusetts Coast Flood Risk Model (MC-FRM) or EEA's Massachusetts Climate and Hydrologic Risk Project, these projected values may be available through the Tool. With data already available for some design criteria, the level of effort for generating design criteria values is reduced.

Users may follow the instructions to generate values for the recommended design criteria, using the recommended return period (for building and infrastructure assets) or percentile (heat design criteria only) and planning horizon. **All projects are welcome to use a Tier 3 level of effort regardless of Standards recommendations.**

The relationship between criticality and useful life determines the tier the Tool recommends for building and infrastructure assets, as shown in Figure 4.1. Please refer to **Section 2.5.7** for additional information on asset criticality. Tier recommendations for natural resources assets are based on useful life only. Natural resource assets with less than 10 years useful life will receive a recommendation for Tier 1 level of effort. Natural resource assets with greater than or equal to 10 years useful life will receive a Tier 2 level of effort recommendation.



High Criticality	TIER 2	TIER 3	TIER 3
Medium Criticality	TIER 1	TIER 2	TIER 3
Low Criticality	TIER 1	TIER 2	TIER 2
	< 10 years	10 to 50 years	51 years+

Figure 4.1. Relationships Informing Recommended Estimation Method Tier Output for Building and Infrastructure Asset Categories from the Climate Resilience Design Standards Tool

4.4 INTENDED USE

The Climate Resilience Design Standards Tool is free and available to the public. To use the Tool, users will need access to the internet, computer, and must maintain a valid email address.

The recommended Standards and associated guidance are intended to inform planning, early design, and evaluation processes. **The Standards provide a basis-for-discussion and point of reference as plans and designs develop.** They are not to be considered final or appropriate for construction documents without supporting engineering analyses.

- **Planning**: This guidance is generally intended for Asset Owners, including State Agencies and Municipalities, to help inform project planning and recommended studies and assessments. Site suitability and regional coordination guidance and forms should be considered in conjunction with the design criteria specific guidance.

- **Early Design**: This guidance is generally intended for Technical Staff at the planning/pre-design and schematic design stages of a project. The guidance provided within should be considered as design advances in conjunction with site-specific engineering analyses. Flexible adaptive pathways guidance and forms should be considered along with the design criteria specific guidance.

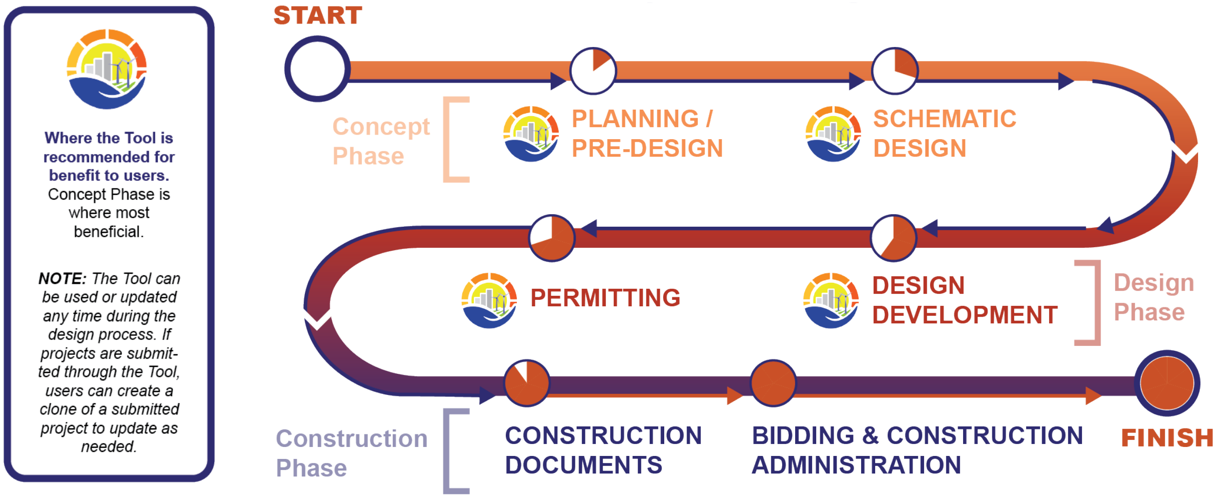
- **Evaluation**: This guidance is generally intended for people reviewing a draft plan or design, including Project Evaluators (e.g., grant administrators, conservation commission agents, and/or State Agencies), to inform project evaluations and prompt follow-up or justification questions when Standards are not able to be met on design projects.

If recommended in the Standards, it is expected that Technical Staff calculate projected design criteria values for project design based on the Standards Output recommendations, including following the step-by-step tiered estimation methods.

The Standards Output should be considered in context of the overall project along with the Climate Resilience Design Guidance (Guidance Document), which includes site suitability, regional coordination, and flexible adaptive pathways considerations. An in-depth stakeholder and community engagement session and social vulnerability assessment is recommended to be conducted for projects with assets for which the Tool recommends generating design criteria with a Tier 3 level of effort (please refer to the Guidance Document for further details).

4.5 WHEN TO USE THE CLIMATE RESILIENCE DESIGN STANDARDS

The Climate Resilience Design Standards are intended for use in design of state-funded projects with physical assets in the Commonwealth. The Standards can be used throughout the typical lifecycle of a design project, as illustrated in Figure 4.2. Use of the Tool is also referenced in several grant applications for state funding and in the MEPA process. For use of the Standards as part of any state grant program and/or application, users should consult the individual program's Request for Proposal (RFP), or equivalent document, for details on how the Standards will be used by the program. This is not a regulatory tool and is intended to provide a basis-of-discussion and point of reference for planning, early design, and evaluation that is standardized across the Commonwealth.



Where the Tool is recommended for benefit to users. Concept Phase is where most beneficial.

***NOTE:** The Tool can be used or updated any time during the design process. If projects are submitted through the Tool, users can create a clone of a submitted project to update as needed.*

Figure 4.2. Typical design process and where the Tool Outputs are recommended to benefit users

4.6 LIMITATIONS

The Climate Resilience Design Standards are **advisory** and intended to be specific for climate resilience design of physical assets and consistent across agencies and municipalities. The Standards do not and are not intended to replace existing practices, regulatory requirements, codes, or existing standards required by other agencies. For example, if the Tool recommends an asset should be designed to a 25-year return period, but regulatory policy only requires that the asset be designed to a 10-year return period, the discrepancy should be reflected in the Forms presented as part of the Climate Resilience Design Guidance.

The goal of the Standards is to provide a **recommended** consistent basis-of-discussion across various projects in the Commonwealth. There may, however, be additional asset types, design criteria, and/or climate parameters that are not included in the Standards. The Standards and Tool have been developed to be flexible and accommodate new climate parameters, data, design criteria, etc. in the future as needed.

The Standards are not a replacement for a detailed risk and vulnerability assessment. Additional studies to evaluate climate risks and identify feasible adaptation strategies to mitigate those risks should be considered as part of design.

The recommended tiered estimation methods to estimate numerical values for design criteria are based on existing industry-accepted and scientific community-published sources. These methods and data sources are referenced in each downloadable PDF (see **Attachment 4-C)**.

The projected values for tidal datums, water surface elevation, wave action water elevation, and wave heights provided through the Tool are based on the MC-FRM outputs as of 9/13/2021, which included GIS-based data for three planning horizons (2030, 2050, 2070). These values are projections based on assumptions as defined in the model and the LiDAR used at the time. Please refer to **Section 4.7.2** and **Attachment 4-A** for further details.

The projected Total Precipitation Depth values and the temperature projected values provided through the Tool are based on the climate projections developed by the Steinschneider research group at Cornell University as part of Phase 1 of EEA's Massachusetts Climate and Hydrologic Risk Project, GIS-based data as of 10/15/21. Please refer to **Section 4.8.2** and **Attachment 4-B** for further details.

The Standards provided within the Tool, including projected design criteria values and associated guidance, may be used to inform plans and designs but do not provide guarantees for future conditions or the resilience of projects designed based on the recommended criteria. The projected values should not be considered final or sufficiently well-characterized to support final design construction documents without supporting engineering analyses. The guidance provided within this Tool is intended to be general and users are encouraged to do their own due diligence.

4.7 SEA LEVEL RISE/ STORM SURGE STANDARDS

4.7.1 OUTPUTS OVERVIEW

Upon completion of Project Inputs, users will receive Standards for each climate parameter from the Tool, for each asset entered. **If the project is not exposed to sea level rise/ storm surge within the longest useful life of the assets entered (as defined in Section 3.2) it will not receive Standards for this climate parameter.** The Standards provided for sea level rise/ storm surge climate parameter for each asset include recommended target and intermediate planning horizon, return period, and the following design criteria that are likely to be affected by climate change:

- projected tidal datums
- projected water surface elevation
- projected wave action water elevation
- projected wave heights
- projected duration of flooding
- projected design flood velocity
- projected scour & erosion

There are either projected values provided for design criteria based on recommended planning horizon and return period, or recommended methods to estimate projected design criteria values.

4.7.2 DATA SOURCE & LIMITATIONS

The recommended Climate Resilience Design Standards for the sea level rise/ storm surge design criteria reference the Massachusetts Coast Flood Risk Model (MC-FRM). The MC-FRM is a probabilistic hydrodynamic model that incorporates the values for sea level rise on resilient.mass.gov (see ResilientMass Maps and Data Center) (RCP 8.5 scenario). The MC-FRM is a physics-based approach to water level increases, wave dynamics, and flooding progression using climate projections described in the 2018 State Hazard Mitigation and Climate Adaptation Plan (SHMCAP), which includes sea level rise projections under a high (RCP8.5) emissions scenario. The MC-FRM is a high-resolution hydrodynamic model, with data results provided in overland areas on the order of 5-10 meters (16-33 feet), and as resolved as 2-3 meters (5-10 feet) in highly populated and developed areas. The model dynamically includes the impacts of tides, waves, wave set-up, wave run-up and overtopping, storm surge, winds, and currents over a range of storm conditions.

The MC-FRM represents the “Level 3” approach, as described by Federal Highway Administration’s Highways in the Coastal Environment, Hydraulic Engineering Circular Number 25 (HEC-25), third edition (FHWA, 2020). The MC-FRM is the result of over 1,000 simulations of storms, including both extra-tropical (i.e., nor-easters) and tropical (i.e., hurricanes) cyclones, and was calibrated to historical and contemporary storm events. This statistically robust approach provides information corresponding to an annual exceedance probability, such as the 1% annual chance event or 100-yr return period.

The landscape of the model is based on topography and bathymetry conditions at the time of model mesh creation (2016-2017), but anthropogenic features are constantly changing and evolving. As such, if a flood protection project was constructed after the model mesh creation, it is unlikely that it is included in the MC-FRM. Inaccurate flood risk may therefore be represented within the model-derived GIS datasets for that area.

The MC-FRM does not model topographic landscape or shoreline changes over time, so the topographic features, landscape elevations, and spatial extents do not erode, accrete or undergo any type of morphologic changes between planning horizons. For example, the ground surface elevations and shorelines within the model grid are the same in 2030 as they are in 2070. In reality it is likely that coastal landscapes will change as a result of increasing sea levels and ongoing storm conditions over time. Exactly how these coastal resources are expected to change in the future is tied to sea level rise projections and the quantity, type, and intensity of coastal storms for various areas, both of which are highly uncertain.

Larger precipitation events may result in localized flooding due to poor drainage and/or undersized capacity of stormwater systems, and in coastal rivers higher than normal discharge flowing downstream can cause overbank flooding in the river itself. The MC-FRM does not include localized precipitation-based flooding beyond changes to increased interactions between discharge and coastal flooding at major rivers. Coastal-based flooding advances upstream in rivers, estuaries, and other connected water bodies and systems. There were three types of freshwater boundary conditions applied in the MC-FRM based on available data. For the Mystic and Charles Rivers, the MC-FRM models backwater effects that propagate upstream and the dynamics of discharge interacting with storm tides because of better data available. Average discharge under current and future climate conditions were assumed for the Taunton, Neponset, and Merrimack rivers. Minor rivers and estuaries did not have freshwater discharges modeled in the MC-FRM. For additional information on the MC-FRM, please refer to **Attachment 4-A**.

The projected values and maps provided through the Tool are based on the MC-FRM outputs as of 9/13/2021, which included GIS-based data for three planning horizons (2030, 2050, 2070). MC-FRM outputs include six return periods (annual probability): 1000-yr (0.1%), 500-yr (0.2%), 200-yr (0.5%), 100-yr (1%), 50-yr (2%), and 20-yr (5%) design storm (annual chance events). These values are projections based on assumptions as defined in the model and the LiDAR used at the time. Projected values for duration of flooding, design flood velocity, and scour and erosion are not available through the Tool. Users are encouraged to consult a professional coastal engineer or scientist/modeler to estimate projected design criteria values as recommended through the Tool following the tiered estimation method.

There are several defined areas of uncertainty in the MC-FRM data, where:

- flooding is caused by intermittent pulses of water from wave overtopping of major coastal structures (e.g., revetments, seawalls) only (i.e., no water directly flows to the location) during simulated events
- shallow water flooding is expected or there is minor water depth during the most extreme events (>1,000-yr [0.1%] design storm)
- flooding may vary drastically due to dynamic landforms and geomorphology

Users will receive an ATTENTION note that accompanies projected values for the design criteria, as shown in Table 4.2, below, if the project polygon intersects one or more of these areas of uncertainty in the MC-FRM data. These areas are visible on the projected water surface elevation and wave action water elevation maps as “hatched” areas; refer to **Section 4.7.6**. Additional site analyses are recommended to establish design criteria values in these cases.

Table 4.2. ATTENTION notes that accompany projected design criteria values where there are known areas of uncertainty within the MC-FRM data

ATTENTION NOTES	ATTENTION: This project intersects areas influenced by wave overtopping based flooding These areas are where flooding is caused by intermittent pulses that come from wave run-up and overtopping at a coastal structure. Additional site analyses are recommended to establish design values associated with design criteria.
	ATTENTION: This project intersects areas that are low probability flooding zones with minimal flood risk and small depth of flooding. These areas are where flooding is expected during the most extreme storm events (>1000-yr return period) or where there is only minor water depth during the 1000-yr return period. Additional site analyses are recommended to establish design values associated with design criteria.
	ATTENTION: This project intersects areas influenced by combined effect of direct flooding and wave overtopping based flooding. These areas are where flooding is caused by surge, tides, and wave setup as well as intermittent pulses that come from wave run-up and overtopping at a coastal structure. Additional site analyses are recommended to establish design values associated with design criteria.
	ATTENTION: This project intersects dynamic landform areas. These areas are where geomorphology is extremely dynamic and expected flooding can vary drastically. Additional site analyses are recommended to establish design values associated with design criteria.

The geographic extents of projected tidal datums are based on the MC-FRM outputs as of 9/13/21, and tidal datums are recommended to be evaluated if a project location is exposed to coastal flooding, even if no projected values are available through the Tool. In this event, users will receive the following ATTENTION note: “The site is exposed to Sea Level Rise / Storm Surge, but projected Tidal Datums are not available within the site. Additional site-specific analyses are recommended to identify projected Tidal Datums for the recommended planning horizon. Consult a professional coastal engineer or modeler to estimate projected Tidal Datums based on the recommended Standards and additional outputs provided through this Tool.”

As referenced in Table 4.4, Natural Resource assets do not receive a recommended return period as a Standard. Projected values from the MC-FRM associated with the **20-yr (5%)** design storm/return period are provided as an output in the Tool with the following ATTENTION note: “Return Period Recommendations for natural resource assets and subsequent projected values are provided as a consideration for users, not a formal standard. Users should follow industry best practices for designing natural resource assets in coordination with the appropriate regulatory agencies.”

The projected values, maps, Standards, and guidance provided within the Tool may be used to inform plans and designs, but they do not provide guarantees for future conditions or resilience. The projected values are not to be considered final or appropriate for construction documents without supporting engineering analyses. The guidance provided within the Tool is intended to be general and users are encouraged to do their own due diligence.

4.7.3 PLANNING HORIZON RECOMMENDATIONS

The Tool may provide up to two planning horizons for assets exposed to sea level rise/storm surge: Target and Intermediate. The Target Planning Horizon refers to a future date to which a project should be designed, which allows the project to incorporate anticipated climate change conditions (e.g., 2070 sea level rise projections). The Intermediate Planning Horizon is provided as an interim planning horizon if the Target Planning Horizon is not achievable in design.

A planning horizon is defined as a future time period to which a project is recommended for design, which allows the project to incorporate anticipated climate change projections.

For example, if an asset is expected to last 40 years before a major reconstruction/renovation, 2070 is the target planning horizon for design, and 2050 is the intermediate planning horizon for design.

For assets that are expected to last beyond 2060, an Intermediate Planning Horizon of 2050 is provided. The Intermediate Planning Horizon is provided to promote flexible adaptive design, such that if design considerations of the asset are not able to accommodate the 2070 climate projections due to site-specific restrictions or other design limitations, or if the rate of climate change shifts beyond mid-century, then it is recommended that the asset be at least designed to the intermediate 2050 climate projections.

Recommended target planning horizons provided by the Tool may vary by asset but do not vary based on climate parameter. **An Intermediate Planning Horizon is only provided and applicable for the sea level rise and storm surge parameter, not for extreme precipitation or extreme heat.**

The recommended planning horizons are determined based on the year through which the asset is expected to last (i.e., before a major reconstruction/renovation), which is calculated by adding the asset's useful life in years to the construction start year (as entered by the user in the Project Inputs of the Tool). The calculated year will be compared against the first column in Table 4.3, and the corresponding planning horizon will be provided as output.

Table 4.3. Recommended Target and Intermediate Planning Horizons Provided by the Tool, based on the Asset's Useful Life and Construction Start Year

END OF USEFUL LIFE[1]	RECOMMENDED TARGET PLANNING HORIZON OUTPUT	RECOMMENDED INTERMEDIATE PLANNING HORIZON OUTPUT
2021 - 2029	**2030**	**Not Applicable**
2030 - 2039	**2030**	**Not Applicable**
2040 – 2049	**2050**	**Not Applicable**
2050 – 2059	**2050**	**Not Applicable**
2060 – 2069	**2070**	**2050**
2070 - 2079	**2070**	**2050**
2080 - 2089	**2070**	**2050**
2090 - 2099	**2070[2]**	**2050[2]**

1. Calculated by adding the asset's useful life in years, to the estimated year construction of the asset will start.
2. MC-FRM currently does not cover 2100 scenarios, so the 2070 planning horizon is recommended until 2100 results are available.

4.7.4 RETURN PERIOD RECOMMENDATIONS

Different state agencies and municipalities may have their own standards for return periods. **The recommended return periods provided by the Tool are advisory and do not replace regulatory requirements.**

A return period is defined as the annual probability that an event of a specific magnitude will be equaled or exceeded. Return period may also be known as a recurrence interval. Return periods are selected based on the tolerance for risk that an event will affect, damage, or destroy the asset. **The Tool will provide a recommended return period for each building and infrastructure asset.** The recommended return period will also be provided in terms of percent annual exceedance probability (% AEP or “annual probability”). This distinction is based on industry practice and is described in further detail in the **Glossary of Terminology**.

These recommended return periods for each climate parameter are based on industry standards and professional judgment, asset criticality, and useful life. Please refer to **Section 2.5.7** for additional information on asset criticality. Return period recommendations for sea level rise/ storm surge are based on the *exposure service life* of the asset, which is defined as the number of years from when an asset is first exposed to coastal flooding to the end of its service/useful life. The year when an asset is first exposed to coastal flooding is estimated using probability of flooding maps from the MC-FRM.

Exposure Service Life: For example, for an asset with a 40 year useful life proposed to be built in 2022, the end of useful life will be 2066 and it will receive a 2070 target planning horizon recommendation.

However, if the project area is not exposed to flooding until 2050, the asset has an exposure service life of 16 years, which is assessed by subtracting 2050 from 2066.

For sea level rise /storm surge, the recommended return periods for buildings and infrastructure assets are shown in Table 4.4 on the following page. Natural Resource assets do not receive a recommended return period as a Standard; projected values from the MC-FRM associated with the **20-yr (5%)** design storm/return period are provided in the Tool as a consideration for users, not a formal standard. Users should follow industry best practices for designing natural resource assets in coordination with the appropriate regulatory agencies.

Table 4.4. Recommended Return Periods Provided by the Tool for the Sea Level Rise/Storm Surge Climate Parameter

SEA LEVEL RISE / STORM SURGE	Criticality[1]	Exposure Service Life[1]	BUILDINGS / FACILITIES	INFRASTRUCTURE				
				Transportation	Dams & Flood Control Structures	Utilities	Green Infrastructure[2]	Solid / Hazardous Waste
			Recommended Return Period (Annual Probability)					
	High	51-100 years	500-yr (0.2%)	1000-yr (0.1%)	500-yr (0.2%)	500-yr (0.2%)	N/A	1000-yr (0.1%)
	Medium	51-100 years	200-yr (0.5%)	200-yr (0.5%)	200-yr (0.5%)	200-yr (0.5%)	N/A	200-yr (0.5%)
	Low	51-100 years	100-yr (1%)	100-yr (1%)	100-yr (1%)	100-yr (1%)	N/A	100-yr (1%)
	High	11-50 years	200-yr (0.5%)	500-yr (0.2%)	200-yr (0.5%)	200-yr (0.5%)	N/A	500-yr (0.2%)
	Medium	11-50 years	100-yr (1%)	200-yr (0.5%)	100-yr (1%)	100-yr (1%)	N/A	200-yr (0.5%)
	Low	11-50 years	50-yr (2%)	100-yr (1%)	50-yr (2%)	50-yr (2%)	N/A	100-yr (1%)
	High	10 years or less	100-yr (1%)	100-yr (1%)	100-yr (1%)	100-yr (1%)	N/A	100-yr (1%)
	Medium	10 years or less	50-yr (2%)	50-yr (2%)	50-yr (2%)	50-yr (2%)	N/A	50-yr (2%)
	Low	10 years or less	20-yr (5%)	20-yr (5%)	20-yr (5%)	20-yr (5%)	N/A	20-yr (5%)

1. **Criticality and Exposure Service Life are not outputs of the Tool, but the relationship informs the recommended return period from the Tool.** Return period recommendations for sea level rise / storm surge is based on the exposure service life of the asset, which is defined as the number of years from when an asset is first exposed to coastal flooding to the end of its service/useful life (estimated using probability of flooding maps from the MC-FRM). For example, if an asset with a 60-year anticipated useful life is proposed to be built in 2022, the asset will receive a 2070 planning horizon recommendation. However, based on the MC-FRM probability of flooding maps, if the project area is not exposed to flooding until 2050, the asset has an exposure service life of 32 years, which is assessed by subtracting 2050 from 2082 (2022 + 60 years).
2. Green infrastructure assets do not receive a recommended return period for coastal design criteria. Green infrastructure assets as listed in **Section 2.5** are typically proposed for stormwater management. Green infrastructure that is exposed to sea level rise/storm surge should consider impacts related to projected tidal datums, duration of flooding, design flood velocity, and scour and erosion.
3. **Natural Resource assets will receive projected values associated with a 20-yr (5%) return period from the Tool**, but this is not a recommended Standard.

4.7.4.1 CUMULATIVE PROBABILITY

As described above, recommended return periods for assets by climate parameter are based on industry standards and professional judgment, asset criticality, and useful life. **However, the recommended return period output from the Tool is also informed by an asset's cumulative probability of being exposed to a climate event.** The median cumulative probability from sea level rise/ storm surge for an asset can be assessed based on the asset's recommended planning horizon and site-specific projected flood elevation from sea level rise / storm surge. The projected sea level rise/storm surge elevations for a site corresponding to different annual exceedance probabilities (AEPs) by planning horizon can be obtained from the Massachusetts Coast Flood Risk Model (MC-FRM) and are referred to as the "Probability of Exceedance (PEx)" output. <u>The PEx output is not a standard MC-FRM output available through the Tool, but it may be requested as additional data through the MC-FRM</u>.

Cumulative probability is defined as the measure of the total probability that a certain event will happen during a given period of time. Cumulative probability is calculated based on the equation:

$$p_n = 1 - (1-p)^n$$

where 'p_n' equals the cumulative probability over 'n' number of years and 'p' equals annual exceedance probability, which is not constant due to climate change.

An example site-specific PEx output table that shows projected flood elevations from sea level rise /storm surge corresponding to different annual exceedance probabilities (AEPs) by planning horizon is shown in Table 4.5. Table 4.5 illustrates how elevations associated with AEPs change over time for a site, for example, the AEP for Elevation 17.0 (ft-BCB) is approximately 500-yr (0.2%) currently, increases to approximately 100-yr (1%) in 2030, increases to approximately 5- to 10-yr (10-20%) in 2050, and is greater than 4-yr (25%) by 2070.

Table 4.5. Example of site-specific Probability of Exceedance (PEx)[1] with AEPs and corresponding water surface elevations (ft-BCB)

Design Storm Event	Annual Exceedance Probability	Water Surface Elevation (ft-BCB) at Example Site (Boston, MA)			
		Present	2030	2050	2070
1000-yr	0.1%	17.4	18.5	20.4	22.1
500-yr	0.2%	17.0	18.1	20.0	21.7
200-yr	0.5%	16.5	17.5	19.3	21.0
100-yr	1%	16.0	17.1	18.9	20.6
50-yr	2%	15.6	16.7	18.4	20.1
20-yr	5%	15.1	16.2	17.8	19.5
10-yr	10%	14.6	15.8	17.3	19.0
5-yr	20%	14.2	15.3	16.7	18.5
4-yr	25%	14.0	15.2	16.5	18.3

1. The water surface elevations are site-specific to Joe Moakley Park in Boston, MA only and are provided in ft-BCB, which is the vertical datum used by the City of Boston. **This type of output is NOT provided through the Tool**. Users

receive the water surface elevation based on the recommended return period (or Annual Exceedance Probability) and planning horizon.

Table 4.6 shows the cumulative probabilities estimated for the example site using the AEPs in Table 4.5, and connects this concept to the recommended return periods for sea level rise /storm surge relationships for a Dams & Flood Control Structure Asset, as defined in Table 4.4. The recommended return periods provided through the Tool vary based on exposure service life and criticality, but the general cumulative probabilities associated with criticality remain similar.

Table 4.6. Example of Cumulative Probability that supported informing the Recommended Return Periods for Sea Level Rise / Storm Surge

			INFRASTRUCTURE			
			Dams and Flood Control Structure Asset			
				Example Site – Boston, MA		
SEA LEVEL RISE/STORM SURGE	**Criticality**	**Exposure Service Life**	**Recommended Return Period (% AEP)**	***Target Planning Horizon***[1]	***Projected Water Surface Elevation (ft-BCB)***[2]	***Cumulative Probability***[1]
	High	51-100 years	**500-yr (0.2%)**	2070	21.7	4%
	Medium	51-100 years	**200-yr (0.5%)**	2070	21.0	11%
	Low	51-100 years	**100-yr (1%)**	2070	20.6	21%
	High	11-50 years	**200-yr (0.5%)**	2050	19.3	7%
	Medium	11-50 years	**100-yr (1%)**	2050	18.9	11%
	Low	11-50 years	**50-yr (2%)**	2050	18.4	20%
	High	10 years or less	**100-yr (1%)**	2030	17.1	6%
	Medium	10 years or less	**50-yr (2%)**	2030	16.7	12%
	Low	10 years or less	**20-yr (5%)**	2030	16.2	26%

1. The target planning horizons, water surface elevations, and cumulative probability are examples site-specific to Joe Moakley Park in Boston, MA only. The durations over which cumulative probabilities were estimated were 60 years, 30 years, and 10 years, respectively. The cumulative probabilities were estimated using the planning horizons and elevations from the PEx for the sample site, as shown in Table 4.5. **This type of output is NOT provided through the Tool**.
2. The water surface elevations are site-specific to Joe Moakley Park in Boston, MA only and are provided in ft-BCB, which is the vertical datum used by the City of Boston. The BCB datum is 6.46 ft below the ft-NAVD88 datum. To convert elevation in ft-NAVD88 to elevation in ft-BCB, add 6.46 to the ft-NAVD88 elevation.

Please note: refer to Table 4.4 for specific return periods and Table 4.3 for specific planning horizons that are provided through the Tool. The information provided in Table 4.5 and 4.6 are site-specific and are provided to illustrate how cumulative probability informed return period relationship recommendations based on exposure service life and criticality.

4.7.5 DESIGN CRITERIA RECOMMENDATIONS

Design criteria are recommended parameters to incorporate into design of physical assets, generated by the Climate Resilience Design Standards as an output, which vary by climate parameter, location, and asset type. The design criteria that are recommended through the Tool based on asset type and location, as presented in Table 4.7, below.

Table 4.7. Relationships for how Design Criteria are recommended for Sea Level Rise/ Storm Surge

	Design Criteria	Design Criteria Recommended For[1]	
		Asset Type	Project Polygon Location
SEA LEVEL RISE / STORM SURGE	**Projected Tidal Datums**	All assets	Located within the extents of the MC-FRM 1000-yr (0.1% annual chance) event for specified planning horizon
	Projected Water Surface Elevation	All assets, except green infrastructure assets	Located within the MC-FRM water surface elevation raster for the recommended return period for the recommended planning horizon
	Projected Wave Action Water Elevation	All assets, except green infrastructure assets	Located within the MC-FRM wave action water elevation raster for the recommended return period for the recommended planning horizon
	Projected Wave Heights	All assets, except green infrastructure assets	Located within the MC-FRM wave heights raster for the recommended return period for the recommended planning horizon
	Projected Duration of Flooding	Infrastructure assets, building assets	Located within the extents of the MC-FRM 1000-yr (0.1% annual chance) event for specified planning horizon
	Projected Design Flood Velocity	Infrastructure assets, building assets	Located within extents of the MC-FRM 1000-yr (0.1% annual chance) event for specified planning horizon
	Projected Scour or Erosion	Infrastructure assets, and coastal resource area assets	Located within extents of the MC-FRM 1000-yr (0.1% annual chance) event for specified planning horizon

* Design criteria are recommended if both the asset type and project location are true.
** Based on MC-FRM GIS files as of 9/13/2021.

4.7.5.1 DESIGN CRITERIA GUIDANCE

There is additional guidance for the design criteria within the user interface to help users integrate this information into planning, early design, and evaluation processes. If a design criterion is applicable, there will be a dropdown with the following subsections:

- *Definition*
- *[Applicable Design Criterion] Values OR How to Estimate [Applicable Design Criterion] Values*
- *How [Applicable Design Criterion] may inform Planning*
- *How [Applicable Design Criterion] may inform Early Design*
- *How [Applicable Design Criterion] may inform Project Evaluation*
- *Limitations for [Applicable Design Criterion] Values, Standards, & Guidance*

Please refer to **Attachment 4-D** for guidance associated with each of the sea level rise/storm surge design criteria.

4.7.5.2 PROJECTED VALUES FOR DESIGN CRITERIA

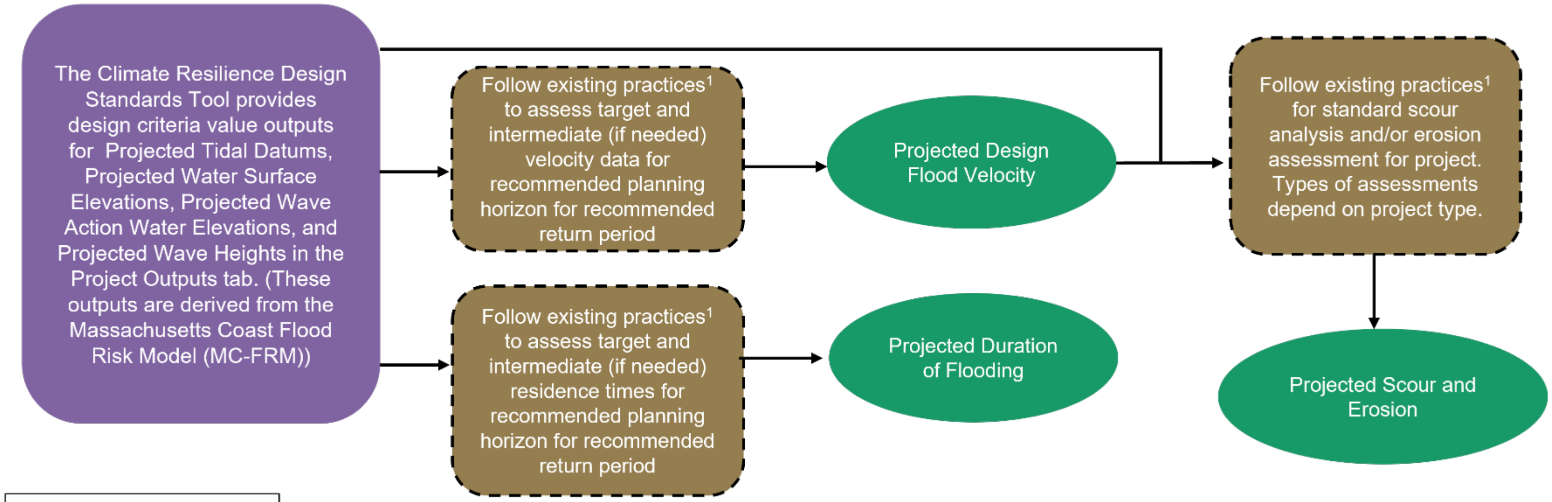
Values for recommended design criteria are provided through the Tool as projected numerical values and/or may need to be calculated by the user following the recommended tiered estimation methods. Please refer to **Section 4.3** for further details.

Table 4.8. Projected Values and/or Calculation Method Recommended by the Tool for the Sea Level Rise /Storm Surge Design Criteria

	Design Criteria	Tool Output
SEA LEVEL RISE / STORM SURGE	**Projected Tidal Datums**	Projected values (MLW, MLLW, MTL, MHW, MHHW) provided in ft.-NAVD88, where MC-FRM data are available
	Projected Water Surface Elevation	Projected values (minimum, maximum, and area-weighted average) provided in ft.-NAVD88, where MC-FRM data are available
	Projected Wave Action Water Elevation	Projected values (minimum, maximum, and area-weighted average) provided in ft.-NAVD88, where MC-FRM data are available
	Projected Wave Heights	Projected values (minimum, maximum, and area-weighted average) provided in feet, where MC-FRM data are available
	Projected Duration of Flooding	Tiered Estimation Methods PDF for calculating design criteria value using information provided through the Tool and existing standard practices. Example PDF shown in Figure 4.3. For information on Tiers, see Section 4.3.
	Projected Design Flood Velocity	
	Projected Scour or Erosion	

Method to Assess
Projected Sea Level Rise / Storm Surge Design Criteria

Given Standards Output from Tool: Planning Horizon (2030, 2050, 2070); Return Period [Annual Exceedance Probability] (20-yr [5%], 50-yr [2%], 100-yr [1%], 200-yr [0.5%], 500-yr [0.2%], 1000-yr [0.1%])



The Climate Resilience Design Standards Tool provides design criteria value outputs for Projected Tidal Datums, Projected Water Surface Elevations, Projected Wave Action Water Elevations, and Projected Wave Heights in the Project Outputs tab. (These outputs are derived from the Massachusetts Coast Flood Risk Model (MC-FRM))

Follow existing practices[1] to assess target and intermediate (if needed) velocity data for recommended planning horizon for recommended return period

Projected Design Flood Velocity

Follow existing practices[1] for standard scour analysis and/or erosion assessment for project. Types of assessments depend on project type.

Projected Scour and Erosion

Follow existing practices[1] to assess target and intermediate (if needed) residence times for recommended planning horizon for recommended return period

Projected Duration of Flooding

Legends
Tool Output ▭
Calculation steps ▭
Design Criteria ⬭
Existing practice ⬚

1. Consult a professional coastal engineer or scientist/modeler to estimate projected Duration of Flooding, Design Flood Velocity, and Scour & Erosion based on the recommended Standards and outputs provided through this Tool.

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Figure 4.3. Tiered Estimation Methods for Sea Level Rise/ Storm Surge Design Criteria Values as Recommended by the Climate Resilience Design Standards output from the Tool

4.7.6 WATER SURFACE ELEVATION & WAVE ACTION WATER ELEVATION MAPS

In addition to projected elevation values, maps are available for both water surface elevation and wave action water elevation to illustrate the values across the project site as drawn by the user and surrounding area (0.1-mile minimum buffer). Regardless of recommended planning horizon, maps are provided for three planning horizons (2030, 2050, and 2070) to support site suitability, regional coordination, and flexible adaptive pathway considerations.

Each applicable project will receive water surface elevation and wave action water elevation maps associated with the asset with the least frequent (i.e., most extreme) return period recommended through the Tool. The asset with maps available for review will be indicated in the asset carousel in the Tool. Please see Table 4.9 below for an example of a project with multiple assets and when maps are available.

Table 4.9. Example of a project with multiple assets and when maps are available

Example Project Assets	Example Recommended Return Period	Projected Water Surface Elevation/Wave Action Water Elevation recommended?	Projected Water Surface Elevation/Wave Action Water Elevation maps available?
Asset #1: Building Asset	100- yr (1%)	Yes	No
Asset #2: Green Infrastructure Asset	N/A	No	No
Asset #3: Natural Resource Asset	20-yr (5%)	Yes	No
Asset #4: Stormwater Utility Asset	200-yr (0.5%)	Yes	**Yes**

Example projected water surface elevation maps as they appear in the Tool are shown in Figure 4.4 and Figure 4.5. The projected water surface elevation maps illustrate

- the project boundary (as drawn by the user) with a minimum 0.1 mile buffer around the project area
- projected water surface elevation values with a table summarizing minimum, maximum, and area weighted average values within the project boundary
- a scale bar and north arrow
- a legend with the projected water surface elevation values (or ranges of values) assigned to a color and hatched areas (if present)

An example projected wave action water elevation maps as they appear in the Tool are available in Figure 4.6. The projected wave action water elevation maps illustrate:

- the project boundary (as drawn by the user) with a minimum 0.1 mile buffer around the project area
- projected wave action water elevation values with a table summarizing minimum, maximum, and area weighted average values within the project boundary
- a scale bar and north arrow

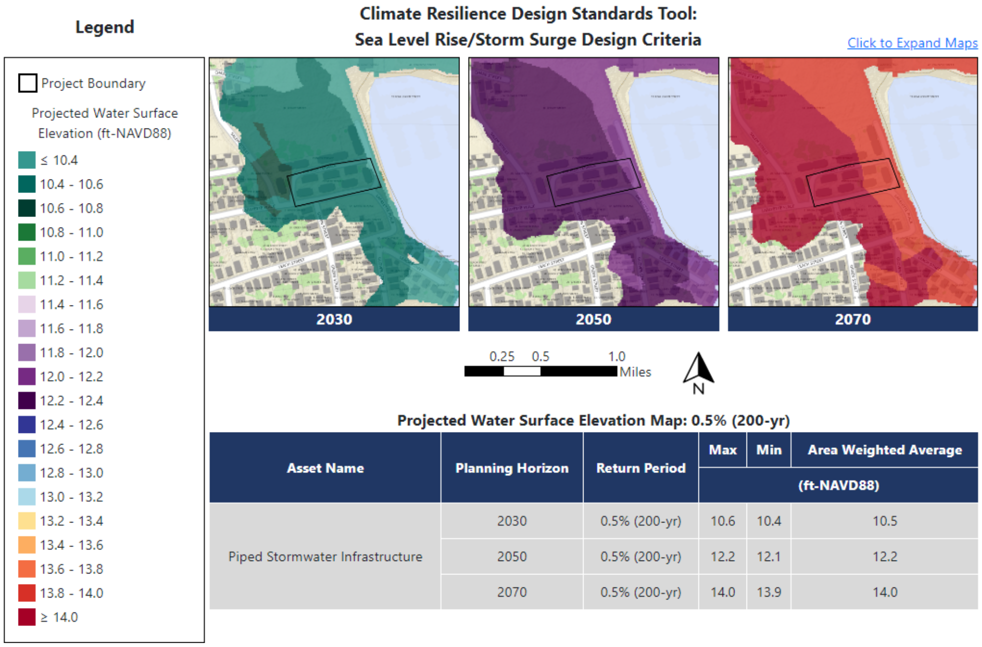
- a legend with the projected wave action water elevation values (or ranges of values) assigned to a color and hatched areas (if present)

For both types of maps the legend is constant across the three planning horizons, but will vary based on the project and asset, as it is based on the minimum projected water surface elevation (wave action water elevation) in 2030 and maximum projected water surface elevation (wave action water elevation) in 2070 within the project polygon associated with the recommended return period.

The values on the map represent the projected water surface elevations or wave action water elevation associated with the recommended return period and corresponding planning horizon. There may be hatched areas that are visible on the map, as shown in Figure 4.5 and 4.6. If the project boundary overlaps with a hatched area, there will be an additional statement that accompanies the maps and projected water surface elevation value tables, as described in Table 4.2.

Users may click "Click to Expand Maps" that will open the projected water surface elevation or wave action water elevation maps in a new browser tab. Users may zoom in and zoom out (up to 0.5 mile buffer) in this interface, with zooming and panning synced across the three maps. Users will receive four maps for each parameter (water surface elevation or wave action water elevation) in the project report: a composite map of the three planning horizons and individual 2030, 2050, and 2070 maps (i.e., eight maps in total).

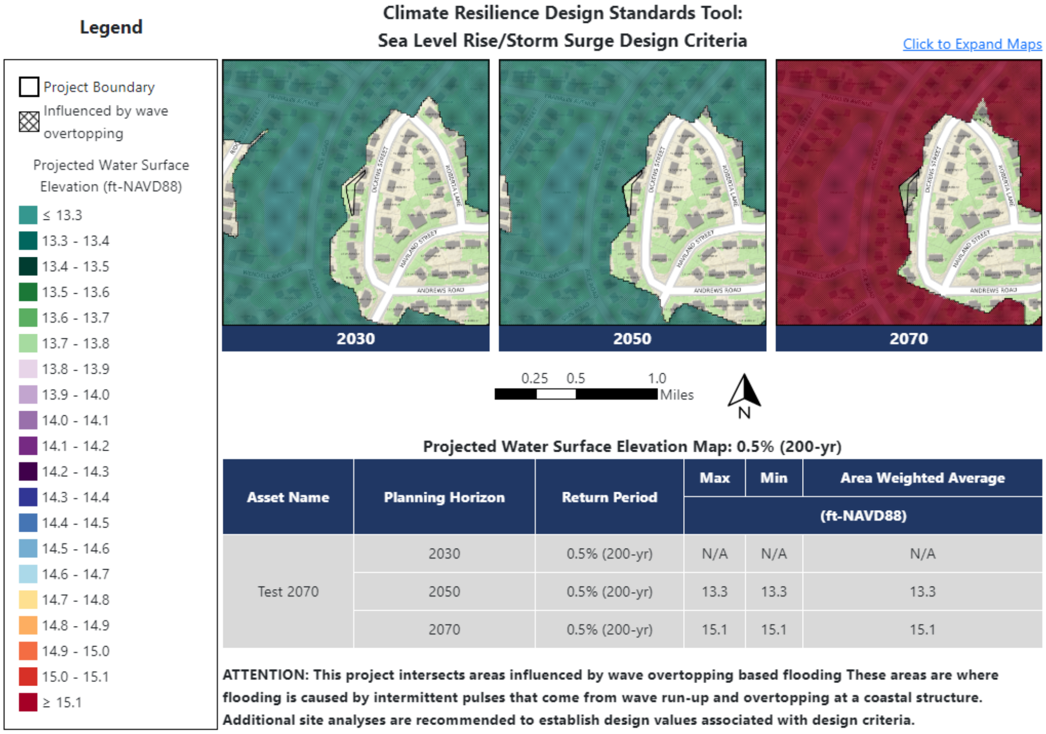
Note: The edges of the mapped projected water surface elevation or wave action water elevation should be considered as approximate boundaries and not definitive lines. For example, the seaward edges of the data are based on the mean high water shoreline that is extracted from the simulations in the MC-FRM, so the edges will not align perfectly with the basemap. Please refer to **Section 4.7.2** for information regarding the data source and limitations.



Projected Water Surface Elevation Map: 0.5% (200-yr)

Asset Name	Planning Horizon	Return Period	Max	Min	Area Weighted Average
			(ft-NAVD88)		
Piped Stormwater Infrastructure	2030	0.5% (200-yr)	10.6	10.4	10.5
	2050	0.5% (200-yr)	12.2	12.1	12.2
	2070	0.5% (200-yr)	14.0	13.9	14.0

Figure 4.4. Example Projected Water Surface Elevation Maps (hatched areas not present) viewable within the Tool



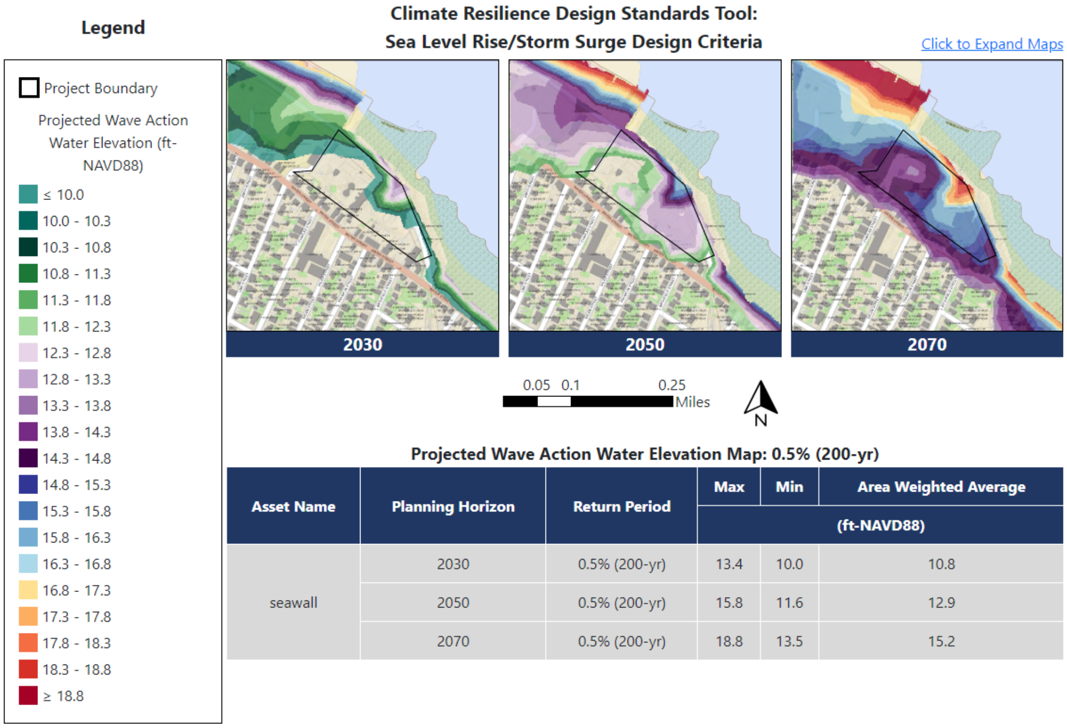
Climate Resilience Design Standards Tool:
Sea Level Rise/Storm Surge Design Criteria

Projected Water Surface Elevation Map: 0.5% (200-yr)

Asset Name	Planning Horizon	Return Period	Max	Min	Area Weighted Average
			(ft-NAVD88)		
Test 2070	2030	0.5% (200-yr)	N/A	N/A	N/A
	2050	0.5% (200-yr)	13.3	13.3	13.3
	2070	0.5% (200-yr)	15.1	15.1	15.1

ATTENTION: This project intersects areas influenced by wave overtopping based flooding These areas are where flooding is caused by intermittent pulses that come from wave run-up and overtopping at a coastal structure. Additional site analyses are recommended to establish design values associated with design criteria.

Figure 4.5. Example Projected Water Surface Elevation Maps (hatched areas present) viewable within the Tool



Climate Resilience Design Standards Tool:
Sea Level Rise/Storm Surge Design Criteria

Projected Wave Action Water Elevation Map: 0.5% (200-yr)

Asset Name	Planning Horizon	Return Period	Max	Min	Area Weighted Average
			(ft-NAVD88)		
seawall	2030	0.5% (200-yr)	13.4	10.0	10.8
	2050	0.5% (200-yr)	15.8	11.6	12.9
	2070	0.5% (200-yr)	18.8	13.5	15.2

Figure 4.6: Example Projected Wave Action Water Elevation Maps (hatched areas not present) viewable within the Tool

4.8 EXTREME PRECIPITATION STANDARDS OUTPUTS AND RELATIONSHIPS

4.8.1 OUTPUTS OVERVIEW

Upon completion of Project Inputs, the Tool will provide recommended Standards for each climate parameter for each asset entered. The Standards provided for the extreme precipitation climate parameter include recommended target planning horizon, return period, and the following design criteria that are likely to be affected by climate change: Projected Total Precipitation Depth & Peak Intensity for 24-hour Design Storms; Projected Riverine Peak Discharge; and Peak Riverine Flood Elevation. There are either projected values provided for design criteria based on the recommended planning horizon and return period, or recommended methods to estimate projected design criteria values if not directly available through the Tool.

4.8.2 DATA SOURCE & LIMITATIONS

The Projected Total Precipitation Depth for 24-hr Design Storms values references the climate-informed precipitation frequency tables developed by the Steinschneider research group as part of Phase 1 of EEA's Massachusetts Climate and Hydrologic Risk Project, which was transmitted as GIS-based data on 10/15/21. The methods used to develop this dataset represent a Tier 3 level of effort.

For additional information on the methods used to develop these design storms and how the climate-informed design storms compare with design storms developed through other methods referenced in this document, please refer to **Attachment 4-B**.

In addition to projected values for total precipitation depth for 24-hr design storms which are provided by the Tool, there are two special cases when the Tool will recommend that calculate additional projected values following methods defined in external resources. For Infrastructure assets that are Dams & Flood Control Structures and receive a Tier 3 designation based on relationships as defined in **Section 4.3**, users will see the following text with a link to a downloadable PDF providing a step-by-step process to estimate total precipitation depth:

- ATTENTION: This is a Tier 3, Dams & Flood Control Structures project. Due to the criticality and useful life of this project, it is recommended that NCHRP15-61 method be used to calculate total precipitation depth for 24-hour design storms, and those results be compared to the provided total storm depth Tool output. (Link to Downloadable Methods PDF)

Similarly, if an asset receives a Tier 1 designation based on relationships as defined in Section 4.3, users will see the following text with a link to a downloadable PDF providing a step-by-step process to estimate total precipitation depth:

- ATTENTION: This is a Tier 1 project. It is advised to compare the extreme precipitation output values to the NOAA+ method to calculate total precipitation depth for 24-hr design storms. This method can be found in the following PDF. (Link to Downloadable Methods PDF)

As referenced in Table 4.11, Natural Resource assets do not receive a recommended return period as a Standard. Projected values from the climate-informed design storm dataset associated with the **25-yr (4% annual chance event)** design storm/return period are provided as an output in the Tool with the following note:

- Return Period Recommendations for natural resource assets and subsequent projected values are provided as a consideration for users, not a formal standard. Users should follow industry best practices for designing natural resource assets in coordination with the appropriate regulatory agencies.

It is important to note that the NOAA+ method may provide higher design values for the same duration and return period than climate-informed design storms developed through Phase 1 of EEA's Massachusetts Climate and Hydrologic Risk Project for certain storm return periods and recommended planning horizons. The NOAA+ method is based on uncertainty in the depth of NOAA Atlas 14 design storms as estimated based on past storms, which can be very high for short durations and/or more extreme storms (lower annual chance). In contrast, the design storms provided via EEA's Massachusetts Climate and Hydrologic Risk Project are created by scaling the same estimates of design storm precipitation depth estimates in NOAA Atlas 14 by projected temperature change using relationships between atmospheric moisture content and temperature without considering uncertainty in either projected future temperature or statistical uncertainty in the NOAA Atlas 14 estimates. Because statistical uncertainty in the estimates is high, NOAA+ values may be higher than the values provided through the Tool from the Massachusetts Climate and Hydrologic Risk Project climate-informed design storms in some cases. Uses may wish to consider both the projected design storm depth recommended through the Tool and the design storm depth generated by the NOAA+ method for highly sensitive or critical assets.

While projected total precipitation depth for 24-hr design storms & peak intensity are useful to inform planning and design, it is recommended to also consider additional longer- and shorter-duration precipitation events and intensities in accordance with best practices. Longer-duration, lower-intensity storms allow time for infiltration and reduce the load on infrastructure over the duration of the storm. Shorter-duration, higher-intensity storms often have higher runoff volumes because the water does not have enough time to infiltrate infrastructure systems (e.g., catch basins) and may overflow or back up during such storms, resulting in flooding. In the Northeast, short-duration high intensity rain events are becoming more frequent, and there is often little early warning for these events, making it difficult to plan operationally. While the Tool does not provide recommended design standards for these scenarios, users should still consider both short- and long-duration precipitation events and how they may impact the asset. Users can access climate-informed design storms of longer or shorter durations from the same dataset used in the Tool on the ResilientMass Climate Projections Dashboard.

The applicability of Projected Riverine Peak Discharge & Peak Flood Elevation design criteria is based on a screening-level exposure assessment to riverine flooding as defined in **Section 3.2**. Users should do their own due diligence to evaluate whether their project site is or is not likely to be exposed to riverine flooding within its useful life through a formal vulnerability assessment based on site-specific information, and refer to this document for associated recommended Standards.

The projected design criteria values, Standards, and guidance provided within this Tool may be used to inform plans and designs, but they do not provide guarantees for future conditions or resilience. The projected design criteria values are not to be considered final or appropriate for construction documents without supporting engineering analyses. The guidance provided within this Tool is intended to be general and users are encouraged to do their own due diligence.

4.8.3 PLANNING HORIZON RECOMMENDATIONS

The Target Planning Horizon refers to a future date to which a project should be designed, which allows the project to incorporate anticipated climate change conditions (e.g., 2070 rainfall projections). Recommended planning horizons provided by the Tool do not vary based on climate parameter but may vary by asset.

The recommended planning horizons are determined based on the year through which the asset is expected to last (i.e., before a major reconstruction/renovation), which is calculated by adding the asset's useful life in years, to the estimated year construction of the asset will start (as entered by the user in the Project Inputs of the Tool). The calculated year through which the asset is expected to last will be compared against the first column in Table 4.10 below, and the corresponding recommended planning horizon will be provided as output.

Table 4.10. Recommended Planning Horizons Provided by the Tool, based on the Asset's Useful Life and Construction Start Year

END OF USEFUL LIFE[1]	RECOMMENDED PLANNING HORIZON OUTPUT
2021 - 2029	**2030**
2030 - 2039	**2030**
2040 – 2049	**2050**
2050 – 2059	**2050**
2060 – 2069	**2070**
2070 - 2079	**2070**
2080 - 2089	**2070**
2090 - 2099	**2070**[2]

1. Calculated by adding the asset's useful life in years, to the estimated year construction of the asset will start.
2. MC-FRM currently does not cover 2100 scenarios, so for consistency across climate parameters, the 2070 planning horizon is recommended until 2100 results are available for all climate parameters.

4.8.4 RETURN PERIOD RECOMMENDATIONS

Different state agencies and municipalities may have their own standards for return periods. **The recommended return periods provided by the Tool are advisory and do not replace regulatory requirements.**

A return period is defined as the annual probability that an event of a specific magnitude will be equaled or exceeded. Return periods may also be described as a recurrence interval. **The Tool will provide a recommended return period for each asset in a project.** The recommended return period will also be provided in terms of percent annual exceedance probability (AEP or "annual probability"). This distinction is based on industry practice and is described in further detail in the **Glossary of Terminology**.

These recommended return periods for each climate parameter are based on industry standards and professional judgment, asset criticality, and useful life[1]. For extreme precipitation, the exposure service life (described in **Section 4.7**, for coastal flooding) is equal to the asset's useful

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[1] https://sites.tufts.edu/richardvogel/files/2019/04/2017_riskReliabilityReturnPeriods.pdf

life since assets are exposed to precipitation throughout their useful life. The recommended return periods for each asset type are shown in Table 4.11.

Table 4.11. Recommended Return Periods Provided by the Tool for the Extreme Precipitation Climate Parameter

EXTREME PRECIPITATION	Criticality	Useful Life	BUILDINGS / FACILITIES	INFRASTRUCTURE				
				Transportation	Dams & Flood Control Structures	Utilities	Green Infrastructure[1]	Solid / Hazardous Waste
			Return Period (Annual Probability)					
	High	51-100 years	100-yr (1%)	100-yr (1%)	500-yr (0.2%)	100-yr (1%)	N/A	100-yr (1%)
	Medium	51-100 years	50-yr (2%)	50-yr (2%)	100-yr (1%)	50-yr (2%)	N/A	50-yr (2%)
	Low	51-100 years	25-yr (4%)	25-yr (4%)	50-yr (2%)	25-yr (4%)	N/A	25-yr (4%)
	High	11-50 years	50-yr (2%)	50-yr (2%)	100-yr (1%)	50-yr (2%)	5-yr (20%)	50-yr (2%)
	Medium	11-50 years	25-yr (4%)	25-yr (4%)	50-yr (2%)	25-yr (4%)	5-yr (20%)	25-yr (4%)
	Low	11-50 years	10-yr (10%)	10-yr (10%)	25-yr (4%)	10-yr (10%)	5-yr (20%)	10-yr (10%)
	High	10 years or less	25-yr (4%)	25-yr (4%)	50-yr (2%)	25-yr (4%)	5-yr (20%)	25-yr (4%)
	Medium	10 years or less	10-yr (10%)	10-yr (10%)	25-yr (4%)	10-yr (10%)	5-yr (20%)	10-yr (10%)
	Low	10 years or less	5-yr (20%)	5-yr (20%)	10-yr (10%)	5-yr (20%)	5-yr (20%)	5-yr (20%)

1. Green infrastructure assets will not receive a recommended return period for assets with a useful life of greater than 50 years since green infrastructure assets typically need significant reconstruction/renovation or replacement before then.
2. Natural Resource assets will receive projected values associated with a 25-yr (4%) return period from the Tool, but this is not a recommended Standard.

4.8.4.1 CUMULATIVE PROBABILITY

The recommended return periods for assets by climate parameter are based on industry standards and professional judgment, asset criticality, and useful life. **However, the recommended return period output from the Tool is also informed by an asset's cumulative probability of being exposed to a climate event.** The cumulative probability associated with a specific projected total precipitation depth can be estimated by comparing the projected total precipitation depth value associated with an asset's recommended planning horizon to the current return period.

Cumulative probability is defined as the measure of the total probability that a certain event will happen during a given period of time. Cumulative probability is calculated based on the equation:

$$p_n = 1 - (1-p)^n$$

where ‘p_n’ equals the cumulative probability over ‘n’ number of years and ‘p’ equals annual exceedance probability, which is not constant due to climate change.

Table 4.12 below shows how the recommended return period relationships for a Dams & Flood Control Structure Asset, as defined in Table 4.11, relate to an example site in Boston using associated planning horizons, projected total precipitation depth values, approximation to current return periods, and median cumulative probabilities. The approximation to current return periods is based on comparing to current NOAA Atlas 14 median total precipitation depths and 24-hr return periods; for example, the 2050 100-yr (1%) projected total precipitation depth value of 10.1 inches is similar to the current 500-yr (0.2%) return period total precipitation depth value. The recommended return periods provided through the Tool vary based on useful life and criticality, but the general cumulative probabilities associated with criticality remain similar.

Table 4.12. Example of Cumulative Probability Calculation Informing the Recommended Return Periods for the Extreme Precipitation Climate Parameter Output from the Tool

	Criticality	Useful Life	INFRASTRUCTURE				
			Dams and Flood Control Structure Asset				
			Recommended Return Period (Annual Probability)	*Example Site –Boston, MA*			
				Planning Horizon[1]	*Projected Total Precipitation Depth (in./24-hr)* [1]	*Approximation to Current Return Period*[1]	*Median Cumulative Probability*[1]
EXTREME PRECIPITATION	High	51-100 years	**500-yr (0.2%)**	**2070**	**16.8**	0.05%	4%
	Medium	51-100 years	**100-yr (1%)**	**2070**	**11.2**	0.2%	14%
	Low	51-100 years	**50-yr (2%)**	**2070**	**9.7**	0.5%	31%
	High	11-50 years	**100-yr (1%)**	**2050**	**10.1**	0.2%	5%
	Medium	11-50 years	**50-yr (2%)**	**2050**	**8.8**	0.5%	12%
	Low	11-50 years	**25-yr (4%)**	**2050**	**7.5**	2%	40%
	High	10 years or less	**50-yr (2%)**	**2030**	**7.6**	1.5%	7%
	Medium	10 years or less	**25-yr (4%)**	**2030**	**6.7**	3%	14%
	Low	10 years or less	**10-yr (10%)**	**2030**	**5.5**	5%	23%

1. The planning horizons, projected total precipitation depth for 24-hr design storm, and approximation to current return period were used to inform the median cumulative probability presented in the table. This example is site-specific to Joe Moakley Park in Boston, MA only, and this type of analyses were used to inform return period relationships in addition to industry standards and professional judgement. **This type of output is NOT provided through the Tool**.

Please note: refer to Table 4.11 for specific return periods and Table 4.10 for specific planning horizons that are provided through the Tool. The information provided in Table 4.12 is site-specific and provided to illustrate how cumulative probability informed return period relationship recommendations based on useful life and criticality.

4.8.5 DESIGN CRITERIA RECOMMENDATIONS

Design criteria are recommended parameters to incorporate into design of physical assets, generated by the Climate Resilience Design Standards as an output, which vary by climate parameter, location, and asset type. The design criteria that are recommended through the Tool based on asset type and location, as presented in Table 4.13, below.

Table 4.13. Relationships for how Design Criteria are recommended for Extreme Precipitation

EXTREME PRECIPITATION	Design Criteria	Design Criteria Recommended For*	
		Asset Type	***Project Polygon Location***
	Projected Total Precipitation Depth & Peak Intensity for 24-hour Design Storms	All infrastructure, building and natural resource assets *except* coastal resource areas	All locations
	Projected Riverine Peak Discharge & Peak Flood Elevation	All infrastructure, building and natural resource assets *except* coastal resource areas	Exposed to riverine environment based[1]

* Design criteria are recommended if both the asset type and project location are true.

[1] Riverine environment includes areas outside the 0.1% annual coastal flood exceedance probability extent from MC-FRM for the recommended planning horizon, and 500 ft. of an existing water body, and/or within the current 0.2% annual chance (500-year) FEMA floodplain. Waterbody determined using MassGIS data layer MassDEP Hydrography and poly codes 1, 6 and arc codes 4,5. This is further described in **Section 3, Attachment 3.A– GIS Component Table for Version 1.4**.

4.8.5.1 DESIGN CRITERIA GUIDANCE

There is additional guidance for the design criteria within the user interface to help users integrate this information into planning, early design, and evaluation processes. If a design criterion is applicable, there will be a dropdown with the following subsections:

- *Definition*
- *[Applicable Design Criterion] Values OR How to Estimate [Applicable Design Criterion] Values*
- *How [Applicable Design Criterion] may inform Planning*
- *How [Applicable Design Criterion] may inform Early Design*
- *How [Applicable Design Criterion] may inform Project Evaluation*
- *Limitations for [Applicable Design Criterion] Values, Standards, & Guidance*

Please refer to **Attachment 4-D** for guidance associated with each of the extreme precipitation design criteria.

4.8.5.2 PROJECTED VALUES FOR DESIGN CRITERIA

Values for recommended design criteria are provided through the Tool as projected numerical values and/or may need to be calculated by the user following the recommended Tiered Estimation Methods output from the Climate Resilience Design Standards Tool. Please refer to **Section 4.3** for further details on Tiered Estimation Methods.

For the extreme precipitation climate parameter, the data sources and tiered estimation methods recommended by the Standards for each design criteria are shown in Table 4.14 and Table 4.15. Further detailed methods for calculating design criteria values are shown in the Figures below. Example calculations using tiered estimation methods for design criteria values are included as **Attachment 4-C**.

Table 4.14. Data Sources & Methods Recommended from the Tool for the Extreme Precipitation Design Criteria

	Design Criteria	Tool Output		
		Tier 3 - High Level of Effort[2]	Tier 2 - Average Level of Effort	Tier 1 - Low Level of Effort[3]
EXTREME PRECIPITATION	**Projected Total Precipitation Depth and Peak Intensity for 24-hour Design Storms[1,2,3]**	Projected value provided in inches based on recommended return period and planning horizon based on methods developed by Cornell University's Steinschneider Research Group for EEA's Massachusetts Climate and Hydrologic Risk Project[1]		
		Tiered Estimation Methods PDF to calculate peak intensity value using NOAA Atlas 14/NRCS Types C and D/SCS Type III distribution with Projected Total Precipitation Depth (Figure 4.7)		
	Projected Riverine Peak Discharge and Peak Flood Elevation	Tiered Estimation Methods PDF: Hydrologic/hydraulic modeling at watershed/sub-watershed scale using future design storms (Figure 4.7)		Tiered Estimation Methods PDF: StreamStats using Zariello's Equation for Peak Discharge; Stage Discharge Curve from corresponding gage location used in StreamStats for Peak Flood Elevation (Figure 4.9)

1. See Table 4.15 for additional information related to methods related to projected total precipitation depth
2. Dam and Flood Control Structure assets that are Tier 3 will receive additional NCHRP 15-61 method to estimate projected total precipitation depth as described in Table 4.15
3. Tier 3 assets will receive additional NOAA+ method to estimate projected total precipitation depth as described in Table 4.15.

Table 4.15. Methods to obtain values for Projected Total Precipitation Depth for 24-hr Design Storms

Method	Brief Description
Method developed by Steinschneider Research Group for EEA's Massachusetts Climate and Hydrologic Risk Project[2]	EEA's Climate and Hydrologic Risk Project generated a database of updated IDF curves across different temperature changes (for each 0.5 °C warming starting from 0.5 °C to 8 °C warming scenarios) using regionalized scaling rates with dew point temperature both in observations across the Northeast United States and for a subset of downscaled CMIP5 projections within the state of MA.
NOAA+ Method	*Note: Provided for Tier 1 Assets Only* Represents a factor of 0.9 applied to the upper bound of the 90% confidence interval for the present NOAA Atlas 14 values. This approach is being considered by MassDEP as part of updating the Stormwater Handbook, which currently references TP-40. *Note: Provided for Tier 1 Assets Only*
NCHRP15 -61 Method[3]	*Note: Provided for Tier 3, Dams & Flood Control Structure Assets Only* National Cooperative Highway Research Program (NCHRP) Project 15-61 titled "Applying Climate Change Information to Hydrologic and Coastal Design of Transportation Infrastructure," which uses local design storm estimates from NOAA Atlas 14 for present day baseline and combined with locally downscaled ensemble GCMs for that specific location, fit to an extreme value distribution and ratios between modeled baseline and modeled future data are applied to site specific NOAA Atlas 14 values to calculate the site-specific design storm projections.

For additional information on these methods, refer to **Attachment 4-B**.

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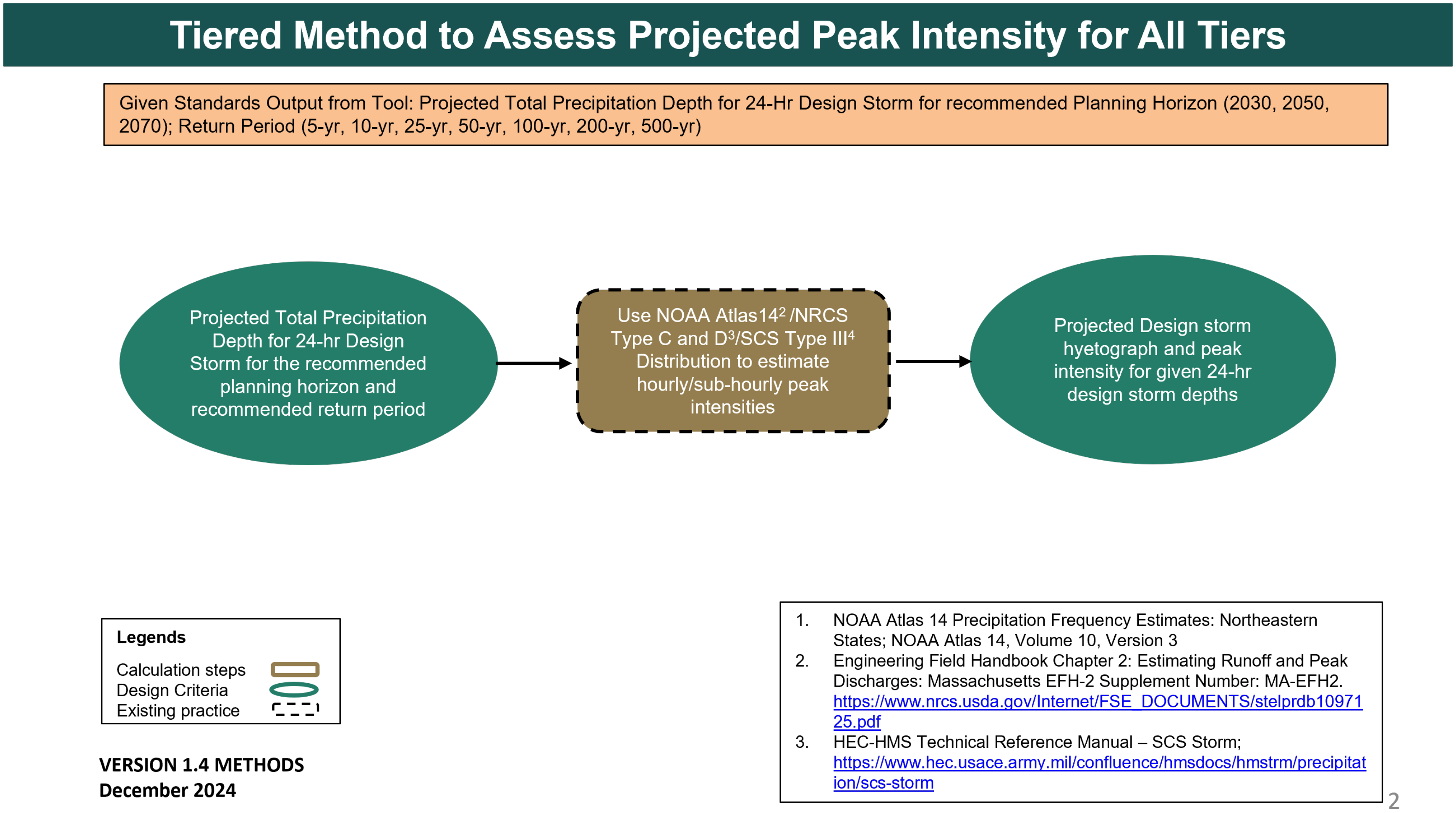
[2] *Steinschneider, S., & Najibi, N. (2022). Observed and Projected Scaling of Daily Extreme Precipitation with Dew Point Temperature at Annual and Seasonal Scales across the Northeastern United States, Journal of Hydrometeorology, 23(3), 403-419. https://journals.ametsoc.org/view/journals/hydr/23/3/JHM-D-21-0183.1.xml*

[3] *National Cooperative Highway Research Program, Transportation Research Board. Applying Climate Change Information to Hydrologic and Coastal Design of Transportation Infrastructure Final Report, 2019. http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP1561FinalReport.pdf*

Tiered Estimation Method for Projected Peak Intensity – All Tiers



Tiered Method to Assess Projected Peak Intensity for All Tiers

Given Standards Output from Tool: Projected Total Precipitation Depth for 24-Hr Design Storm for recommended Planning Horizon (2030, 2050, 2070); Return Period (5-yr, 10-yr, 25-yr, 50-yr, 100-yr, 200-yr, 500-yr)

Projected Total Precipitation Depth for 24-hr Design Storm for the recommended planning horizon and recommended return period

Use NOAA Atlas14[2] /NRCS Type C and D[3]/SCS Type III[4] Distribution to estimate hourly/sub-hourly peak intensities

Projected Design storm hyetograph and peak intensity for given 24-hr design storm depths

Legends

Calculation steps ▭
Design Criteria ⬭
Existing practice ┅

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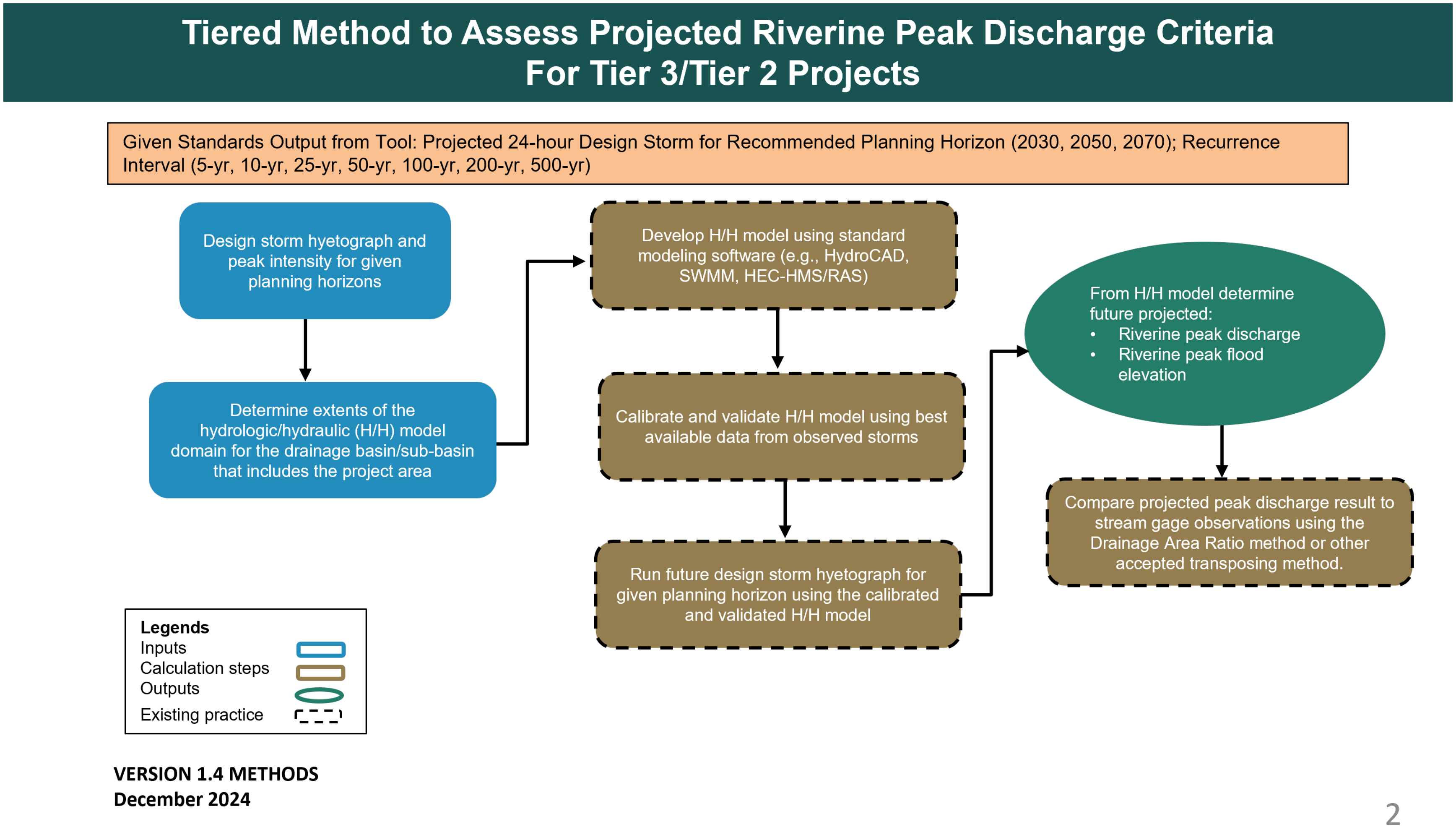
1. NOAA Atlas 14 Precipitation Frequency Estimates: Northeastern States; NOAA Atlas 14, Volume 10, Version 3
2. Engineering Field Handbook Chapter 2: Estimating Runoff and Peak Discharges: Massachusetts EFH-2 Supplement Number: MA-EFH2. https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1097125.pdf
3. HEC-HMS Technical Reference Manual – SCS Storm; https://www.hec.usace.army.mil/confluence/hmsdocs/hmstrm/precipitation/scs-storm

2

Figure 4.7. Method to Assess Projected Peak Intensity for All Tiers

Refer to **Attachment 4-C** for a complete example of method to assess extreme precipitation intensity.

Tiered Estimation Method for Riverine Peak Discharge – Tiers 3 and 2



Tiered Method to Assess Projected Riverine Peak Discharge Criteria For Tier 3/Tier 2 Projects

Given Standards Output from Tool: Projected 24-hour Design Storm for Recommended Planning Horizon (2030, 2050, 2070); Recurrence Interval (5-yr, 10-yr, 25-yr, 50-yr, 100-yr, 200-yr, 500-yr)

Design storm hyetograph and peak intensity for given planning horizons

Determine extents of the hydrologic/hydraulic (H/H) model domain for the drainage basin/sub-basin that includes the project area

Develop H/H model using standard modeling software (e.g., HydroCAD, SWMM, HEC-HMS/RAS)

Calibrate and validate H/H model using best available data from observed storms

Run future design storm hyetograph for given planning horizon using the calibrated and validated H/H model

From H/H model determine future projected:
- Riverine peak discharge
- Riverine peak flood elevation

Compare projected peak discharge result to stream gage observations using the Drainage Area Ratio method or other accepted transposing method.

Legends

Inputs	▭
Calculation steps	▭
Outputs	⬭
Existing practice	┅

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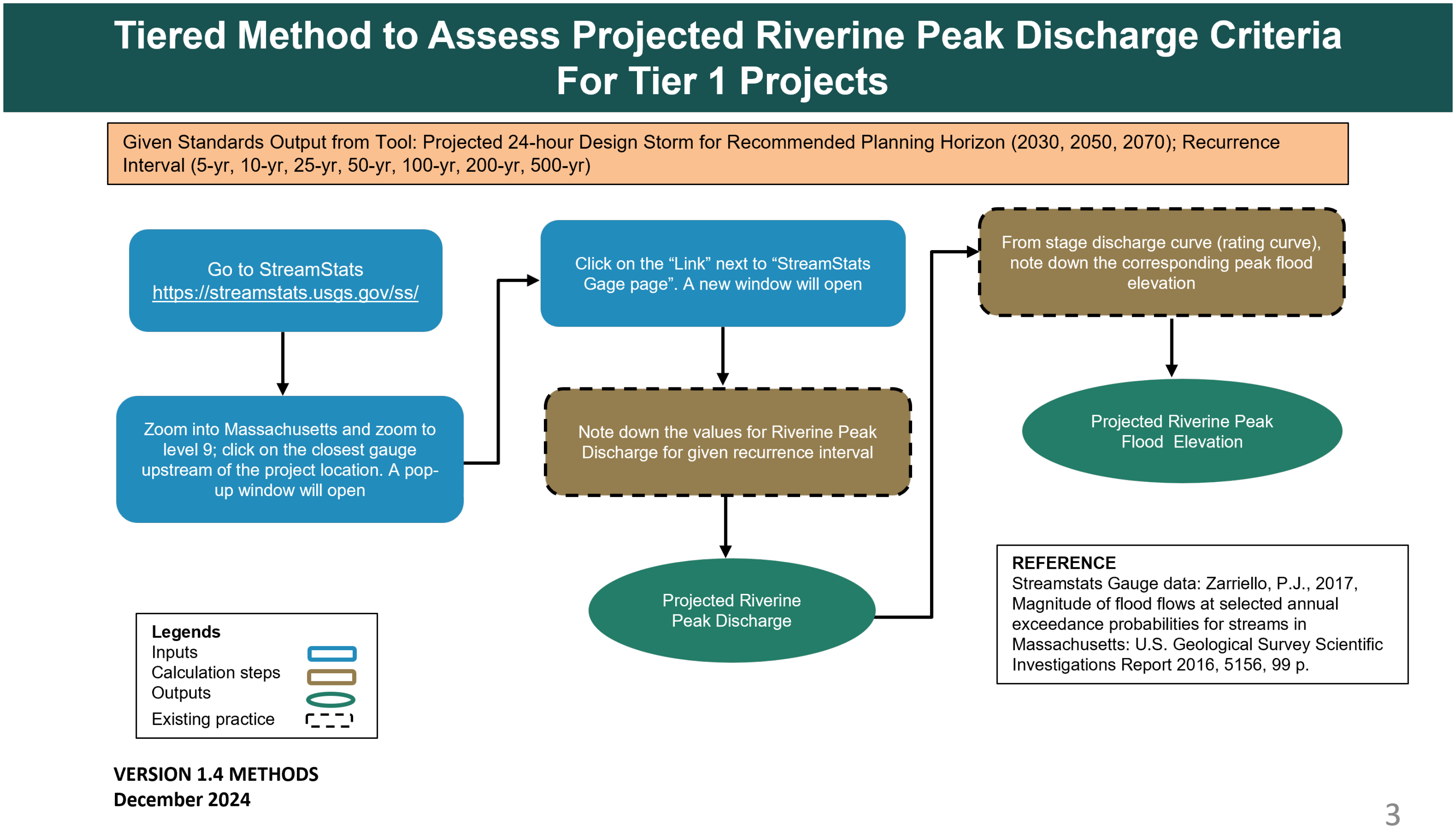
Figure 4.8. Tier 3/Tier 2 Estimation Method for Extreme Precipitation Riverine Peak Discharge Design Criteria Values as Recommended by the Climate Resilience Design Standards Tool

Tiered Estimation Method for Riverine Peak Discharge – Tier 1



Tiered Method to Assess Projected Riverine Peak Discharge Criteria For Tier 1 Projects

Given Standards Output from Tool: Projected 24-hour Design Storm for Recommended Planning Horizon (2030, 2050, 2070); Recurrence Interval (5-yr, 10-yr, 25-yr, 50-yr, 100-yr, 200-yr, 500-yr)

Go to StreamStats https://streamstats.usgs.gov/ss/

Zoom into Massachusetts and zoom to level 9; click on the closest gauge upstream of the project location. A pop-up window will open

Click on the "Link" next to "StreamStats Gage page". A new window will open

Note down the values for Riverine Peak Discharge for given recurrence interval

Projected Riverine Peak Discharge

From stage discharge curve (rating curve), note down the corresponding peak flood elevation

Projected Riverine Peak Flood Elevation

Legends
Inputs 🟦
Calculation steps 🟫
Outputs ⬭
Existing practice ⬚

REFERENCE
Streamstats Gauge data: Zarriello, P.J., 2017, Magnitude of flood flows at selected annual exceedance probabilities for streams in Massachusetts: U.S. Geological Survey Scientific Investigations Report 2016, 5156, 99 p.

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Figure 4.9. Tier 1 Estimation Method for Extreme Precipitation Riverine Peak Discharge Design Criteria Values as Recommended by the Climate Resilience Design Standards Tool

4.9 EXTREME HEAT STANDARDS OUTPUTS AND RELATIONSHIPS

4.9.1 OUTPUTS OVERVIEW

Upon completion of Project Inputs, users will receive Standards for each climate parameter from the Tool, for each asset entered. The Standards provided for the extreme heat climate parameter include recommended planning horizon, percentile, and the following design criteria that are likely to be affected by climate change: Projected Annual/Summer/Winter Average Temperature, Projected Heat Index, Projected Days per year with max temperature > 95°F, > 90°F, < 32°F, Projected Number of Heat Waves Per Year and Average Heat Wave Duration (days), Projected Cooling Degree Days (base = 65°F) and Heating Degree Days (base = 65°F), and Projected Growing Degree Days. There are either projected values provided for design criteria based on the recommended planning horizon and percentile, or recommended methods to estimate projected design criteria values if not directly available through the Tool.

4.9.2 DATA SOURCE & LIMITATIONS

Version 1.4 of the Tool provides projected values associated with most extreme heat design criteria with the exception of Projected Heat Index. The recommended Climate Resilience Design Standards for extreme heat and associated calculation methods reference climate projection sources as described in Table 4.20. The Standards may be used to inform plans and designs, but do not provide guarantees of future conditions or the resilience of projects designed to the recommended values resilience. Projected values calculated by the user should not be considered final or sufficiently well characterized for final design (e.g., construction documents) without supporting analyses, and users are encouraged to do their own due diligence.

4.9.3 PLANNING HORIZONS RECOMMENDATIONS

The Target Planning Horizon refers to a future date to which an asset should be designed, which allows the project to incorporate anticipated climate change conditions (e.g., 2070 extreme heat projections). Recommended planning horizons provided by the Tool do not vary based on climate parameter but may vary by asset.

The recommended planning horizons are determined based on the year through which the asset is expected to last (i.e., before a major reconstruction/renovation), which is calculated by adding the greatest asset's useful life in years, to the estimated year construction of the asset will start (as entered by the user in the Project Inputs of the Tool). The calculated year through which the asset is expected to last will be compared against the first column in Table 4.16, and the corresponding recommended planning horizon will be provided as output.

Table 4.16. Recommended Planning Horizons Provided by the Tool, based on the Asset's Useful Life and Construction Start Year

END OF USEFUL LIFE[1]	RECOMMENDED PLANNING HORIZON OUTPUT
2021 - 2029	**2030**
2030 - 2039	**2030**
2040 – 2049	**2050**
2050 – 2059	**2050**
2060 – 2069	**2070**
2070 - 2079	**2070**

2080 - 2089	**2070**
2090 - 2099	**2070[2]**

1. Calculated by adding the asset's useful life in years, to the estimated year construction of the asset will start.
2. MC-FRM currently does not cover 2100 scenarios, so for consistency across climate parameters, the 2070 planning horizon is recommended until 2100 results are available for all climate parameters.

4.9.4 PERCENTILES RECOMMENDATIONS

For the extreme heat climate parameter, the Tool will provide a recommended percentile (50th or 90th percentile) within the ensemble of the projected extreme heat parameter for each asset.

Assets' useful life does not inform the recommended percentile output for the extreme heat climate parameter. This difference is recommended since impacts from flooding are episodic, whereas impacts from heat are likely to be experienced by an asset regularly over its useful life and cannot be typically assigned a frequency of occurrence.

Why Percentiles? Climate projections for heat were developed through EEA's Massachusetts Climate and Hydrologic Risk Project. The downscaled analysis included 20 Global Climate Models (GCMs) to model thermodynamic climate change. More about that project can be found on Resilient.Mass.gov. The resulting climate projections are presented as a range of values based on values projected by the different GCMs with a lower, median, and upper bound. These bounds are the 10th (lower bound) and 90th (upper bound) percentiles of heat values projected by the different GCMs. A "percentile" is a statistical value for which a certain percentage of numbers within a group (for example, twenty different future average temperatures projected by twenty GCMs) falls below that value.

The recommended percentile can be interpreted as a proxy of our confidence that actual future extreme heat will be less than or equal to the selected design value based on what we expect about future extreme heat based on many different GCM simulations. For example, if the Tool recommends a 50th percentile design value, that means 50% of GCM simulations in the dataset on which the Standards are based projected an equal or lower value of the extreme heat parameter while about 50% projected higher extreme heat. If the Tool recommends a 90th percentile, that means 90% of model simulations in the dataset project equal or lower extreme heat and only 10% projected higher extreme heat.

These percentiles cannot be interpreted as the actual chance that future extreme heat will be higher or lower than the design value for several reasons: The percentile is based on one of many scenarios for future greenhouse gas emissions, models are useful but necessarily simplified representations of real-world processes which may miss key trends, and more. However, the percentiles may be interpreted as a proxy for our confidence that the design value will not underrepresent future conditions given the selected climate scenario, which in this Tool is the "high" emissions scenario of Representative Concentration Pathway (RCP) 8.5.

The percentiles for design recommended by the Tool are also dependent on asset construction type instead of asset type for the sea level rise / storm surge and extreme precipitation climate parameters. This difference is due to the difficulty in accommodating for extreme heat resilience in existing construction design. The output is therefore based on asset construction type to improve the standard of design criteria for new and existing construction projects, specific to the type of construction materials used each asset category. The recommended percentiles for building and infrastructure assets and construction type are shown in Table 4.17.

Table 4.17. Recommended Percentiles by Construction Type (Infrastructure and Buildings/Facilities) Provided by the Tool for the Extreme Heat Climate Parameter

EXTREME HEAT	Criticality	PERCENTILES FOR BUILDINGS/FACILITIES & INFRASTRUCTURE			
		New Construction	Major Repair/ Retrofit	Renovation	Maintenance (critical repair or environmental restoration)
	High	90th Percentile	90th Percentile	50th Percentile	50th Percentile
	Medium	90th Percentile	50th Percentile	50th Percentile	50th Percentile
	Low	50th Percentile	50th Percentile	50th Percentile	50th Percentile

Natural resources assets do not have criticality scores; therefore, recommended percentiles are based on construction type alone, as shown in Table 4.18.

Table 4.18. Recommended Percentiles by Construction Type (Natural Resources) Provided by the Tool for the Extreme Heat Climate Parameter

EXTREME HEAT	PERCENTILES FOR NATURAL RESOURCE ASSETS			
	New Construction	Restoration or enhancement	Maintenance (environmental)	Dam Removal
	50th Percentile	50th Percentile	50th Percentile	Does not apply

Since dam removal construction type for natural resource assets do not receive recommended percentiles, these assets will also not receive recommended design criteria.

4.9.5 DESIGN CRITERIA RECOMMENDATIONS

Design criteria are recommended parameters to incorporate into design of physical assets, generated by the Climate Resilience Design Standards as an output, which vary by climate parameter, location, and asset type. The design criteria that are recommended through the Tool based on asset type and location, as presented in Table 4.19, below.

Table 4.19. Relationships for how Design Criteria are recommended for Extreme Heat

	Design Criteria	Design Criteria Recommended For	
		Asset Type	**Project Polygon Location**
EXTREME HEAT	**Projected Annual/Summer/Winter Average Temperature**	All assets excluding dam removal	All locations
	Projected Heat Index	All buildings and infrastructure assets, open space assets	
	Projected Days per year with max temperature > 95°F, > 90°F, < 32°F	All buildings and infrastructure assets	
	Projected Number of Heat Waves Per Year and Average Heat Wave Duration (days)	All buildings and infrastructure assets, open space assets	
	Projected Cooling Degree Days (base = 65°F) and Heating Degree Days (base = 65°F)	All buildings assets	
	Projected Growing Degree Days	All natural resources assets excluding coastal ecosystems and dam removal	

* Design criteria are recommended if both the asset type and project location are true.

4.9.5.1 DESIGN CRITERIA GUIDANCE

There is additional guidance for the design criteria within the user interface to help users integrate this information into planning, early design, and evaluation processes. If a design criterion is applicable, there will be a dropdown with the following subsections:

- *Definition*
- *[Applicable Design Criterion] Values OR How to Estimate [Applicable Design Criterion] Values*
- *How [Applicable Design Criterion] may inform Planning*
- *How [Applicable Design Criterion] may inform Early Design*
- *How [Applicable Design Criterion] may inform Project Evaluation*
- *Limitations for [Applicable Design Criterion] Values, Standards, & Guidance*

Please refer to **Attachment 4-D** for guidance associated with each of the extreme heat design criteria.

4.9.5.2 PROJECTED VALUES FOR DESIGN CRITERIA

Projected values for extreme heat are provided through the Tool with the exception of Projected Heat Index. The projected extreme heat values provided through the Tool were developed through EEA's Climate and Hydrologic Risk project, the methods of which represent a Tier 3 level of effort. Users will need to calculate projected values of heat index following the recommended tiered estimation method. Please refer to **Section 4.3** for further details. Table 4.20 provides the data sources for climate projections associated with the design criteria and tiered estimation method.

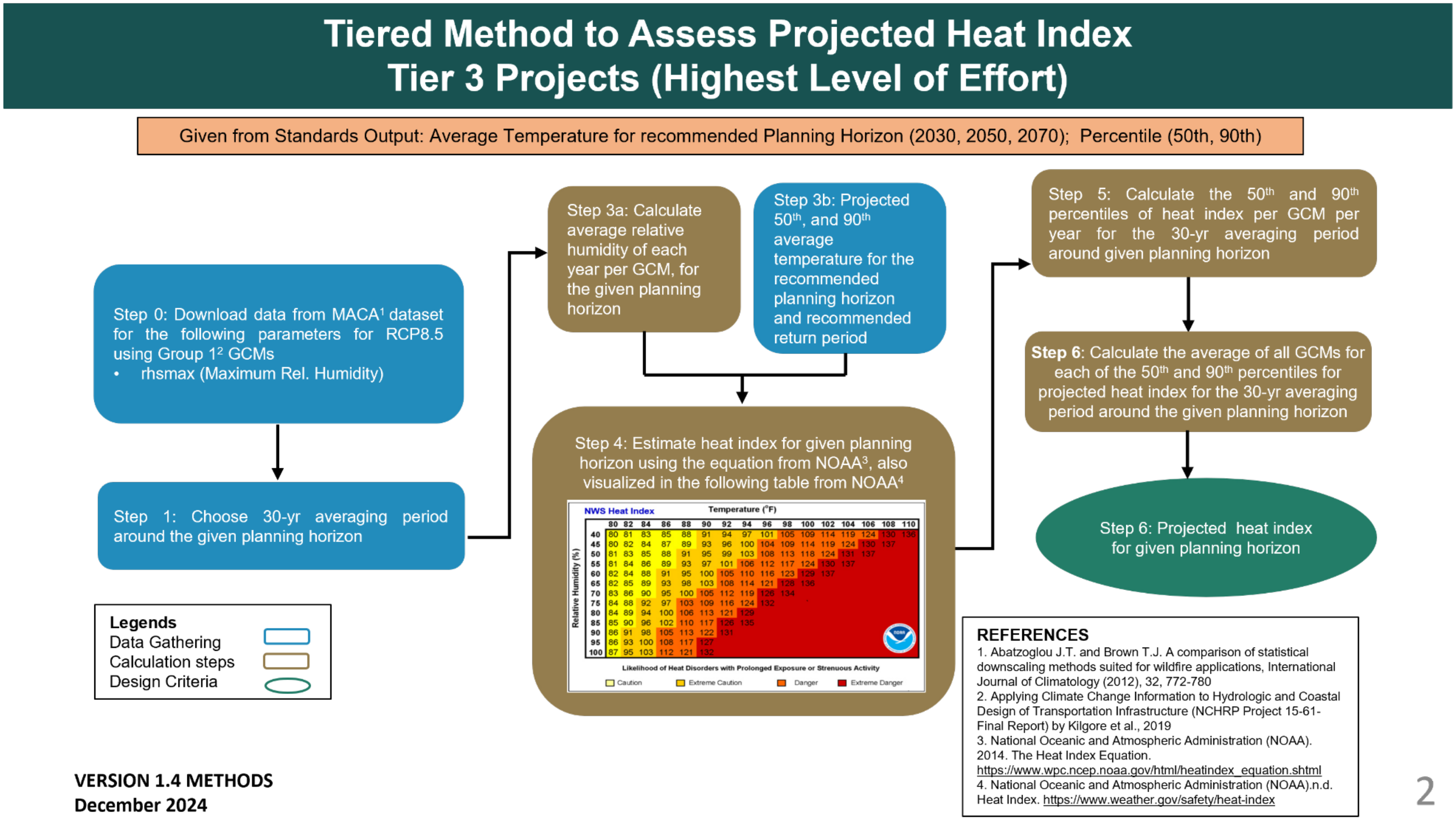
Table 4.20. Data Sources & Methods Recommended from the Tool for the Extreme Heat Design Criteria

	Design Criteria	Tool Outputs		
		Tier 3 - High Level of Effort	Tier 2 - Average Level of Effort	Tier 1 - Low Level of Effort
EXTREME HEAT	**Projected Annual/Summer/Winter Average Temperature**	Values provided from EEA's Climate and Hydrologic Risk Project via Tool output		
	Projected Heat Index	Tiered Estimation Methods PDF: Perform downscaled humidity analysis (from MACA[1] dataset) and temperature values provided via Tool output	Tiered Estimation Methods PDF: Apply percent increase to historic maximums based on City of Cambridge Climate Change Projections Report	
	Projected Days per year with max temperature > 95°F, > 90°F, < 32°F	Values provided from EEA's Climate and Hydrologic Risk Project via Tool output		
	Projected Number of Heat Waves Per Year and Average Duration (days)			
	Projected Cooling Degree Days (base = 65°F) and Heating Degree Days (base = 65°F)			
	Projected Growing Degree Days			

1. MACA - Multivariate Adaptive Constructed Analogs data portal.

Excerpts from the Tiered Estimation Methods PDFs to calculate heat index design criteria values are shown in the Figures 4.10 through 4.11 below. Example calculations using tiered estimation methods for heat index values are presented as **Attachment 4-C**.

Tiered Estimation Method for Extreme Heat – Heat Index



Tiered Method to Assess Projected Heat Index
Tier 3 Projects (Highest Level of Effort)

Given from Standards Output: Average Temperature for recommended Planning Horizon (2030, 2050, 2070); Percentile (50th, 90th)

Step 0: Download data from MACA[1] dataset for the following parameters for RCP8.5 using Group 1[2] GCMs
- rhsmax (Maximum Rel. Humidity)

Step 1: Choose 30-yr averaging period around the given planning horizon

Step 3a: Calculate average relative humidity of each year per GCM, for the given planning horizon

Step 3b: Projected 50th, and 90th average temperature for the recommended planning horizon and recommended return period

Step 4: Estimate heat index for given planning horizon using the equation from NOAA[3], also visualized in the following table from NOAA[4]

NWS Heat Index

Temperature (°F)

Relative Humidity (%)	80	82	84	86	88	90	92	94	96	98	100	102	104	106	108	110
40	80	81	83	85	88	91	94	97	101	105	109	114	119	124	130	136
45	80	82	84	87	89	93	96	100	104	109	114	119	124	130	137	
50	81	83	85	88	91	95	99	103	108	113	118	124	131	137		
55	81	84	86	89	93	97	101	106	112	117	124	130	137			
60	82	84	88	91	95	100	105	110	116	123	129	137				
65	82	85	89	93	98	103	108	114	121	128	136					
70	83	86	90	95	100	105	112	119	126	134						
75	84	88	92	97	103	109	116	124	132							
80	84	89	94	100	106	113	121	129								
85	85	90	96	102	110	117	126	135								
90	86	91	98	105	113	122	131									
95	86	93	100	108	117	127										
100	87	95	103	112	121	132										

Likelihood of Heat Disorders with Prolonged Exposure or Strenuous Activity

🟨 Caution 🟧 Extreme Caution 🟧 Danger 🟥 Extreme Danger

Step 5: Calculate the 50th and 90th percentiles of heat index per GCM per year for the 30-yr averaging period around given planning horizon

Step 6: Calculate the average of all GCMs for each of the 50th and 90th percentiles for projected heat index for the 30-yr averaging period around the given planning horizon

Step 6: Projected heat index for given planning horizon

Legends
Data Gathering ▭
Calculation steps ▭
Design Criteria ⬭

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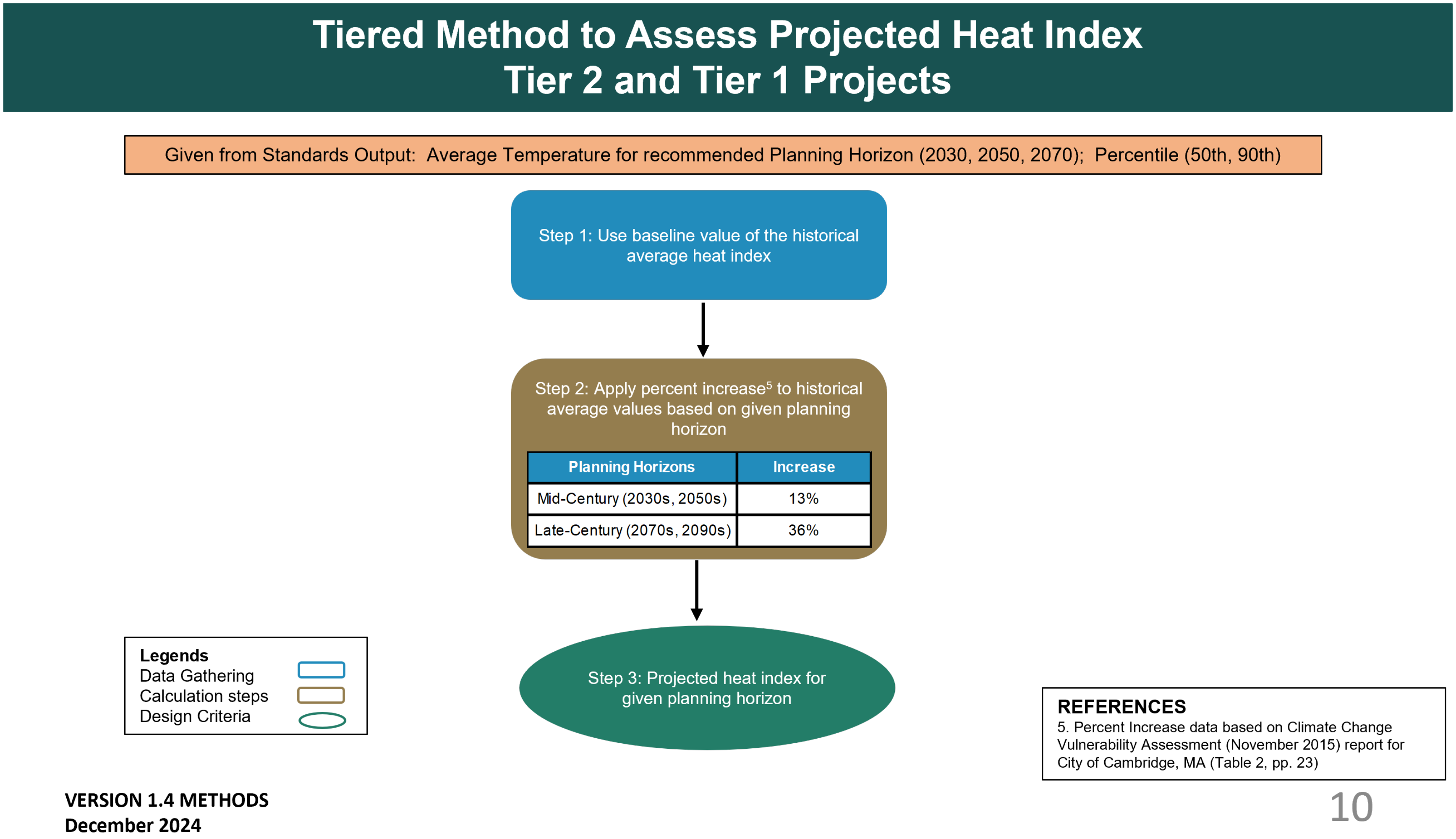
REFERENCES
1. Abatzoglou J.T. and Brown T.J. A comparison of statistical downscaling methods suited for wildfire applications, International Journal of Climatology (2012), 32, 772-780
2. Applying Climate Change Information to Hydrologic and Coastal Design of Transportation Infrastructure (NCHRP Project 15-61-Final Report) by Kilgore et al., 2019
3. National Oceanic and Atmospheric Administration (NOAA). 2014. The Heat Index Equation. https://www.wpc.ncep.noaa.gov/html/heatindex_equation.shtml
4. National Oceanic and Atmospheric Administration (NOAA).n.d. Heat Index. https://www.weather.gov/safety/heat-index

Figure 4.10. Tier 3 Estimation Method for Heat Index Design Criteria Values as Recommended by the Extreme Heat Climate Parameter Climate Resilience Design Standards Output

Refer to **Attachment 4-C** for an example of draft method to evaluate extreme heat index design criteria values for Tier 3 method.



Tiered Method to Assess Projected Heat Index
Tier 2 and Tier 1 Projects

Given from Standards Output: Average Temperature for recommended Planning Horizon (2030, 2050, 2070); Percentile (50th, 90th)

Step 1: Use baseline value of the historical average heat index

Step 2: Apply percent increase[5] to historical average values based on given planning horizon

Planning Horizons	Increase
Mid-Century (2030s, 2050s)	13%
Late-Century (2070s, 2090s)	36%

Step 3: Projected heat index for given planning horizon

Legends
Data Gathering ▭
Calculation steps ▭
Design Criteria ⬭

REFERENCES
5. Percent Increase data based on Climate Change Vulnerability Assessment (November 2015) report for City of Cambridge, MA (Table 2, pp. 23)

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Figure 4.11. Tier 1 and 2 Estimation Method for Heat Index Design Criteria Values as Recommended by the Extreme Heat Climate Parameter Climate Resilience Design Standards Output

Refer to **Attachment 4-C** for an example of method to evaluate extreme heat index design criteria values for Tier 2/Tier 1 method.

SECTION 4 ATTACHMENTS

Attachment 4-A – MC-FRM FAQ Document

Attachment 4-B – Comparative Precipitation Method Report

Attachment 4-C – Compiled Tiered Estimation Method PDFs

Attachment 4-D – Compiled Design Criteria Guidance Language

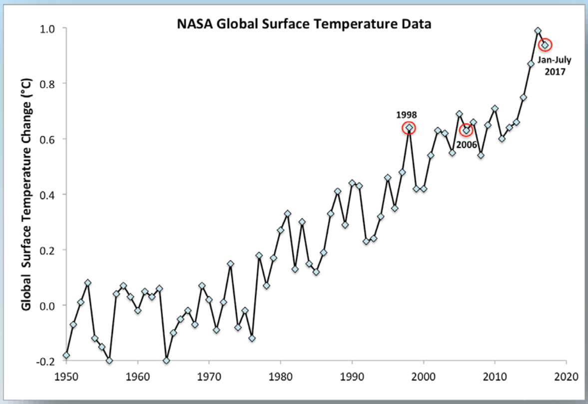
Attachment 4-A– MC-FRM FAQ DOCUMENT

The Massachusetts Coast Flood Risk Model

Modeling Overview and Frequently Asked Questions

Background

Massachusetts' coastal communities were settled during a time when sea levels were remarkably stable. For centuries, natural and built infrastructure such as salt marshes, dune communities, seawalls and bulkheads have allowed people to live, work and play at the edge of the ocean with well-understood, manageable risks of flood damage. However, increases in global temperatures have resulted in 16 of the 17 warmest years on record occurring from 2001 to 2017. People born after 1980 have never experienced a cooler-than-average year. As global temperatures rise, so do sea levels (melting ice sheets, expansion of water), and the Mid-Atlantic and Northeast US coasts are experiencing faster-than-average sea level rise. As seas rise and storms impact our coastlines, communities need access to the most comprehensive information to determine when, where, and how much to invest to decrease potential damages from coastal flooding. The Massachusetts Coast Flood Risk Model (MC-FRM)[1] helps property owners, planners and policy makers consider ways to cost-effectively build resilience and plan for the expected changes.



Change in average global surface temperatures 1950-2017 (0.0 = historic average temperature; courtesy NASA).

Flooding in Boston during Storm Grayson (January 4, 2018).

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[1] Funding for the development of the MC-FRM was provided by the Commonwealth of Massachusetts.

What is special about the MC-FRM?

Sea level rise (SLR), combined with storms, has commonly been evaluated with a “bathtub” approach that simply increases the water surface elevation and compares that to topographic elevations of the land (i.e., fills the land up like a bathtub). When incorporating the effects of storms, the bathtub approach assumes the ocean stays perfectly flat. Anyone who has been to the coastline understands that the ocean is not a flat body of water during a storm. Water is aggressively being moved in various directions by waves, winds, and currents. As such, the bathtub approach does not account for critical physical processes during a storm, including waves, winds, and overtopping, and is unable to represent the dynamic nature of flooding. In many cases, the bathtub approach predicts flooding where none will occur, while misidentifying dry areas that would actually flood. Even some models that appear to be more complex only model the water levels up to the shoreline, then use bathtub approaches over land, ignoring important processes of over land flow. These models also tend to be low resolution, lacking details that can have a significant impact on the movement of water. The MC-FRM simulates the physics-based flow of water not only in water bodies, but also over land; including the time-varying, physical movement of water as it propagates inland. The MC-FRM also includes wave run-up and overtopping flow, and the physical based spreading inland of that water, in areas where waves intermittently overtop major coastal structures (e.g., seawalls, revetments). Areas with critical infrastructure and/or complex landscapes need to consider dynamic modeling of the changing climate and storms in order to ensure proper siting, design, and construction of significant investments.

Accurate storm surge probability modeling requires detailed representation of the physical processes (beyond a bathtub model), as well as high resolution inundation predictions based on a combination of sea level rise and storm surge. When simulating hurricanes and nor’easters, the MC-FRM dynamically includes the expected impacts of tides, waves, wave run-up and overtopping, storm surge, winds, and currents over a range of storm conditions and at high spatial resolution.

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The Massachusetts Coast Flood Risk Model

Modeling Overview and Frequently Asked Questions

What makes the MC-FRM more accurate than other inundation models and flood maps that have been created for the region?

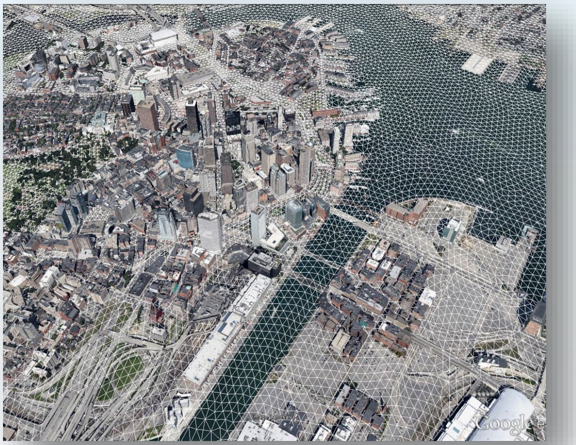
The MC-FRM is a more accurate representation of flooding risk because it is (1) a dynamic model that includes the critical processes associated with storm induced flooding (winds, waves, wave-setup, storm surge, wave run-up and overtopping, etc.), (2) calibrated to historical storm events that impacted Massachusetts with observed high water data and measurements, (3) high enough resolution to capture flood pathways in complex urban topographies, (4) a model that includes both hurricanes and nor'easters under changing climate conditions, and (5) able to capture the net effect of varying storm types, magnitudes, and frequencies.

How do the MC-FRM results relate/compare to the FEMA Flood Insurance Rate Maps (FIRMs)?

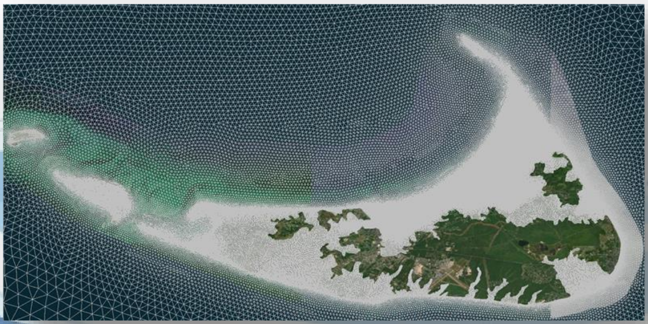
The MC-FRM is focused on present and future flooding projections based on a robust set of storm events, while FEMA results estimate present flood risk based on single historical based event. The methods used to produce the FIRMs are substantially different and FIRMs have a completely different purpose. ***They should not be directly compared.***

What is the resolution of the MC-FRM model grid?

In order to turn complex mathematical equations into high resolution maps, the MC-FRM uses a detailed modeling mesh, in which every intersecting point represents a specific set of data where the model equations are solved. Flood risk data are calculated as frequently as every ten (10) feet in populated areas on land. This provides more localized and accurate data for flood risk analysis and planning.

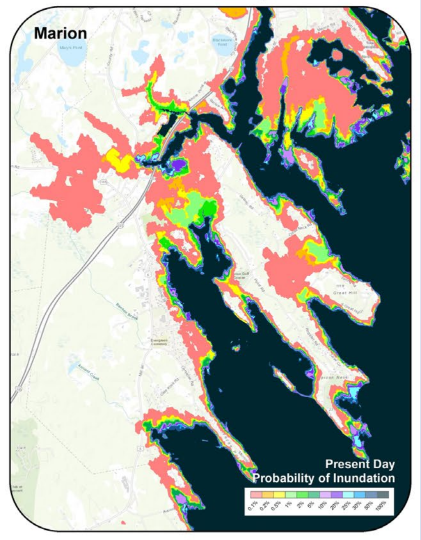


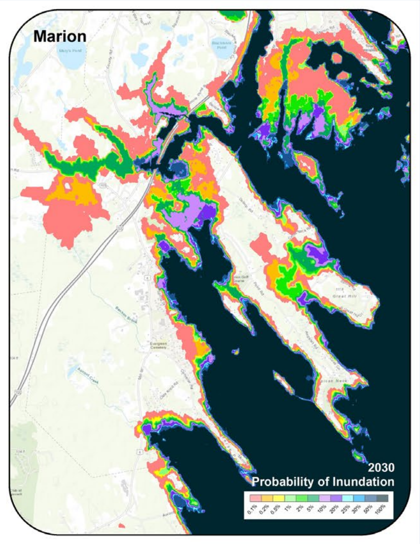
Example of the high-resolution MC-FRM modeling mesh for Boston (above) and Nantucket (below).

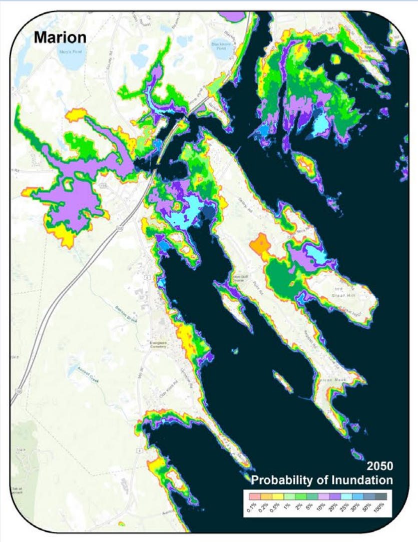


The MC-FRM is a probabilistic model. What does that mean?

Coastal storm events striking an area result in different impacts depending on factors, such as the timing of the storm with the tide cycle, the storm track, radius to maximum wind of the tropical storm, the amount of precipitation, etc. Probabilistic modeling evaluates a statistically robust set of viable coastal storm conditions that produce spatially distributed flood probabilities. The MC-FRM doesn't just simulate one storm or a few storms – the MC-FRM dynamically simulates hundreds to thousands of storms to produce flood exceedance probabilities at high spatial resolution. Using this statistically robust approach, the coastal flood exceedance probability (CFEP) can be defined as the probability of flood water inundating the land surface at a particular location. For example, a building that lies within the 2% CFEP zone would have a 2% chance (50-year return period) of flooding. In other words, there is a 2% percent chance that this location will get wet with salt water during a coastal storm event. Stakeholders can then determine if that is tolerable, or if some action may be required to improve resiliency, engineer an adaptation, consider relocation, or implement an operational plan. Critical assets, such as hospitals and evacuation routes, have different risk tolerances than parklands or parking lots.


Present Day


2030


2050

By mapping various future years (e.g., 2030 to 2050), individual structures, assets, and areas can be compared to determine how coastal flooding is changing over time. The overall influence of climate change projections can also be evaluated. These maps can also be used to assess flood entry points and pathways and identify potential regional adaptations. In many cases, large upland areas are flooded by a relatively small and distinct entry point (e.g., a low elevation area along the coastline). In cases like this, a more cost-effective and regional solution (rather than evaluating local adaptation options at each building in the area) can be prioritized. A targeted coastal protection project at the flood entry point (e.g., increasing seawall elevation, installing a natural berm, etc.) could protect a whole neighborhood. Maps showing the probability of flooding provide stakeholders the ability to identify areas expected to be flooded, and the probability of flooding. This helps them weigh their tolerance for risk, evaluate when adaptation options may need to be considered, and most importantly, prioritize funding to higher consequence areas.

The Massachusetts Coast Flood Risk Model

Modeling Overview and Frequently Asked Questions

What timeframes and sea level rise scenarios are being simulated in the MC-FRM?

MC-FRM scenarios currently include present day, 2030, 2050, and 2070 climate conditions. The sea level rise projections utilized for these scenarios are based on Massachusetts specific analysis (DeConto and Kopp, 2017) and include Antarctic ice sheet projections as of 2017. Sea level rise values vary for the north and south portions of the state. These scenarios are consistent with the projections being used by the Commonwealth of Massachusetts[1].

Location	**Relative Mean Sea Level (feet, NAVD88)**		
	2030	2050	2070
North	1.2	2.4	4.2
South	1.2	2.5	4.3

Will the MC-FRM results of flooding risk be publicly available?

Yes. MC-FRM flood probabilities and depths will be publicly available through the Commonwealth's Climate Change Clearinghouse.

Are the results of the MC-FRM available for the entire coastline?

Yes. The model includes every Massachusetts coastal city and town potentially influenced by future coastal storm surge-induced flooding during this century. GIS data will be available for download.

Are the results precise enough to be applied to specific buildings or structures?

Yes. The model predicts the likelihood and depth of flooding at a resolution high enough to be able to analyze individual buildings.

What types of flooding does the model cover?

It simulates storm surge-induced coastal flooding from hurricanes and nor'easters, which differ in speed, direction and duration. The model also includes climate-change induced increases in river discharge from precipitation for major rivers. Upstream freshwater flooding events that have no ocean-based component are not included in the analysis.

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[1] https://resilientma.org/changes/sea-level-rise

The Massachusetts Coast Flood Risk Model

Modeling Overview and Frequently Asked Questions

What types of storms does the MC-FRM simulate?

The MC-FRM simulates storm surge induced flooding that could occur from both tropical (hurricanes) or extra-tropical (nor'easter) storm events. The intensity and frequency of these storm events change with the changing climate conditions. The model also includes climate-change induced increases in river discharge from precipitation within major rivers. It does not include flooding caused by rainfall that does not drain adequately to a water body, such as ponding in a low spot in a parking lot.

How has the MC-FRM changed from the Boston Harbor Flood Risk Model (BH-FRM)?

The MC-FRM improves upon the BH-FRM in numerous ways. Beyond the inclusion of the entire coastal area of Massachusetts, the MC-FRM also (1) includes updated sea level rise projections consistent with the state standard; (2) expands the storm sets used to include more historical and recent storms as well as hundreds of additional future storms; (3) includes dynamic wave runup and overtopping of coastal structures like seawalls; and (4) adds regular nuisance flooding by projecting future tidal datums.

I'm a town official. How do I use this information?

The MC-FRM provides the public with the best available science-based projections on coastal flooding during this century, helping you understand the level of risk potentially faced by areas within your community. This information can help prioritize adaptation actions across multiple assets throughout a town, therefore allowing more cost-effective, science-based approaches and timing for building resilience.

I'm concerned about a specific property. How do I use this information?

By examining the MC-FRM flood risk projections, property managers can assess the potential timing and depth of saltwater flooding over time for a given location. Buildings and infrastructure exposed to periodic storm flooding—especially in the absence of damaging waves—can be retrofitted to prevent harm. However, every specific property should also consider regional level protection approaches when evaluating risk.

Are dams included in the model?

Major dams, and dam operations, are included in the model.

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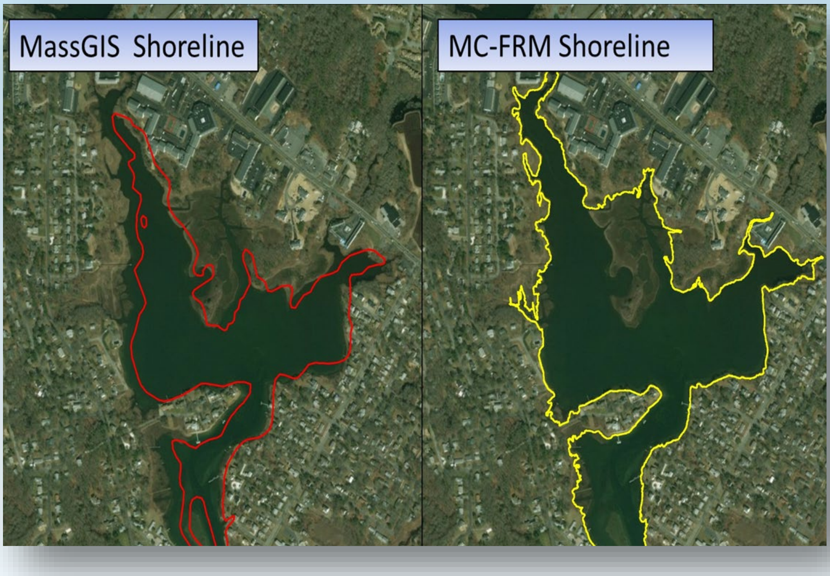
How is the MC-FRM assisting resiliency projects and engineering designs?

The MC-FRM results, at a site-specific scale, provide a breadth of information useful for informing decisions as to where protection may be required, selecting potential adaptations, planning, and assisting with engineering design. The high-resolution model results offer detailed information at an individual building and parcel level for assessment of existing or developing sites. While potential inundation probability and depths may be manageable under current risk levels, this may change over the service life of the asset. The dynamic model can also provide flood pathways to the site, which gives an indication of how long the flooding is expected to last for a given probability level. In many cases, this is important for determining economic impacts related to out-of-service time frames. Understanding the volume of water and flood pathways gives another layer of information that helps inform design and consideration of local and/or regional adaptation measures. The flood pathway insight allows stakeholders to consider local measures (e.g., raising the elevations of the buildings on the parcel, flood proofing structures, local on-site berms or walls), and regional approaches (e.g., berms, tide gates, flood walls, etc.) to control the source of flooding for a region that may co-benefit other properties.

Towns, communities, and stakeholders throughout the Commonwealth of Massachusetts can use, and have already been using, MC-FRM results to complete comprehensive vulnerability assessments, develop engineering adaptations, and design resilient green, gray, or hybrid solutions. The probabilistic results have given communities the ability to prioritize adaptations and start to build resilience in fiscally manageable ways. Communities and landowners can take action to manage projected imminent risks, while waiting for more certainty when dealing with long-term climate change projections that may not have near-term impacts.

What about non-storm based flooding or flooding that will occur just due to sea level rise?

The MC-FRM results are also being used to define the present and anticipated future (e.g., 2030) mean high water shorelines across the state, resulting in a marked improvement over some current shorelines. These shorelines also provide an indication of where nuisance (daily) flooding can be expected in the future climate.



How does wave run-up and overtopping impact flooding?

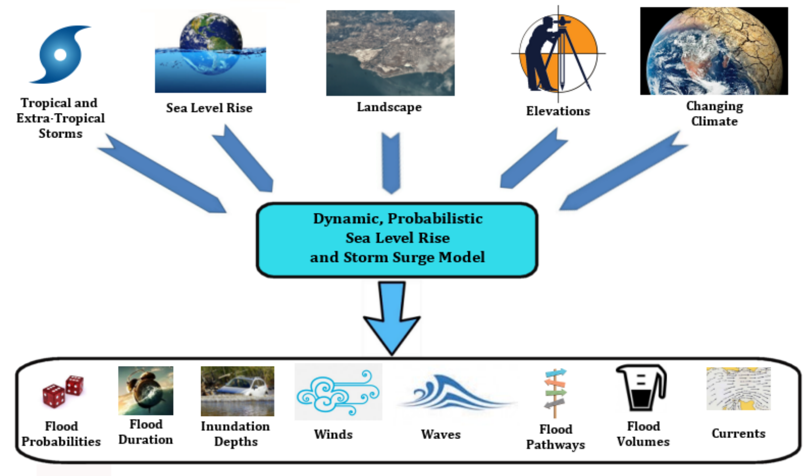
In addition to the numerical simulation of the physical flow of water directly over land, the MC-FRM also incorporates dynamic wave run-up and overtopping to determine the volume of water that is thrown over coastal structures during storm events. The MC-FRM accounts for this volume overtopping coastal structures for each wave during the storm event and models the flow of this water behind the structure as it propagates inland or is returned to the ocean. This volume of water is incorporated into the dynamic results of over land water movement that is already simulated in the model.

The Massachusetts Coast Flood Risk Model

Modeling Overview and Frequently Asked Questions

What are the products from the MC-FRM?

MC-FRM products for the Commonwealth include data for every community in Massachusetts that could be impacted by coastal flooding this century. Data products include the probability of flooding in each year (present day, 2030, 2050, and 2070) and water depths associated with the 1% (100-year), 0.5% (200-year), and 0.1% (1000-year) annual exceedance probability levels. Additionally, the water surface elevations associated with the 5% (20-year), 2% (50-year), 1% (100-year), 0.5% (200-year), 0.2% (500-year), and 0.1% (1000-year) annual exceedance probability levels are provided.



Overarching approach using dynamic probabilistic modeling to create the MC-FRM. Outputs provided by the dynamic model provide the ability for a more comprehensive assessment.

These water surface elevations include the effects of tides, storm surge, and wave setup. Further outputs include wave heights and distributions, wave action water elevations, and full tidal datums. Projected wave action water elevations are flood elevations that are calculated from the MC-FRM results by including the site-specific projected wave crest amplitudes above the water surface elevations.

Attachment 4-B– COMPARATIVE PRECIPITATION METHOD REPORT

1 INTRODUCTION AND BACKGROUND

This technical report presents a comparative analysis conducted by Weston & Sampson Engineers, Inc. (Weston & Sampson) among the different methodologies that have been used to estimate projected total precipitation depths in the Climate Resilient Design Standards Tool developed by the Resilient Massachusetts Action Team (RMAT). This technical report is being published concurrently with Version 1.2 of the Tool (July 2022) as a reference documenting the comparison of methodologies to generate projected total precipitation depth for 24-hr design storms referenced in Version 1.2 and prior versions.

The Climate Resilience Design Standards Tool (the Tool) was developed to support efforts by Massachusetts agencies and municipalities to integrate best available statewide climate change projections for sea level rise/storm surge, extreme precipitation, and extreme heat into the conceptual planning and design of capital projects with physical assets. The Tool outputs provide a basis-of-discussion for planning, early design, and evaluation that is standardized across the Commonwealth based on asset type, location, criticality, construction type, and useful life of physical assets. There are two primary outputs from the Tool: the Preliminary Climate Risk Screening and the Climate Resilience Design Standards ("Standards").

The Standards for each climate parameter include the following: recommended planning horizon, recommended return period (sea level rise / storm surge and precipitation) or percentile (heat), and a list of applicable design criteria that are likely to be affected by climate change; the recommendations provided through the Tool are based on pre-defined relationships between asset type, useful life, criticality, project location, and construction type. Please refer to the **Supporting Documents: Section 4: Climate Resilience Design Standards** for more information behind these relationships.

Many projects throughout the Commonwealth are currently using climate projections for design. The Standards provide a recommended uniform statewide methodology for consistent use of available climate projections.

The term "standards" has been used in many different ways in climate resilience literature, so the RMAT developed a draft definition for this effort as follows:

"A Climate Resilience Design Standard is a ***scientifically based process or method*** *that* ***produces a consistent outcome****, which uniformly guides users in the selection of planning horizons, return period, and flexible design criteria, by climate parameter."*

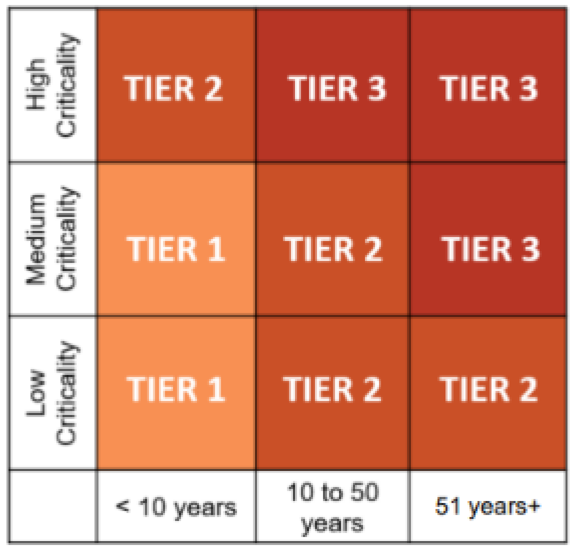
Projected design criteria values associated with the recommended planning horizon and return period (or percentile) are estimated using available climate projections and established, peer-reviewed methodologies. The RMAT worked with a scientific working group and consultant team to identify recommended methodologies and climate projections to integrate into the Standards and prior versions of the Tool: beta (released April 2021) and Version 1.0 (released February 2022). Through a separate project associated with the Executive Office of Energy and Environmental Affairs (EEA)'s Massachusetts Climate and Hydrologic Risk Project, Cornell

University developed an alternative methodology to produce projections for total precipitation depth for 24-hr design storms in the Northeast.[1] As of April 2022, the Tool provides both:

- Projected design criteria values for several sea level rise/storm surge design criteria and projected total precipitation depth for 24-hr design storms based on the recommended planning horizon and return period, and
- tiered methodologies with step-by-step instructions on how to estimate projected values for design criteria based on the recommended planning horizon and return period or percentile using available climate projections on ResilientMA.org or downscaled Global Climate Models (GCMs).

The tiers in the Tool are recommended based on a combination of useful life and criticality for building and infrastructure assets, as shown in Figure 1.

Useful life (shown on the horizontal axis) is defined by the user in the Tool for each building and infrastructure asset. Criticality (shown on the vertical axis) is assessed by user provided answers to a series of questions for each building and infrastructure asset. Refer to **Supporting Documents: Section 2** for additional information regarding criticality. Refer to **Supporting Documents: Section 4.3** for the definitions of the tiers.



High Criticality	TIER 2	TIER 3	TIER 3
Medium Criticality	TIER 1	TIER 2	TIER 3
Low Criticality	TIER 1	TIER 2	TIER 2
	< 10 years	10 to 50 years	51 years+

Figure 1. *Relationship Table that informs recommended tier output for building and infrastructure assets*

This technical report summarizes the methodologies referenced within Version 1.2 of the Tool, as well as methodologies referenced in prior versions (beta, Version 1.0, and Version 1.1).

2 SUMMARY OF METHODOLOGIES

Several methodologies to estimate projected total precipitation depth for 24-hour design storms have been referenced within the Climate Resilience Design Standards Tool since the beta version was launched April 2021. Table 1 provides a brief description of the methodologies referenced.

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[1] *Steinschneider, S., & Najibi, N. (2022). Observed and Projected Scaling of Daily Extreme Precipitation with Dew Point Temperature at Annual and Seasonal Scales across the Northeastern United States, Journal of Hydrometeorology, 23(3), 403-419.* https://journals.ametsoc.org/view/journals/hydr/23/3/JHM-D-21-0183.1.xml

Table 1: Methodologies assessed for use within the Climate Resilience Design Standards Tool

Methodology to estimate projected total precipitation depth for 24-hour design storms	
Title*	**Brief Description**
Methodology developed by Cornell University for EEA's Massachusetts Climate and Hydrologic Risk Project[2]	Cornell University generated a database of updated IDF curves across different temperature changes (for each 0.5 °C warming starting from 0.5 °C to 8 °C warming scenarios) using regionalized scaling rates with dew point temperature both in observations across the Northeast United States and for a subset of downscaled CMIP5 projections within the state of MA.
NOAA + Methodology	A factor of 0.9 applied to the upper bound of the 90% confidence interval for the present NOAA Atlas 14 values. This approach is being considered by MassDEP as part of updating the Stormwater Handbook, which currently references TP-40. ***Note: Provided for Tier 1 Assets Only in Version 1.2***
NCHRP15 -61 Methodology[3]	National Cooperative Highway Research Program (NCHRP) Project 15-61 titled "Applying Climate Change Information to Hydrologic and Coastal Design of Transportation Infrastructure," which uses local historical data from NOAA Atlas 14 for present day baseline in combination with a locally downscaled ensemble of GCMs for that specific location that fit to an extreme value distribution. Ratios between modeled baseline and modeled future data are applied to site specific NOAA Atlas 14 values to calculate the site-specific design storm projections. ***Note: Provided for Tier 3, Dams & Flood Control Structure Assets Only in Version 1.2***
Regionalized Percent Increase Methodology**	Regionalized percent increase based on location, design storm frequency, and end of useful life developed for the Tool in 2020 using NCHRP 15-61 methodology at nine long-term weather stations across Massachusetts. ***Note: Not provided in Version 1.2*** *(replaced by Methodology developed by Cornell University for EEA's Massachusetts Climate and Hydrologic Risk Project as of Version 1.1 – April 2022)*

* The titles presented in this table are for reference in this technical report only.
** Refer to Appendix A for a summary of this methodology.

While this technical report does not discuss different methodologies used to calculate projected peak intensity for design storms, the methodology to calculate projected peak intensity is included in the Tool as part of the Tiered Methodology PDF. Based on the Tool's guidance, projected peak intensity values can be calculated using either NOAA Atlas14**Error! Bookmark not defined.** or NRCS Type

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[2] *Steinschneider, S., & Najibi, N. (2022). Observed and Projected Scaling of Daily Extreme Precipitation with Dew Point Temperature at Annual and Seasonal Scales across the Northeastern United States, Journal of Hydrometeorology, 23(3), 403-419.* *https://journals.ametsoc.org/view/journals/hydr/23/3/JHM-D-21-0183.1.xml*

[3] *National Cooperative Highway Research Program, Transportation Research Board. Applying Climate Change Information to Hydrologic and Coastal Design of Transportation Infrastructure Final Report, 2019.* *http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP1561FinalReport.pdf*

C and D[4] or SCS Type III[5] rainfall distribution to estimate hourly/sub-hourly peak intensities and develop the corresponding design storm hyetograph(s).

In the subsections below, we describe the methodologies in Table 1 in more detail and present the projected values associated with them using a long-term weather station near Cambridge, MA. Appendix B provides a detailed comparison of projected total precipitation depths at nine locations spread across the Commonwealth using each of these methodologies.

2.1 Summary of Methodology Developed by Cornell University for EEA's Massachusetts Climate and Hydrologic Risk Project

Cornell University as part of the EEA's Massachusetts Climate and Hydrologic Risk Project developed projected total precipitation depths across the Northeast United States.[6] Version 1.2 of the Tool provides projected total precipitation depths for 24-hr design storms for all projects (regardless of tier).

Using extreme precipitation scaling rates with dew point temperature both in observations across the Northeast United States and for a subset of downscaled CMIP5 projections within the state of MA, Cornell University generated a database of updated IDF curves across different temperature changes. The report from EEA's Massachusetts Climate and Hydrologic Risk Project scales design storms at sub-daily to daily time scales from the NOAA Atlas 14 product at the theoretical (Clausius-Clapeyron) rate of 7% per °C, which is the rate at which the moisture-holding capacity of the atmosphere increases with warming. Based on the target planning horizon and the associated warming for that planning horizon from an ensemble of GCM projections, new climate-change informed IDF curves can be retrieved for any location in the state. As part of EEA's Massachusetts Climate and Hydrologic Risk Project, IDF curves have been generated for each 0.5 °C warming from 0.5 °C to 8 °C for the following:

- Return periods from 1-yr, 2-yr, 5-yr, 10-yr, 25-yr, 50-yr, 100-yr, 200-yr, 500-yr, 1000-yr
- Storm duration from 5-min, 10-min, 15-min, 60-min, 2-hr, 3-hr, 6-hr, 12-hr, 24-hr, 48-hr

Cornell University provided the output data in ASCII format. As part of the Climate Resilience Design Standards Tool, Weston & Sampson clipped the NE data to the MA state boundary and reprojected it to the WGS1984 coordinate system to use the data in Version 1.2 of the Tool.

In addition, Cornell University has also developed statewide climate change projections for different precipitation parameters (e.g., days per year above 2" rainfall, total precipitation, max precipitation and more) and heat (e.g., change in temperature, days above 90°F, cooling degree days, heating degree days and more) using a Stochastic Weather Generator (SWGEN) model. The SWGEN data was developed at the HUC-8 Basin scale[7] to produce annual, winter, spring,

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[4] *Engineering Field Handbook Chapter 2: Estimating Runoff and Peak Discharges: Massachusetts EFH-2 Supplement Number: MA-EFH2. https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1097125.pdf*

[5] *HEC-HMS Technical Reference Manual – SCS Storm; https://www.hec.usace.army.mil/confluence/hmsdocs/hmstrm/precipitation/scs-storm*

[6] *Steinschneider, S., & Najibi, N. (2022). Observed and Projected Scaling of Daily Extreme Precipitation with Dew Point Temperature at Annual and Seasonal Scales across the Northeastern United States, Journal of Hydrometeorology, 23(3), 403-419. https://journals.ametsoc.org/view/journals/hydr/23/3/JHM-D-21-0183.1.xml*

[7] *MassGIS Data: NRCS HUC Basins (8,10,12): https://www.mass.gov/info-details/massgis-data-nrcs-huc-basins-81012*

summer, and fall statistics. The SWGEN was used to further downscale future climate model projections from the Multivariate Adaptive Constructed Analogs (MACA) statistically downscaled product.[8] MACA downscales global climate model (GCM) output from the ensemble of CMIP5 GCMs to higher spatial resolutions while maintaining covariance patterns in multiple variables across space. The SWGEN uses temperature changes from MACA to parameterize a series of weather simulations that capture the behavior of local extreme events. The SWGEN data was developed under both RCP4.5 and RCP8.5 scenarios for the 10th, 50th, and 90th percentiles of MACA-projected temperature increase for different target planning horizons of 2030, 2050, 2070 and 2090. Based on EEA's recommendations and stakeholder input, the RCP8.5 50th percentile scenario was used to look up annual average change in temperature for the recommended planning horizon from the Tool, which in turn is used to select the projected total precipitation depth for 24-hr design storms in the Tool.

The Tool recommends 24-hr duration design storm depths for the 2-yr, 5-yr, 10-yr, 25-yr, 50-yr, 100-yr, and 500-yr return periods. The Tool automatically performs the following processes to look up projected total precipitation depth using EEA's Massachusetts Climate and Hydrologic Risk Project: first annual average temperature change for the project location for the recommended planning horizon is looked up from the SWGEN dataset (for example 8.1°F for Cambridge by 2070 as an example, shown in Figure 2). The SWGEN dataset is in °F whereas the warming scenarios for the IDF curves are in °C (Figure 3). Therefore, the degree warming value from SWGEN data is divided by 1.8 to get the corresponding °C warming (4.5°C for Cambridge in 2070 as an example). For this annual average temperature change, the projected total precipitation depth for the 24-hr design storm for the recommended return period from the Tool is then looked up based on the project location. Using Zonal Statistics as a Table function from ArcGIS, the projected total precipitation depth for 24-hr design storm is calculated for the location for the recommended planning horizon and recommended return period. The project location (Cambridge in this case) is used as the input zone and the 24-hr precipitation projection raster (4.5°C for 2070 24-hr event in this case) is used as the input value raster in the Zonal Statistics function and "Weighted Average" data from the resulting table is used as the final value for projected total precipitation depth for that project location for the recommended return period and planning horizon. A summary of the methodology is presented in a tabular format in Figure 4 below.

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[8] *Abatzoglou, J.T., and Brown, T.J. (2012). A comparison of statistical downscaling methods suited for wildfire applications. International Journal of Climatology, 32, 772-780*

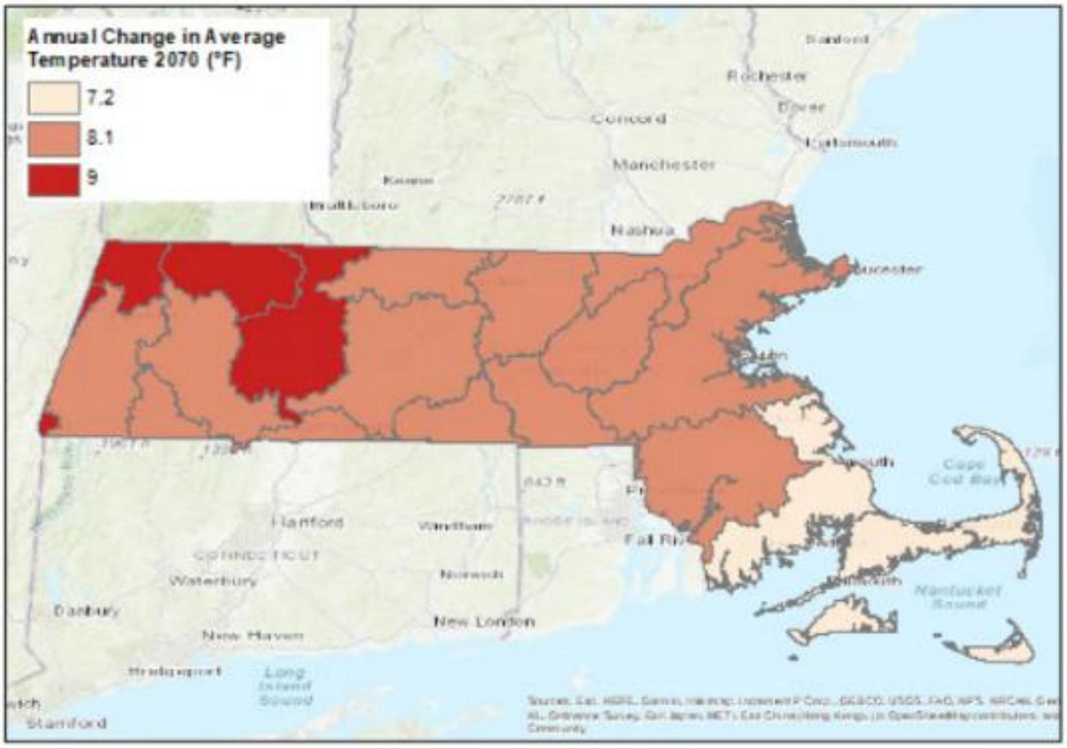

Figure 2. *Annual average temperature change for the State of MA for the 2070 planning horizon using Cornell SWGEN data*[9]

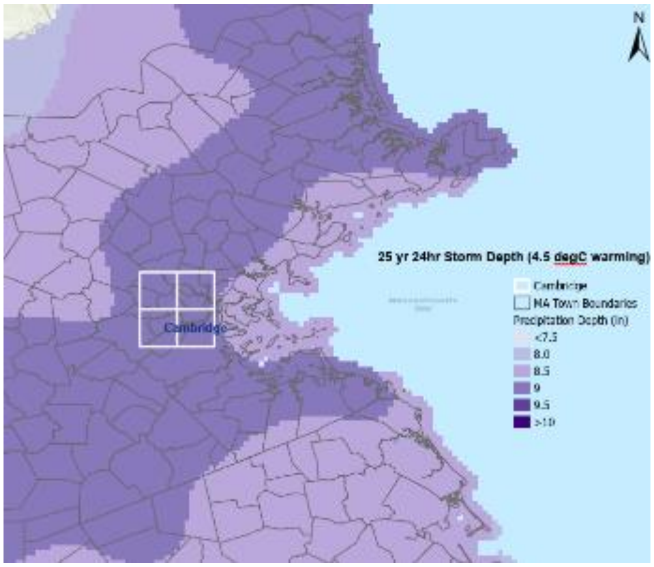

Figure 3. *Map showing the variability of projected total precipitation depth for a 25-yr 24-hr duration design storm under 4.5°C (8.1°F) warming scenario*

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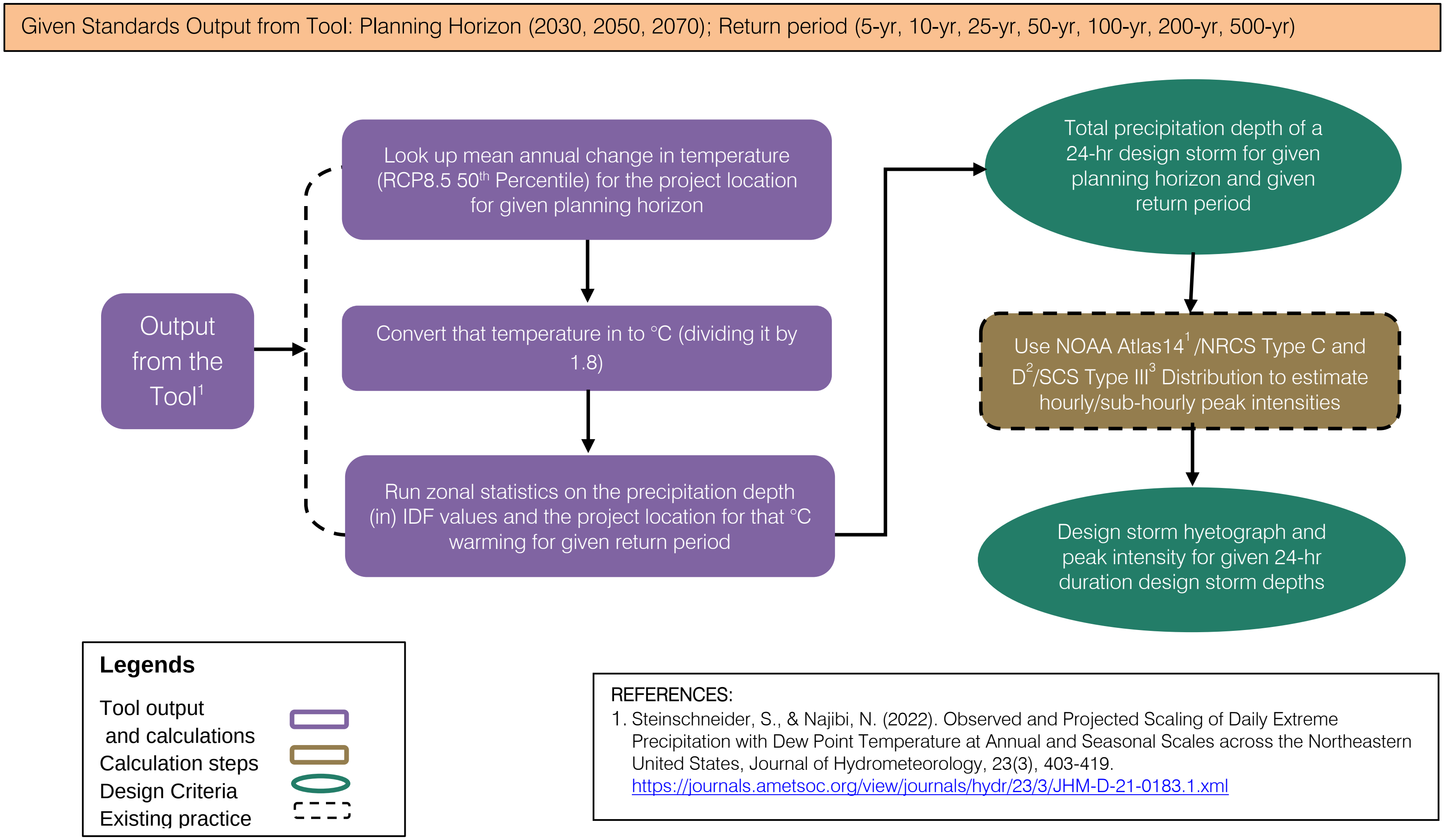
[9] *Steinschneider, S., and Najibi, N. (2022): A weather-regime based stochastic weather generator for climate scenario development across Massachusetts, Technical Documentation, Biological and Environmental Engineering, Cornell University, Ithaca, NY, April 2022. https://www.mass.gov/doc/january-13-2022-presentation-future-climate-projections/download*



REFERENCES:

1. Steinschneider, S., & Najibi, N. (2022). Observed and Projected Scaling of Daily Extreme Precipitation with Dew Point Temperature at Annual and Seasonal Scales across the Northeastern United States, Journal of Hydrometeorology, 23(3), 403-419. https://journals.ametsoc.org/view/journals/hydr/23/3/JHM-D-21-0183.1.xml

Figure 4: *Methodology used in the Climate Resilience Design Standards Tool to output projected total precipitation depth values for 24-hour duration storms for assets across all Tiers. Methodology to calculate projected peak intensity using the projected total precipitation depth is also illustrated.*

2.2 Summary of NOAA+ Methodology

In Version 1.2 of the Tool, all assets receive projected total precipitation depth values for 24-hr design storms from the Tool based on the methodology described above in Section 2.1.1. However, assets with Tier 1 designation[10] are recommended to calculate total precipitation depth using the "NOAA+ methodology" and compare the results with the Tool output.

The NOAA+ methodology includes referring to the 90% upper bound confidence interval values for each given 24-hr duration storm for the project location from the NOAA Atlas 14 website,[11] and applying a factor of 0.9 (90%) to the 90% upper bound confidence interval values for each given 24-hr duration design storm precipitation depth. Since in most cases, assets with Tier 1 designation receive recommended return periods from 2-yr up to 50-yr from the Tool, the comparison of Tool output (using projections from EEA's Climate and Hydrologic Risk Project) with values calculated using the NOAA+ methodology is relevant for only these return periods (more frequent storms). Projected total precipitation depths using the NOAA+ methodology for Cambridge (as an example location) is shown in Table 2 for 24-hour duration storms of different return periods. A summary of the NOAA+ methodology is presented in Figure 5 below.

Table 2: Projected total precipitation depths for 24-hr design storms by 2070 in Cambridge using the NOAA+ methodology

Return period	NOAA Atlas 14 Present Day Baseline Total Precipitation Depth (in)	NOAA 90th Percentile Total Precipitation Depth (in)	Projected Total Precipitation Depth using the NOAA+ methodology (in)
2-yr	3.3	4.0	3.6
5-yr	4.3	5.2	4.7
10-yr	5.2	6.3	5.7
25-yr	6.3	8.2	7.4
50-yr	7.2	9.6	8.6
100-yr	8.2	11.3	10.2
500-yr	11.2	16.3	14.7

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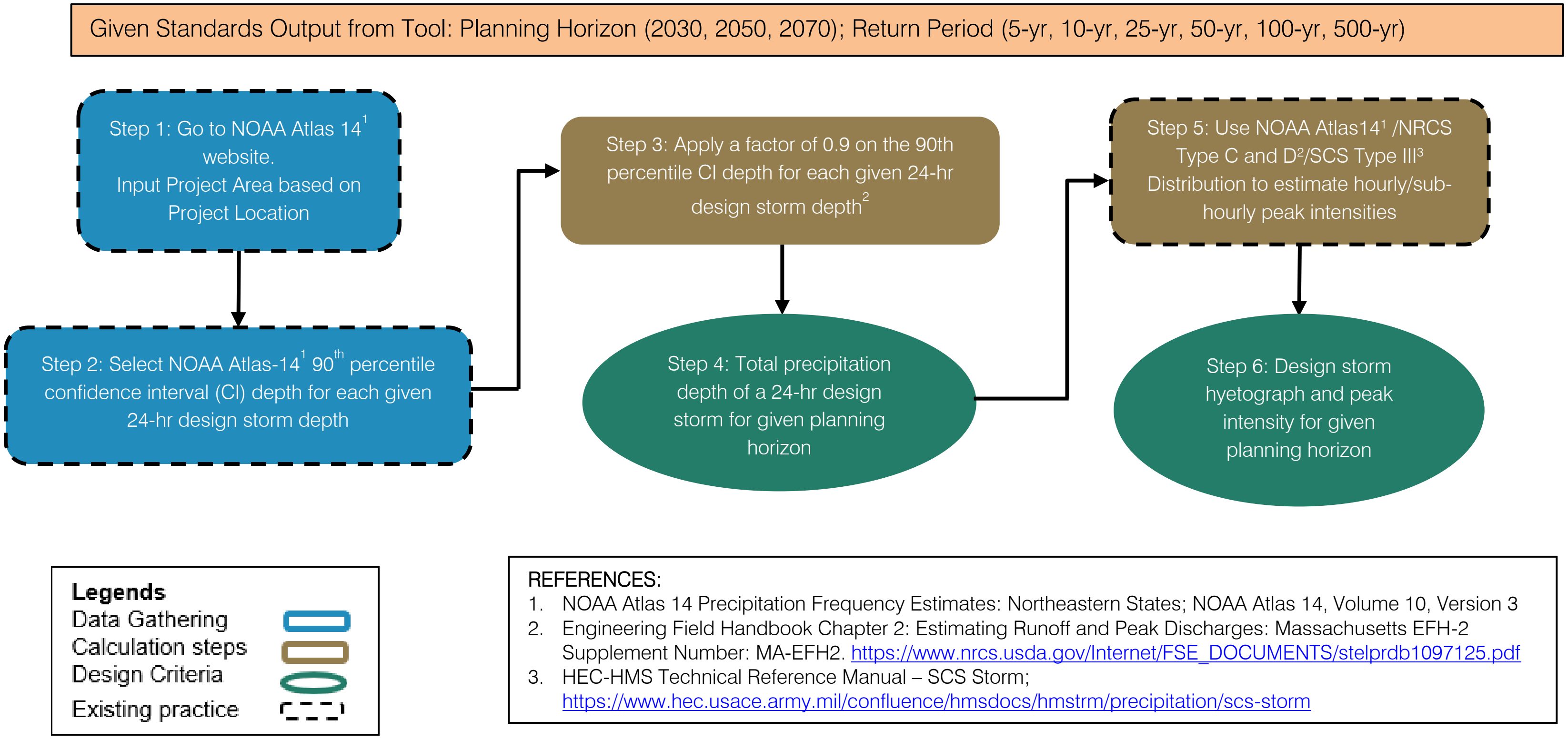
[10] In the Climate Resilience Design Standards Tool, building and infrastructure assets with low and medium criticality and less than 10 years of asset useful life receive Tier 1 designation.

[11] *NOAA Atlas 14 Precipitation Frequency Estimates: Northeastern States; NOAA Atlas 14, Volume 10, Version 3*



REFERENCES:
1. NOAA Atlas 14 Precipitation Frequency Estimates: Northeastern States; NOAA Atlas 14, Volume 10, Version 3
2. Engineering Field Handbook Chapter 2: Estimating Runoff and Peak Discharges: Massachusetts EFH-2 Supplement Number: MA-EFH2. https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1097125.pdf
3. HEC-HMS Technical Reference Manual – SCS Storm; https://www.hec.usace.army.mil/confluence/hmsdocs/hmstrm/precipitation/scs-storm

Figure 5: *NOAA+ methodology to calculate projected total precipitation depth and peak intensity for a 24-hr design storm. This methodology is recommended as comparison with Tool (Version 1.2) output for only assets that received Tier 1 designation*

2.3 Summary of NCHRP15 -61 Methodology

In Version 1.2 of the Tool, all assets receive projected total precipitation depth for 24-hr design storms from the Tool based on the methodology described above in Section 2.1.1. However, for "Dams and Flood Control Structures" infrastructure assets with a Tier 3 designation[12], the Tool recommends using the NCHRP15-61 methodology to calculate the projected total precipitation depth for 24-hr design storms and compare the results with the Tool output. The Tool provides less frequent storms (100-yr and 500-yr) as recommended return periods for Tier 3 Dams and Flood Control Structures asset types based on the relationships presented in the **Supporting Documents: Section 4: Climate Resilience Design Standards.**

The NCHRP15-61 methodology to calculate projected total precipitation depths is based on the report developed as part of the National Cooperative Highway Research Program (NCHRP) Project 15-61 with the final report published in 2019 and titled "Applying Climate Change Information to Hydrologic and Coastal Design of Transportation Infrastructure" (referred to as "NCHRP15-61 Report").[13,14]

This methodology includes downloading daily precipitation projections from the LOCA dataset using 14 Group1 CMIP5 Global Climate Models (GCMs) for the grid(s) corresponding to each project location (Figure 6).[15] The Representative Concentration Pathway (RCP) scenario selected was RCP8.5, the highest greenhouse gas concentration trajectory adopted by the Intergovernmental Panel on Climate Change (IPCC) for its Fifth Assessment Report in 2014. The selection of this RCP 8.5 scenarios was based on guidance from the Commonwealth of Massachusetts. This methodology includes using the downscaled GCM outputs from the LOCA dataset because these were used for the climate change projections published in the 2018 State Hazard Mitigation and Climate Adaptation Plan (SHMCAP) and are the projections that were available on resilientMA.org when the Beta Tool was launched in April 2021. The Group 1 GCMs from the LOCA dataset were recommended since these models are referred in the NCHRP15-61 Report as the "most reliable" models that represent the most recent versions of reliable, very well-documented, long-established GCMs from modeling groups that have worked in climate modeling for decades. The Tiered Methodology PDF provided through the Tool provides steps for users to calculate site-specific projected total precipitation depths using the guidance from the NCHRP15-61 methodology.

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[12] *In the Climate Resilience Design Standards Tool, building and infrastructure assets with medium criticality and more than 50 years of asset useful life and building and infrastructure assets with high criticality and more than 10 years of useful life receive the Tier 3 designation.*

[13] *National Cooperative Highway Research Program, Transportation Research Board. Applying Climate Change Information to Hydrologic and Coastal Design of Transportation Infrastructure Final Report, 2019.* *http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP1561FinalReport.pdf*

[14] *The details of how the methodology can be applied to calculate projected total precipitation depth for 24-hour design storms for assets in the Tool was presented to and reviewed by the project team and leading academic and scientific experts from different universities in the Northeast, including Dr. Jennifer Jacobs (University of New Hampshire), Dr. Ellen Douglas (University of Massachusetts, Boston), Dr. Scott Steinschneider (Cornell University) and Dr. Jonathan Lamontagne (Tufts University). Both Dr. Jacobs and Dr. Douglas are co-authors of the NCHRP15-61 Report and reviewed the proposed NCHRP15-61 methodology recommended from the Tool so that it follows NCHRP15-61 guidelines.*

[15] *Pierce, D.W., D.R. Cayan, and B.L. Thrasher, Statistical Downscaling Using Localized Constructed Analogs (LOCA). Journal of Hydrometeorology, 2014. 15(6): p. 2558-2585*

2.3.1 Example of using NCHRP15-61 Methodology for Location in Cambridge, MA

Daily rainfall projections from 14 GCMs from the LOCA dataset were downloaded for at least three (3) grids for each location per NCHRP15-61 guidance so that a single grid is not an outlier. Grids whose area consists of more than one third water should be avoided so that precipitation projections represent land rather than water. Precipitation data were downloaded for historical (1976-2005), 2030, 2050, and 2070 planning horizons with a 30-yr averaging period around each planning horizon. Annual maximum rainfall for each year in the 30-yr averaging period were obtained for each grid and GCM combination. The Generalized Extreme Value (GEV) distribution was applied to the annual maxima to calculate modeled baseline and modeled future projections for each planning horizon and return period separately for grid and GCM combinations.

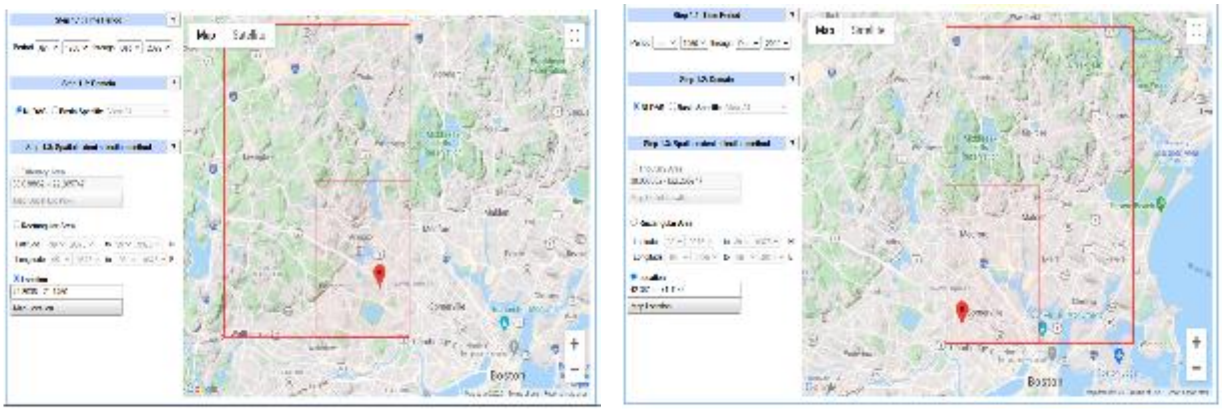

Figure 6. *Example of downloaded grids for Cambridge, MA from LOCA website*

Future projected total precipitation depth values were calculated for 2-, 5-, 10-, 25-, 50-, 100-, and 500-yr return periods for grid and GCM combination for each planning horizon. Daily design storm depths were converted to 24-hour design storm depths by multiplying by a factor of 1.11 based on NOAA guidance.[16]

Percent increase values between the modeled baseline and modeled future projected total precipitation depths were calculated for each planning horizon and return period for each grid and GCM combination. The average of percent increases for all GCMs were calculated for each grid and were then applied to NOAA Atlas 14 median values for each return period to estimate the projected total precipitation depths for 24-hr design storms for each planning horizon per grid. The average of the projected precipitation depths for 24-hr design storms for all grids were taken to estimate the projected total precipitation depth for each location. NOAA Atlas 14 historical estimates were compared with the projected total precipitation quantiles for each period, for each location, and for all return periods, which served as a comparison between historical uncertainty and projected uncertainty from climate change.

Projected total precipitation depths using the NCHRP15-61 methodology for Cambridge (as an example location) is shown in Table 3 for 24-hour duration storms with a range of return periods. A summary of the NCRP 15-61 methodology is presented in Figure 7 below.

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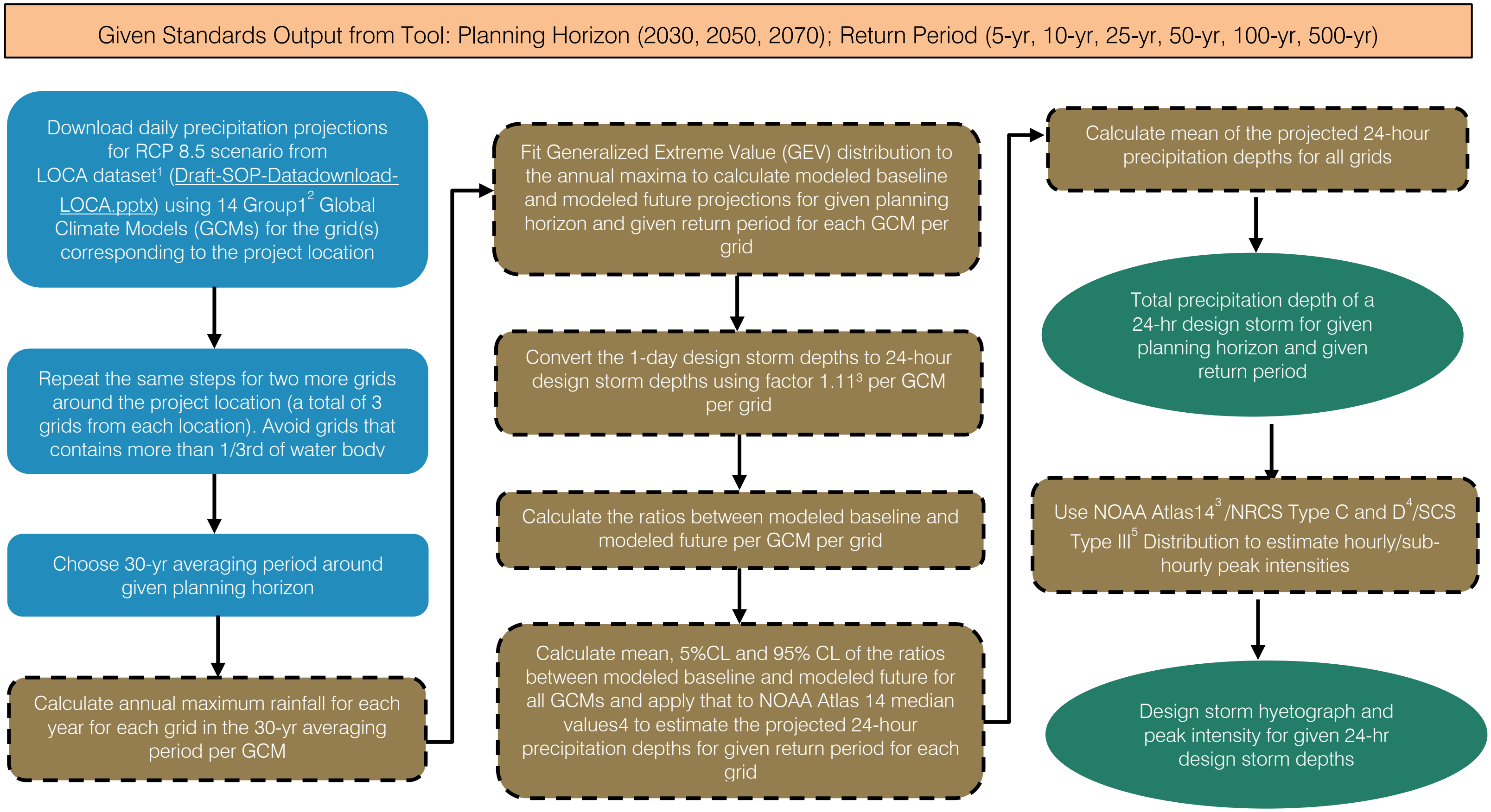
[16] *NOAA Atlas 14 Precipitation Frequency Estimates: Northeastern States; NOAA Atlas 14, Volume 10, Version 3*

Table 3: Projected total precipitation depths for 24-hr design storms by 2070 in Cambridge following the NCHRP15-61 methodology as compared to NOAA Atlas 14

Return period	NOAA Atlas 14 Present Day Baseline (in)	Projected Total Precipitation Depth by 2070 using the NCHRP15-61 methodology (in)
2-yr	3.3	3.8
5-yr	4.3	5.1
10-yr	5.2	6.3
25-yr	6.3	8.0
50-yr	7.2	9.4
100-yr	8.2	11.1
500-yr	11.2	17.8



Given Standards Output from Tool: Planning Horizon (2030, 2050, 2070); Return Period (5-yr, 10-yr, 25-yr, 50-yr, 100-yr, 500-yr)

Download daily precipitation projections for RCP 8.5 scenario from LOCA dataset[1] (Draft-SOP-Datadownload-LOCA.pptx) using 14 Group1[2] Global Climate Models (GCMs) for the grid(s) corresponding to the project location

Repeat the same steps for two more grids around the project location (a total of 3 grids from each location). Avoid grids that contains more than 1/3rd of water body

Choose 30-yr averaging period around given planning horizon

Calculate annual maximum rainfall for each year for each grid in the 30-yr averaging period per GCM

Fit Generalized Extreme Value (GEV) distribution to the annual maxima to calculate modeled baseline and modeled future projections for given planning horizon and given return period for each GCM per grid

Convert the 1-day design storm depths to 24-hour design storm depths using factor 1.11[3] per GCM per grid

Calculate the ratios between modeled baseline and modeled future per GCM per grid

Calculate mean, 5%CL and 95% CL of the ratios between modeled baseline and modeled future for all GCMs and apply that to NOAA Atlas 14 median values4 to estimate the projected 24-hour precipitation depths for given return period for each grid

Calculate mean of the projected 24-hour precipitation depths for all grids

Total precipitation depth of a 24-hr design storm for given planning horizon and given return period

Use NOAA Atlas14[3] /NRCS Type C and D[4]/SCS Type III[5] Distribution to estimate hourly/sub-hourly peak intensities

Design storm hyetograph and peak intensity for given 24-hr design storm depths

Legends
Data Gathering ▭
Calculation steps ▭
Design Criteria ⬭
Existing practice ⌷

REFERENCES:
1. Pierce, D.W., D.R. Cayan, and B.L. Thrasher, Statistical Downscaling Using Localized Constructed Analogs (LOCA). Journal of Hydrometeorology, 2014. 15(6): p. 2558-2585
2. Applying Climate Change Information to Hydrologic and Coastal Design of Transportation Infrastructure (NCHRP Project 15-61- Final Report) by Kilgore et al., 2019
3. NOAA Atlas 14 Precipitation Frequency Estimates: Northeastern States; NOAA Atlas 14, Volume 10, Version 3
4. Engineering Field Handbook Chapter 2: Estimating Runoff and Peak Discharges: Massachusetts EFH-2 Supplement Number: MA-EFH2. https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1097125.pdf
5. HEC-HMS Technical Reference Manual – SCS Storm; https://www.hec.usace.army.mil/confluence/hmsdocs/hmstrm/precipitation/scs-storm

Figure 7: *NCHRP15-61 methodology to calculate projected total precipitation depth and peak intensity for a 24-hr Design Storm. This methodology is recommended as comparison with Tool output for only Dams and Flood Control Structures asset type that receive Tier 3 designation.*

2.4 Summary of Regionalized Percent Increase Methodology

Note: This methodology is no longer referenced in the Tool, but it was referenced in the Beta version (from April 2021 to release of Version 1.1 – April 2022). The summary of this methodology and comparison is included in this technical report as Appendix A for users that used the Tool before April 2022 that may have referenced this methodology for projects previously entered.

3 SUMMARY OF FINDINGS

Projected total precipitation depths for 24-hour design storms using the different methodologies presented in Section 2 were compared for the same nine locations across the State (Newburyport, Boston, Cambridge, and Kingston, Worcester, Pittsfield, Westfield, Springfield, and Amherst).

The Tool recommends comparing the Tool output (using precipitation projections developed by EEA's Massachusetts Climate and Hydrologic Risk Project) with values calculated using

- the NOAA+ methodology for assets that receive Tier 1 designation. Recommended return periods from the Tool for Tier 1 assets could vary from 2-yr up to 50-yr (as presented in **Supporting Documents: Section 4: Climate Resilience Design Standards**). Therefore, the comparative analysis between precipitation projections developed by Cornell University for EEA's Massachusetts Climate and Hydrologic Risk Project and those using the NOAA+ methodology focuses on more frequent storms (2-yr, 5-yr, 10-yr, 25-yr, and 50-yr return periods). The summary of this comparison is presented in Table 4, below.

- the NCHRP15-61 methodology for Dams and Flood Control Structure asset types that receive Tier 3 designation. Recommended return periods from the Tool for Dams and Flood Control Structures asset type with Tier 3 designation are either 100-yr or 500-yr (as presented in **Supporting Documents: Section 4: Climate Resilience Design Standards**). Therefore, the comparative analysis between precipitation projections developed by Cornell University for EEA's Massachusetts Climate and Hydrologic Risk Project and those using the NCHRP 15-61 methodology focuses on less frequent storms (100-yr and 500-yr return periods). The summary of this comparison is presented in Table 5, below.

For more information related to the comparisons across the nine locations and calculated projected values, please refer to the tables and plots compiled in Appendix B.

Table 4: Comparison of precipitation projections developed by Cornell University for EEA's Massachusetts Climate and Hydrologic Risk Project with values calculated using the NOAA+ methodology at nine long-term weather stations

Planning Horizon	Return Period	Precipitation projections developed by Cornell University for EEA's Massachusetts Climate and Hydrologic Risk Project are		
		similar (within ±5%) to NOAA +	higher than NOAA+	lower than NOAA+
2030	2-yr	Cambridge, Newburyport, Kingston, Westfield, Springfield	Boston, Pittsfield, Worcester, Amherst (up to 10% higher)	No locations
	5-yr	Cambridge, Newburyport, Kingston, Amherst, Worcester, Westfield, Springfield	Boston, Pittsfield (up to 10% higher)	No locations
	10-yr, 25-yr	Boston, Cambridge, Newburyport, Kingston, Worcester, Pittsfield Amherst, Westfield, Springfield	No locations	No locations
	50-yr	Boston, Cambridge, Newburyport, Kingston, Worcester, Pittsfield	No locations	Amherst, Westfield, Springfield (up to 10% lower)
2050	2-yr, 5-yr, 10-yr	No locations	Boston, Cambridge, Newburyport, Kingston, Worcester, Pittsfield Amherst, Westfield, Springfield (up to 15% higher)	No locations
	25-yr	Cambridge, Pittsfield, Westfield, Springfield	Boston, Newburyport, Kingston, Worcester, Amherst (up to 10% higher)	No locations
	50-yr	Boston, Cambridge, Worcester, Pittsfield, Amherst, Westfield, Springfield	Newburyport, Kingston (up to 10% higher)	No locations
2070	2-yr, 5-yr, 10-yr, 25-yr, 50-yr	No locations	Boston, Cambridge, Newburyport, Kingston, Worcester, Pittsfield Amherst, Westfield, and Springfield (up to 25% higher)	No locations

Table 5: Comparison of precipitation projections developed by Cornell University for EEA's Massachusetts Climate and Hydrologic Risk Project with values calculated using NCHRP 15-61 methodology at nine long-term weather stations

Planning Horizon	Return Period	Precipitation projections developed by Cornell University for EEA's Massachusetts Climate and Hydrologic Risk Project are		
		similar (within ±5%) to NCHRP 15-61	higher than NCHRP 15-61	lower than NCHRP 15-61
2030	100-yr	Boston, Cambridge, Amherst, Westfield	Newburyport, Kingston, Worcester, Pittsfield (up to 15% higher)	Springfield (up to 10% lower)
	500-yr	Cambridge, Amherst	Newburyport, Kingston, Worcester, Pittsfield (up to 15% higher)	Boston (~6% lower), Westfield, Springfield (up to 30% lower)
2050	100-yr	Cambridge	Newburyport, Kingston, Worcester, Pittsfield, Amherst (up to 20% higher)	Boston (~7% lower), Westfield, Springfield (up to 20% lower)
	500-yr	Kingston, Worcester, Amherst	Newburyport, and Pittsfield (up to 20% higher)	Boston, Cambridge (up to 20% lower), Westfield, Springfield (up to 50% lower)
2070	100-yr	Boston, Cambridge, Worcester, Amherst	Newburyport, Kingston, Pittsfield (up to 25% higher)	Westfield, Springfield (up to 55% lower)
	500-yr	No locations	Newburyport, Kingston, Pittsfield (up to 25% higher)	Boston, Cambridge, Worcester, Amherst (up to 20% lower), Westfield, Springfield (>100% lower)

4 CONCLUSIONS

In general, across the comparative methodologies, future precipitation values are expected to increase over time. There are locations, planning horizons, and return periods that have notable differences among the methods as presented herein. The precipitation projections for 24-hr design storm depths developed by Cornell University for EEA's Massachusetts Climate and Hydrologic Risk Project are provided for all assets entered into the Tool, but actual climate conditions will vary and may be more or less extreme than the projections provided through the Tool and comparative methodologies summarized in this report. Users are encouraged to use the recommendations and projected values provided through the Tool as a basis-of-discussion for planning, early design, and evaluation of projects, and (if applicable) evaluate how the projected values estimated using the comparative recommended methodologies may impact design and performance over the useful life of the asset.

5 LIMITATIONS

No new climate projections have been developed as part of the Climate Resilience Design Standards Tool (the Tool). The climate projections and methodologies to establish projected values referenced in this report are based on best available climate science data and published literature available for the Commonwealth of Massachusetts at this time. The integration of precipitation projections developed as part of EEA's Massachusetts Climate and Hydrologic Risk Project by Cornell University into the Tool is at the direction of EEA to provide a consistent basis-of-discussion and reference point for various projects across the Commonwealth. The climate projections provided by others and underlying assumptions and uncertainties have not been independently reviewed by the project team developing the Tool. The limitations provided in the cited literature by others also apply to this technical report and the Tool.

Actual climate conditions will vary and may be more or less extreme than the projections provided through the Tool and comparative methodologies summarized in this report. The Commonwealth of Massachusetts plans to update their climate projections every five years through the State Hazard Mitigation and Climate Adaptation Plan process. Therefore, the recommended methodologies and/or projected total precipitation depth for 24-hour design storms may change based on future updates.

While total precipitation depth and peak intensity for 24-hour design storms are useful to inform planning and design, it is recommended to also consider additional longer- and shorter-duration precipitation events and intensities in accordance with best practices. Longer-duration, lower-intensity storms allow time for infiltration and reduce the load on infrastructure over the duration of the storm. Shorter-duration, higher-intensity storms often have higher runoff volumes because the water does not have enough time to infiltrate infrastructure systems (e.g., catch basins) and may overflow or back up during such storms, resulting in flooding. In the Northeast short-duration high intensity rain events are becoming more frequent, and there is often little early warning for these events, making it difficult to plan operationally. While the Tool does not provide recommended design standards for these scenarios, users should still consider both short- and long-duration precipitation events and how they may impact planning and design. In addition, with more frequent storms, antecedent soil moisture (ASM) may be higher than historically, leading to great impact by a storm that was modeled individually without the consideration of ASM.

The information and conclusions presented within this report are not intended as final opinions and should continue to be vetted with experts in the field, with updated climate projections, and with regulatory requirements. Within the limitations of scope, schedule, and budget, our services have been executed in accordance with the generally accepted practices in this area at the time this report was prepared. No warranty, expressed or implied, is given.

6 APPENDICIES

6.1 Appendix A. Summary of Regionalized Percent Increase Methodology

6.2 Appendix B. Comparative Methodology Projected Value Tables and Plots

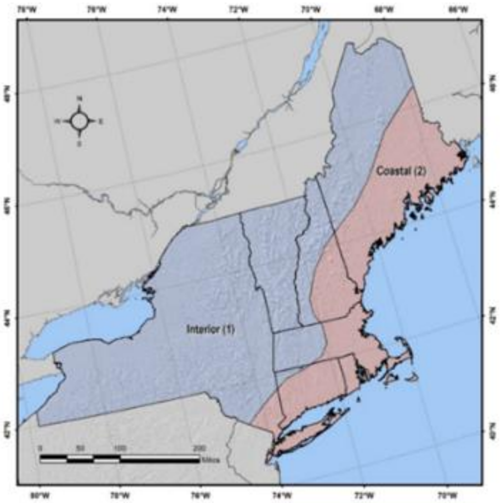
APPENDIX A. SUMMARY OF REGIONALIZED PERCENT INCREASE METHODOLOGY

Note: This methodology is no longer referenced in the Tool, but it was referenced in the Beta version (from April 2021 to release of Version 1.1 – April 2022). The summary of this methodology and comparison is included in this technical report for users that used the Tool before April 2022 that may have referenced this methodology for projects previously entered.

Prior to the availability of the projections developed through the methodology described above in Section 2.1.1, assets with a Tier 2 designation would receive a recommendation to use a regionalized percent increase methodology that was developed for the Climate Resilience Design Standards Tool.

The regionalized percent increase methodology is an extension of the NCHRP15-61 methodology described above in Section 2.1.4. Nine (9) long-term weather stations across Massachusetts were selected to establish regionalized percent increases. The stations selected include locations in each of the two (2) NOAA Climate Regions (Coastal and Interior), as delineated in NOAA Atlas 14 Volume 10, shown in Figure A-1 below. Figure A-2 shows the locations of the nine long-term weather stations.

- Four (4) locations from Coastal MA (Newburyport, Boston, Cambridge, and Kingston),
- Five (5) locations from Interior MA (Worcester, Pittsfield, Westfield, Springfield, and Amherst)



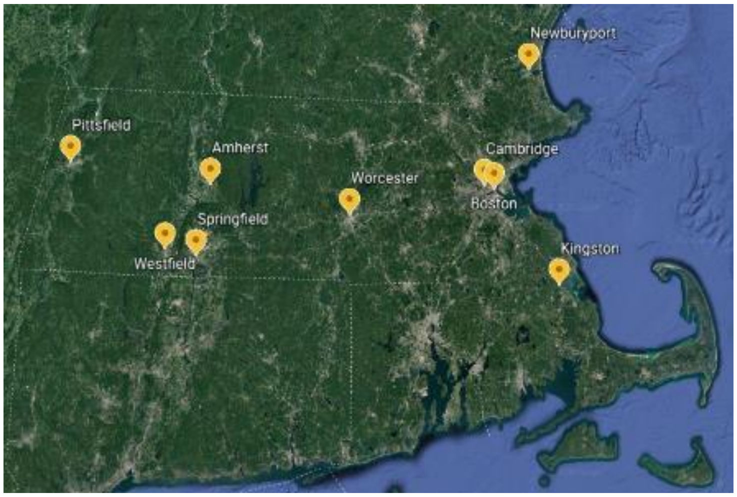


Figure A-1. *(left) Climate regions delineated for NOAA Atlas 14 Volume 10.*[17]
Figure A-2. *(right**)** Nine selected locations to establish regionalized percent increases for RMAT*

Percent increases were calculated between the projected total precipitation depths using the NCHRP15-61 methodology and NOAA historical estimates (using both mean and 90 percent confidence interval values) for 24-hr design storms, for each of the nine locations, for more frequent return periods (2-yr, 5-yr, 10-yr, 25-yr, 50-yr), for the 100-yr storm, and for extreme return periods (200-yr, 500-yr), by near to mid-century (2030/2050) and late century (2070/2090). These percent increases across the nine locations were averaged and binned by planning horizon

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[17] *NOAA Atlas 14 Volume 10; https://www.nws.noaa.gov/oh/hdsc/PF_documents/Atlas14_Volume10.pdf*

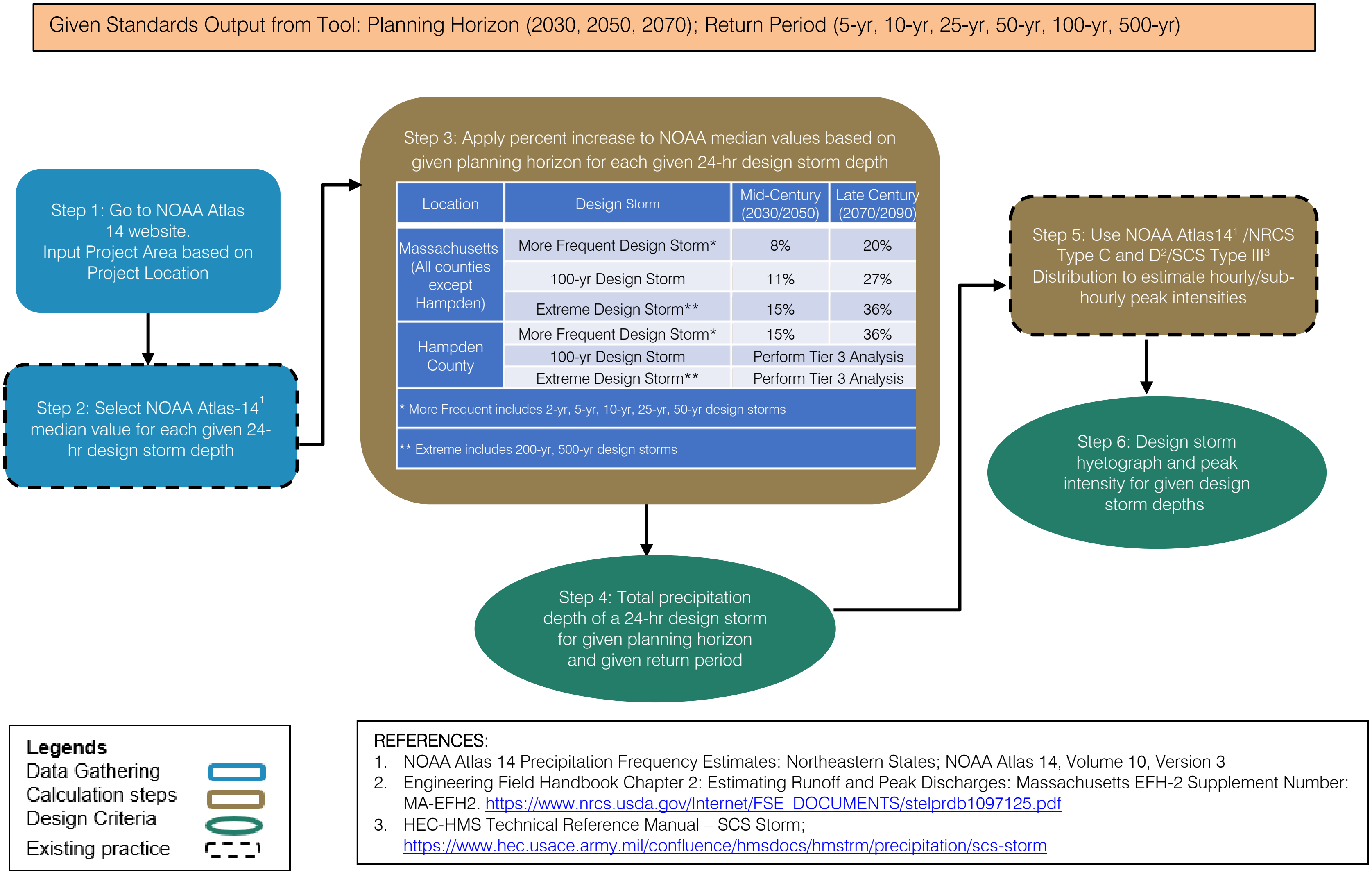
(mid/late century) and design storm return period to estimate the regionalized percent increases across Commonwealth, with input from State Agency stakeholders. A summary of regionalized percent increase methodology is presented in Figure A-3 below.

Analysis of historic and future projections of total precipitation depth for Hampden County (Springfield and Westfield locations) yielded higher percent increases than observed in the other seven locations. A review of projected increases in Amherst provided a better understanding of the spatial extent of these abnormally high projections. The results indicated that percent increases observed in Hampden County were not applicable for the rest of the Connecticut River Valley Region outside of Hampden County. It was therefore decided by stakeholders to recommend that projects located in Hampden County use different percent increases than those recommended for the rest of Massachusetts for more frequent return periods (2-yr, 5-yr, 10-yr, 25-yr, 50-yr), and perform a site-specific analysis following NCHRP15-61 methodology for assets that have 100-yr, 200-yr, and 500-yr return periods recommended through the Tool.

It is important to note that the projections developed by Cornell University as part of the EEA's Massachusetts Climate and Hydrologic Risk Project uses a uniform 7% increase statewide, and thus do not provide higher values for projected total precipitation depth in Hampden County.

Table A-1: Projected total precipitation depths for 24-hr design storms by late century (2070/2090) in Cambridge using the regionalized percent increase methodology as compared to NOAA Atlas 14

Return period	NOAA Atlas 14 Present Day Baseline (in)	Projected Total Precipitation Depth using the Regionalized Percent Increase Methodology (in)
2-yr	3.3	4.0
5-yr	4.3	5.2
10-yr	5.2	6.2
25-yr	6.3	7.6
50-yr	7.2	8.6
100-yr	8.2	10.4
500-yr	11.2	15.2



Given Standards Output from Tool: Planning Horizon (2030, 2050, 2070); Return Period (5-yr, 10-yr, 25-yr, 50-yr, 100-yr, 500-yr)

Step 1: Go to NOAA Atlas 14 website.
Input Project Area based on Project Location

Step 2: Select NOAA Atlas-14[1] median value for each given 24-hr design storm depth

Step 3: Apply percent increase to NOAA median values based on given planning horizon for each given 24-hr design storm depth

Location	Design Storm	Mid-Century (2030/2050)	Late Century (2070/2090)
Massachusetts (All counties except Hampden)	More Frequent Design Storm*	8%	20%
	100-yr Design Storm	11%	27%
	Extreme Design Storm**	15%	36%
Hampden County	More Frequent Design Storm*	15%	36%
	100-yr Design Storm	Perform Tier 3 Analysis	
	Extreme Design Storm**	Perform Tier 3 Analysis	
* More Frequent includes 2-yr, 5-yr, 10-yr, 25-yr, 50-yr design storms			
** Extreme includes 200-yr, 500-yr design storms			

Step 4: Total precipitation depth of a 24-hr design storm for given planning horizon and given return period

Step 5: Use NOAA Atlas14[1] /NRCS Type C and D[2]/SCS Type III[3] Distribution to estimate hourly/sub-hourly peak intensities

Step 6: Design storm hyetograph and peak intensity for given design storm depths

Legends
Data Gathering 🟦
Calculation steps 🟫
Design Criteria ⬭
Existing practice ⬚

REFERENCES:

1. NOAA Atlas 14 Precipitation Frequency Estimates: Northeastern States; NOAA Atlas 14, Volume 10, Version 3
2. Engineering Field Handbook Chapter 2: Estimating Runoff and Peak Discharges: Massachusetts EFH-2 Supplement Number: MA-EFH2. https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1097125.pdf
3. HEC-HMS Technical Reference Manual – SCS Storm; https://www.hec.usace.army.mil/confluence/hmsdocs/hmstrm/precipitation/scs-storm

***Figure A-3:** Regionalized percent increase methodology to assess projected total precipitation depth and peak intensity for 24-hr design storms (used past versions of the Tool (April 2021 – April 2022)*

APPENDIX B. COMPARATIVE METHODOLOGY PROJECTED VALUE TABLES AND PLOTS

Projected total precipitation depths for 24-hour design storms using the different methodologies presented in this report were compared for the same nine locations across the State (Newburyport, Boston, Cambridge, and Kingston, Worcester, Pittsfield, Westfield, Springfield, and Amherst).

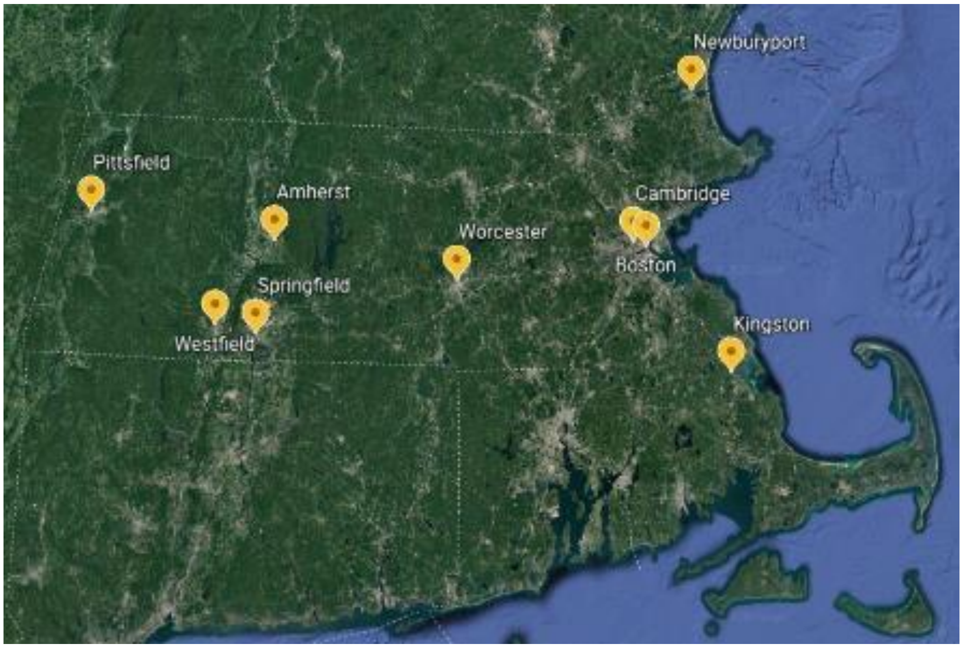


Figure B-1. *Nine locations where comparative analyses performed*

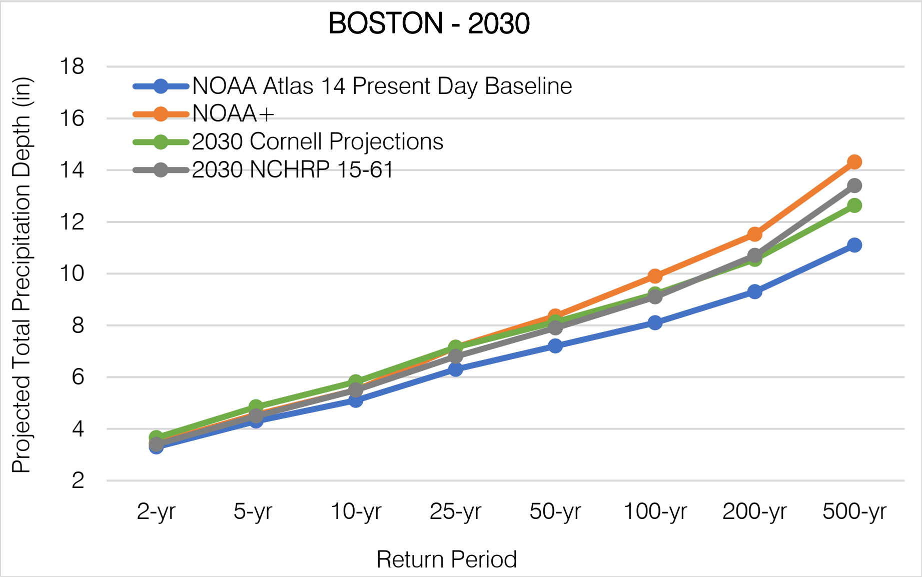
The projected values are shown for all return periods and all methodologies currently within the Tool Version 1.2 for each location, but the Tool recommends comparing the Tool output (using precipitation projections developed by EEA's Massachusetts Climate and Hydrologic Risk Project) with

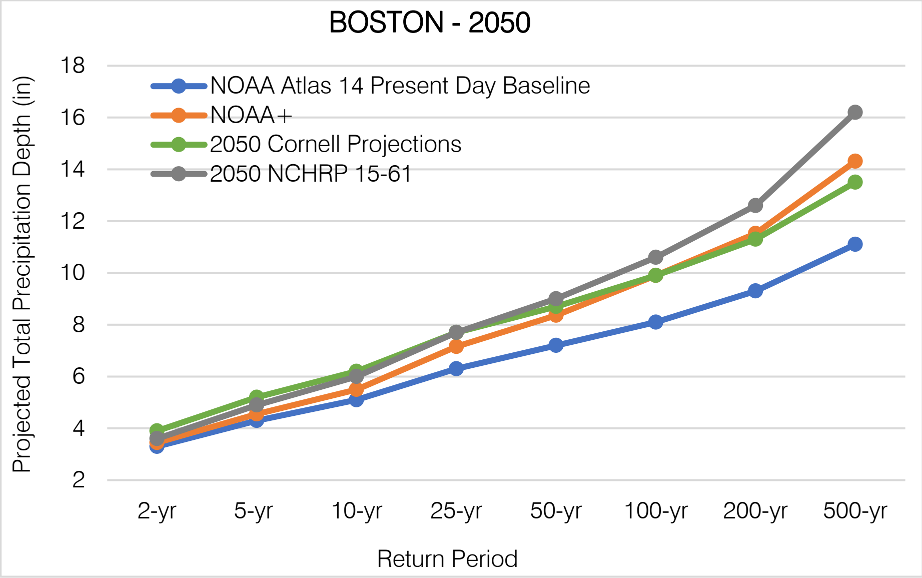
- values calculated using the NOAA+ methodology for assets that receive Tier 1 designation, so the comparison focuses on more frequent storms (2-yr, 5-yr, 10-yr, 25-yr, and 50-yr return periods).

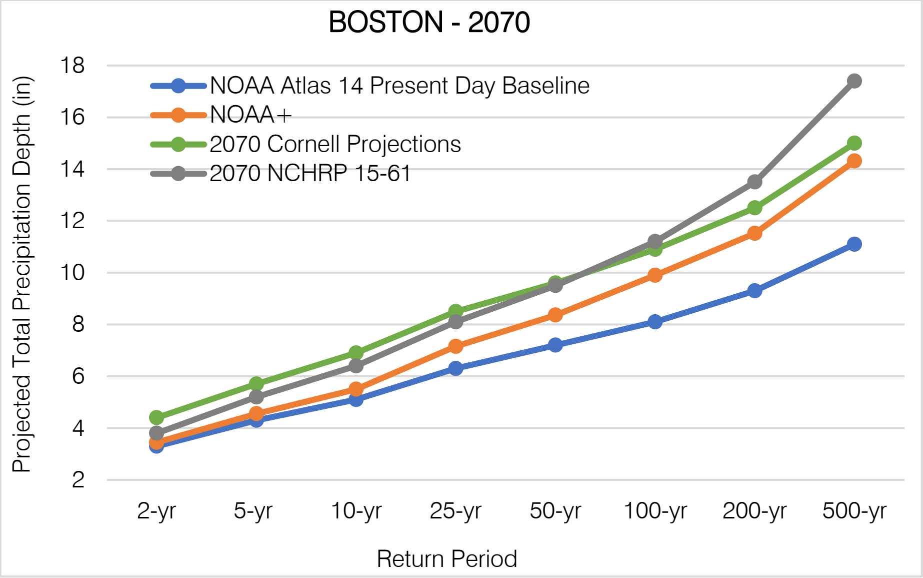
- values calculated using the NCHRP15-61 methodology for Dams and Flood Control Structure asset types that receive Tier 3 designation, so the comparison focuses on less frequent storms (100-yr and 500-yr return periods).

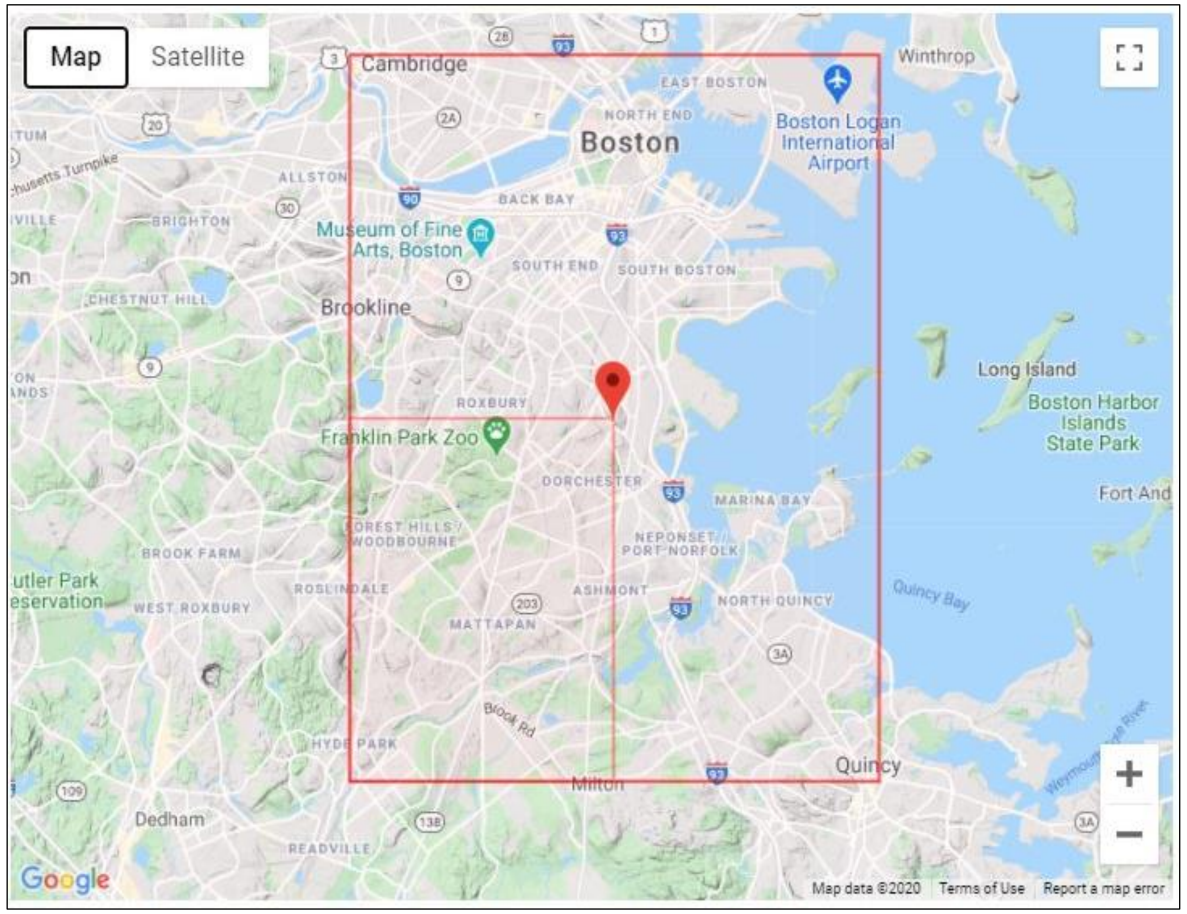
Therefore, for the following tables shown for each location, there are **grayed cells for values that should not be compared** given that the Tool will not recommend this comparative analysis.

Boston









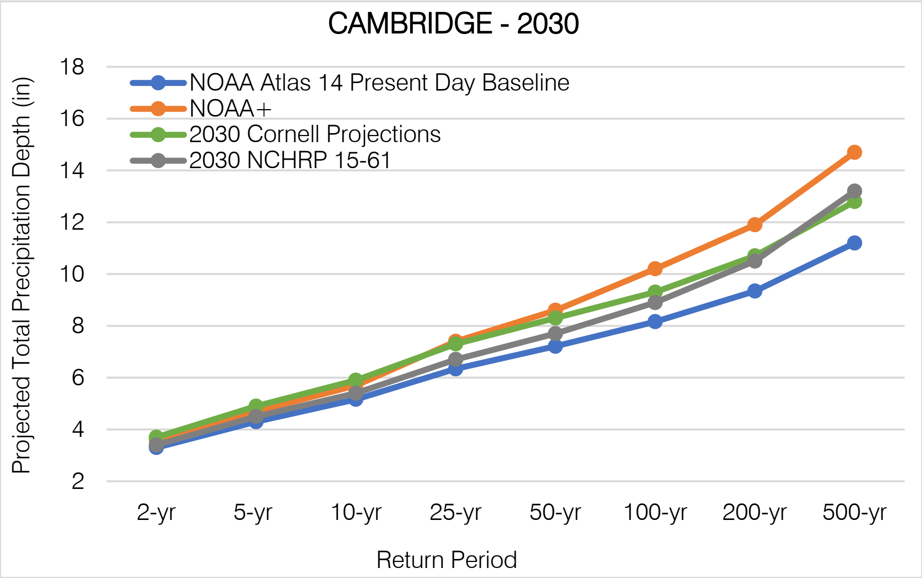
BOSTON (Location: Moakley Park)
Projected Total Precipitation Depths for 24-hr Design Storms (inches)

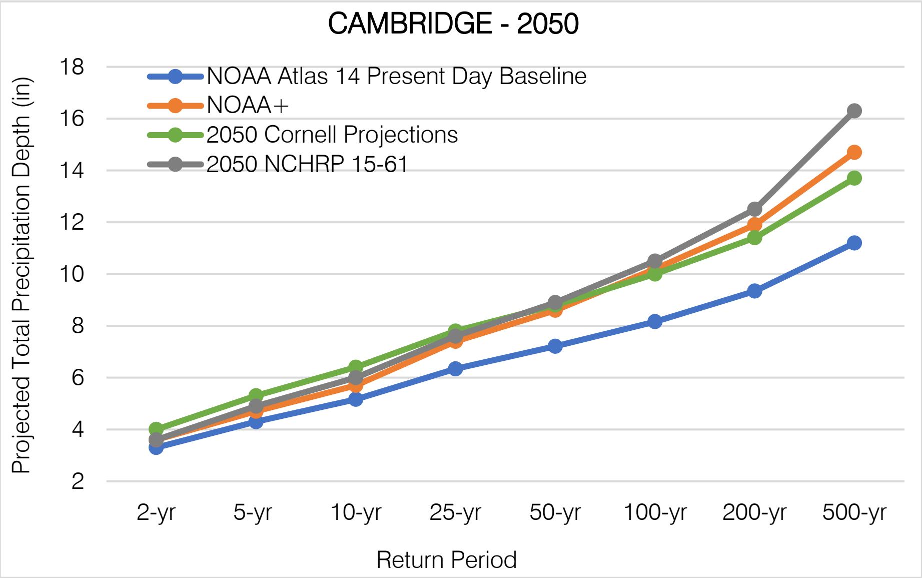
Return Period[4]	Potential Tier Designation for Assets from the Tool	NOAA Atlas 14 Present Day Baseline[1]	NOAA+[2]	2030 Cornell Projections	2030 NCHRP 15-61[3]	2050 Cornell Projections	2050 NCHRP 15-61[3]	2070 Cornell Projections	2070 NCHRP 15-61[3]
2-yr	Tier 1	3.3	3.4	3.7	3.4	3.9	3.6	4.4	3.8
5-yr	Tier 1	4.3	4.6	4.9	4.5	5.2	4.9	5.7	5.2
10-yr	Tier 1/Tier 2	5.1	5.5	5.8	5.5	6.2	6.0	6.9	6.4
25-yr	Tier 1/Tier 2/Tier 3	6.3	7.2	7.2	6.8	7.7	7.7	8.5	8.1
50-yr	Tier 1/Tier 2/Tier 3	7.2	8.4	8.1	7.9	8.7	9.0	9.6	9.5
100-yr	Tier 2/Tier 3	8.1	9.9	9.2	9.1	9.9	10.6	10.9	11.2
500-yr	Tier 3	11.1	14.3	12.6	13.4	13.5	16.2	15.0	17.4

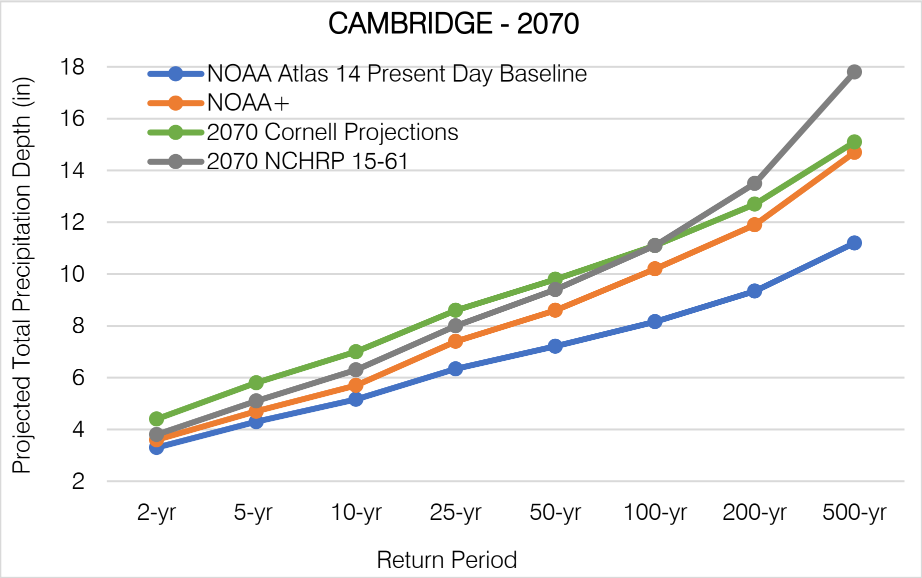
1. Baseline: Median values from NOAA Atlas14 total precipitation depth
2. NOAA+: 90% of the upper bound of the 90% Confidence Interval of NOAA Atlas 14 total precipitation depth; for Tier 1 projects only
3. NCHRP 15-61: Site specific analysis for dams and flood control structures; For Tier 3 projects only

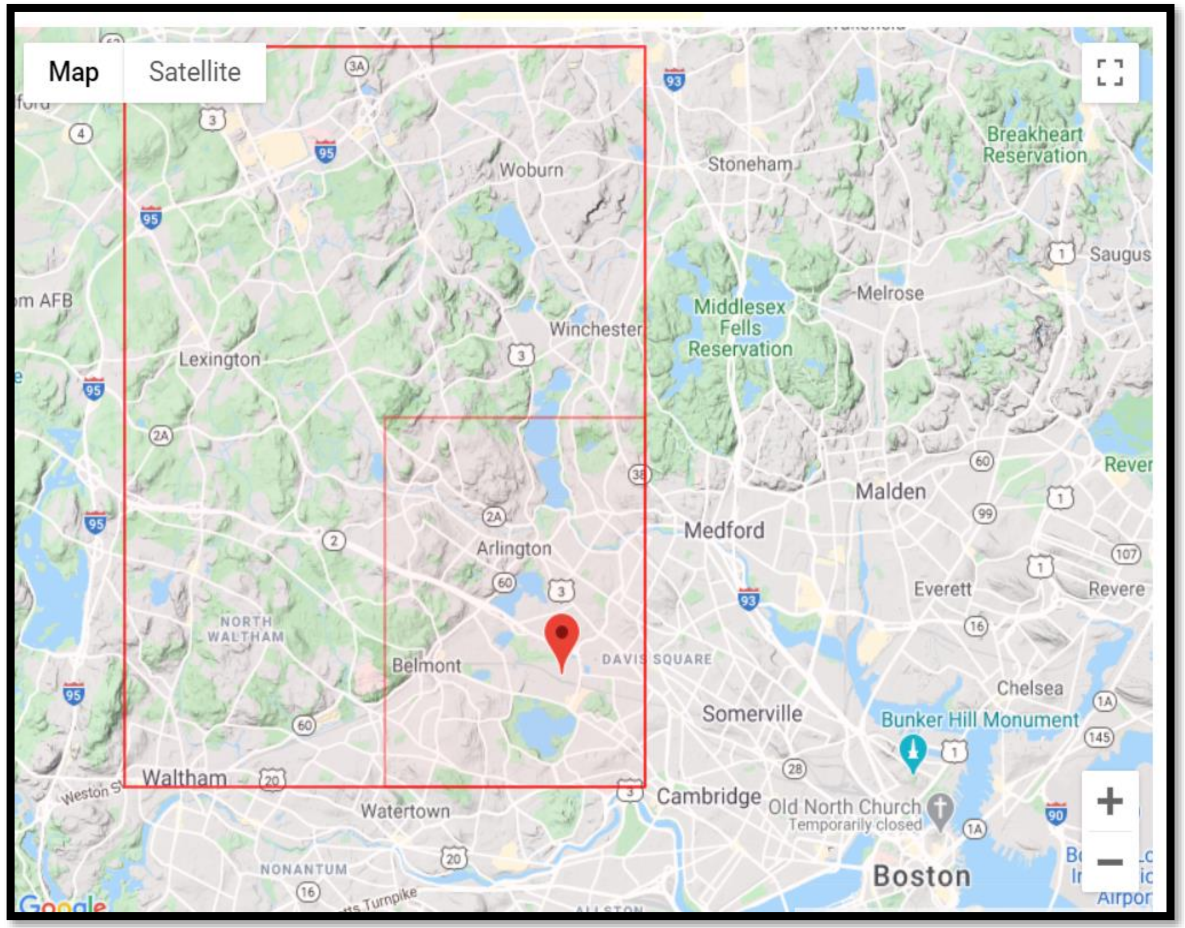
▨	The Tool (V1.2) does not give the highlighted return periods for any asset that receives a Tier 1 designation and/or a “Dams and Flood Control Structures” asset type that receives a Tier 3 designation.

Cambridge







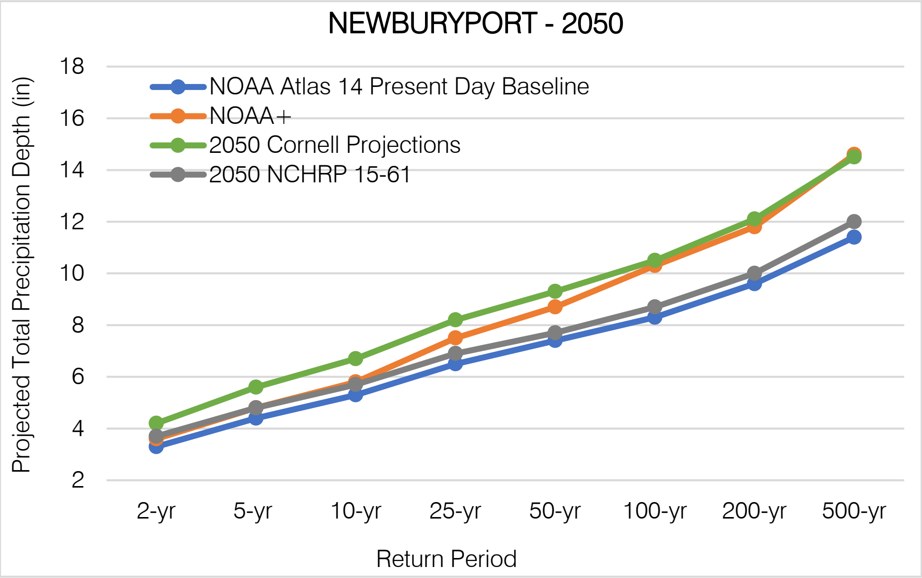


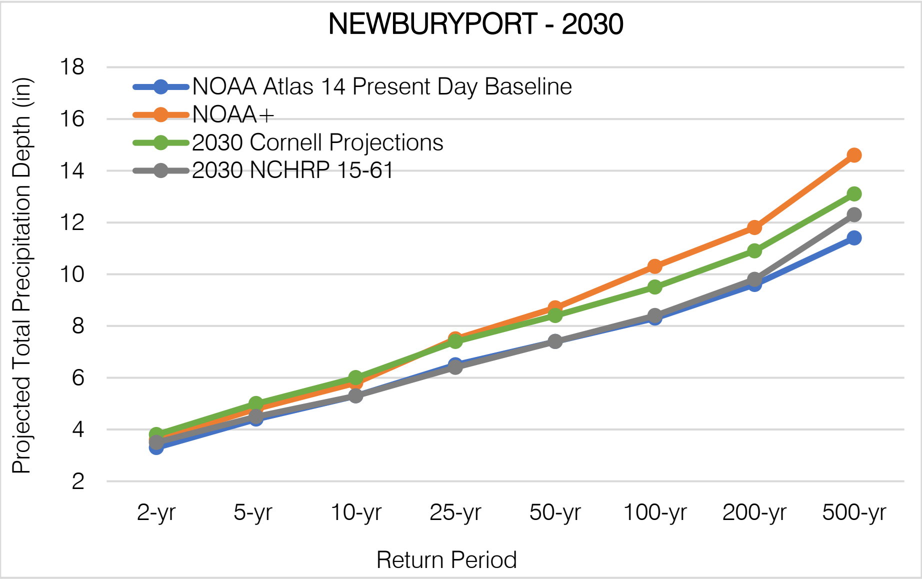
CAMBRIDGE Projected Total Precipitation Depths for 24-hr Design Storms (inches)									
Return Period	Potential Tier Designation for Assets from the Tool	NOAA Atlas 14 Present Day Baseline[1]	NOAA+[2]	2030 Cornell Projections	2030 NCHRP 15-61[3]	2050 Cornell Projections	2050 NCHRP 15-61[3]	2070 Cornell Projections	2070 NCHRP 15-61[3]
2-yr	Tier 1	3.3	3.6	3.7	3.4	4.0	3.6	4.4	3.8
5-yr	Tier 1	4.3	4.7	4.9	4.5	5.3	4.9	5.8	5.1
10-yr	Tier 1/Tier 2	5.2	5.7	5.9	5.4	6.4	6	7	6.3
25-yr	Tier 1/Tier 2/Tier 3	6.3	7.4	7.3	6.7	7.8	7.6	8.6	8.0
50-yr	Tier 1/Tier 2/Tier 3	7.2	8.6	8.3	7.7	8.8	8.9	9.8	9.4
100-yr	Tier 2/Tier 3	8.2	10.2	9.3	8.9	10	10.5	11.1	11.1
500-yr	Tier 3	11.2	14.7	12.8	13.2	13.7	16.3	15.1	17.8

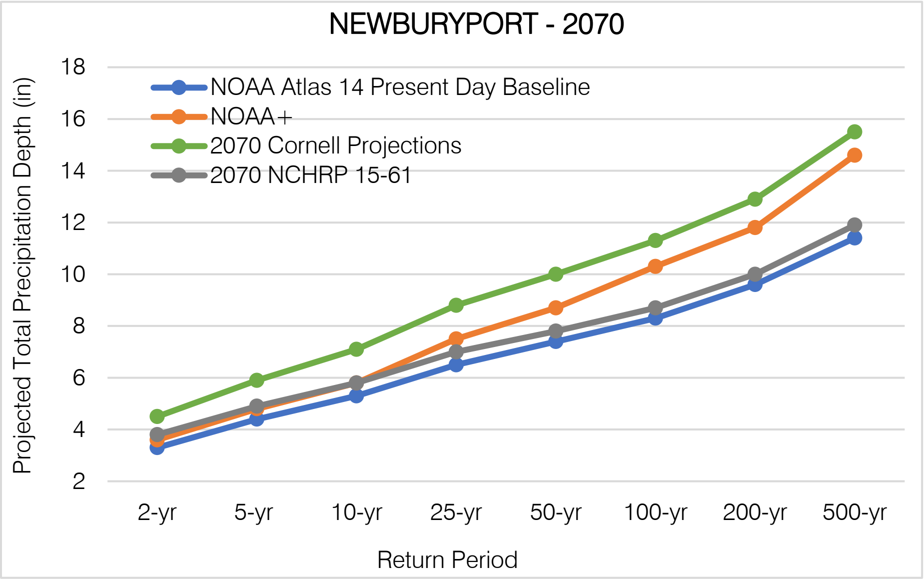
1. Baseline: Median values from NOAA Atlas14 total precipitation depth
2. NOAA+: 90% of the upper bound of the 90% Confidence Interval of NOAA Atlas 14 total precipitation depth; for Tier 1 projects only
3. NCHRP 15-61: Site specific analysis for dams and flood control structures; For Tier 3 projects only

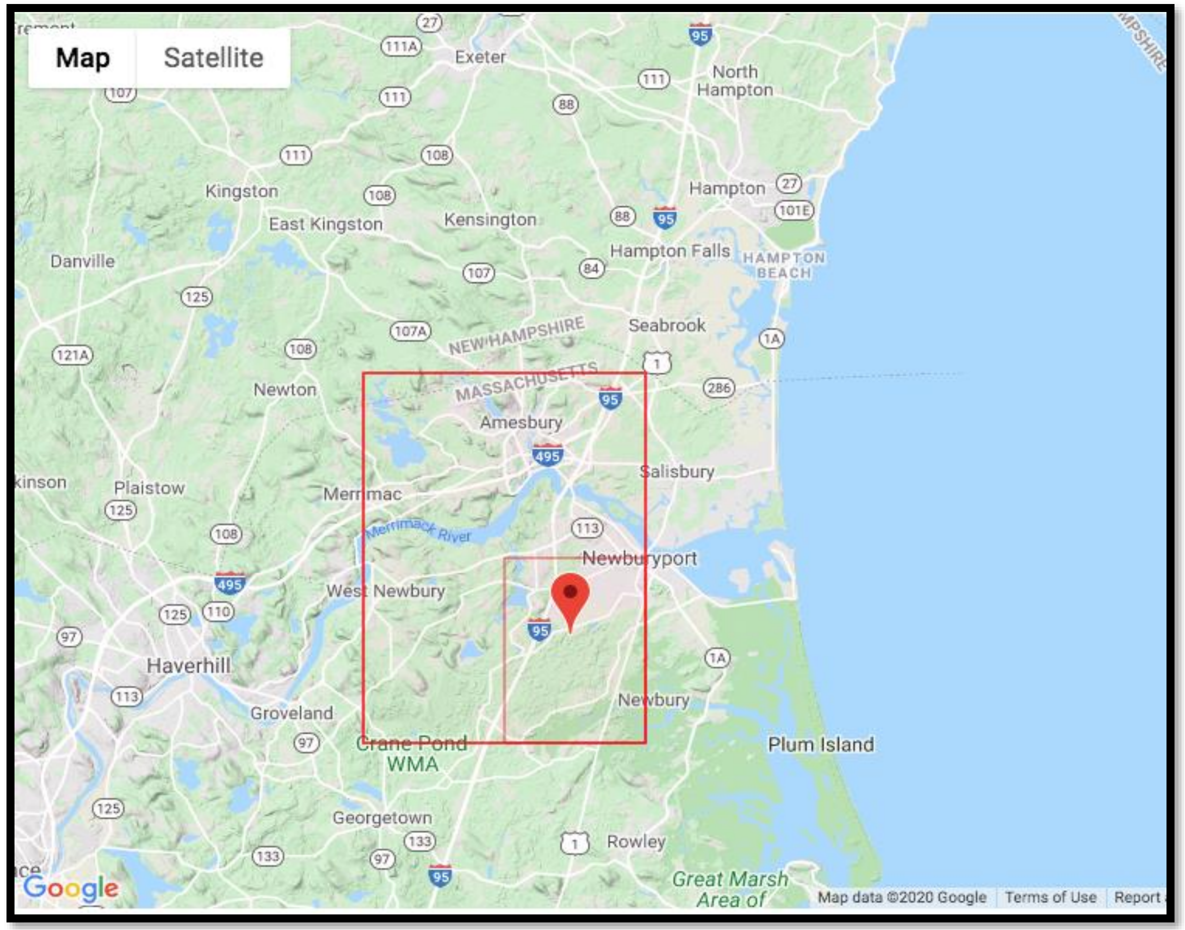
▨ The Tool (V1.2) does not give the highlighted return periods for any asset that receives a Tier 1 designation and/or a "Dams and Flood Control Structures" asset type that receives a Tier 3 designation.

Newburyport







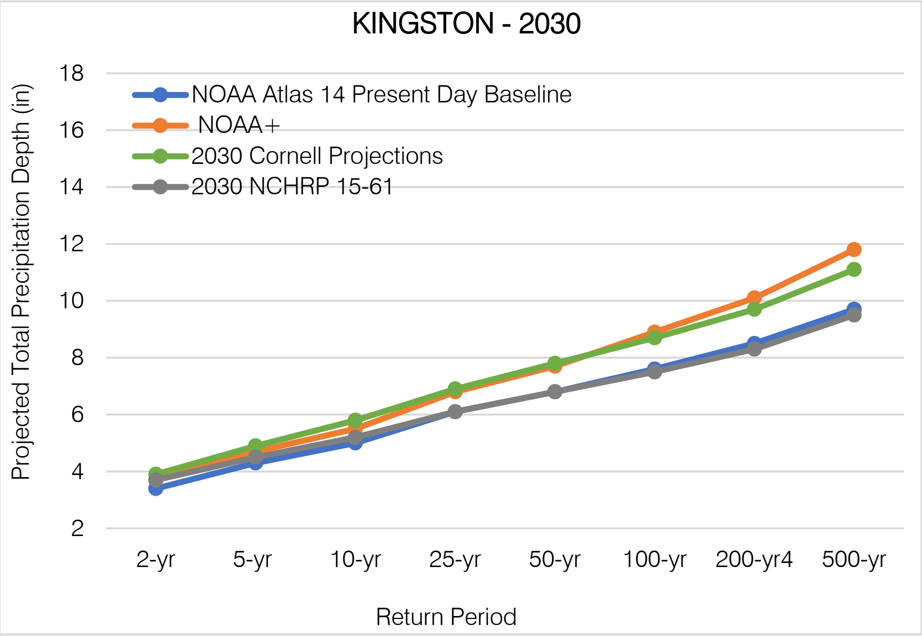


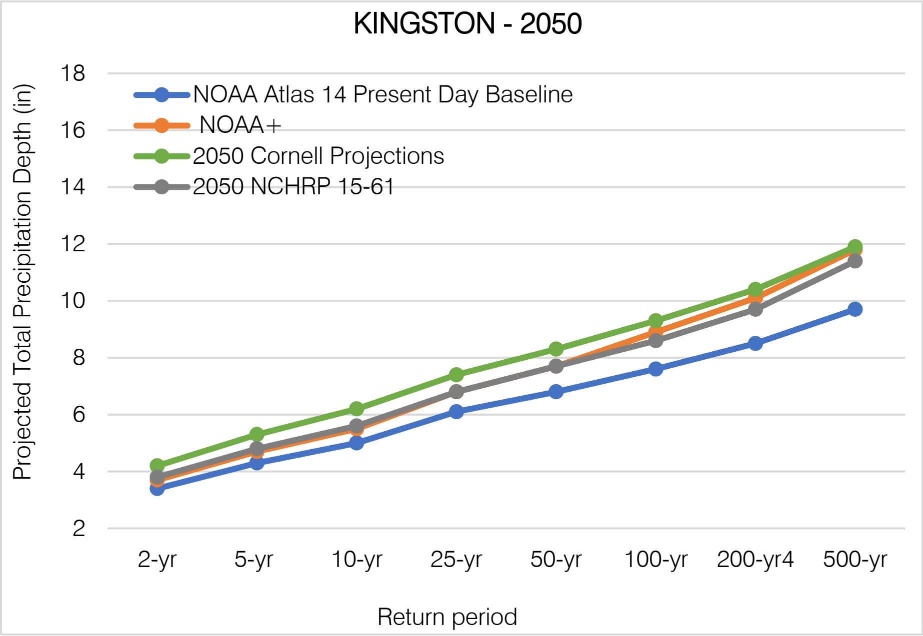
NEWBURYPORT Projected Total Precipitation Depths for 24-hr Design Storms (inches)									
Return period	Potential Tier Designation for Assets from the Tool	NOAA Atlas 14 Present Day Baseline[1]	NOAA+[2]	2030 Cornell Projections	2030 NCHRP 15-61[3]	2050 Cornell Projections	2050 NCHRP 15-61[3]	2070 Cornell Projections	2070 NCHRP 15-61[3]
2-yr	Tier 1	3.3	3.6	3.8	3.5	4.2	3.7	4.5	3.8
5-yr	Tier 1	4.4	4.8	5.0	4.5	5.6	4.8	5.9	4.9
10-yr	Tier 1/Tier 2	5.3	5.8	6.0	5.3	6.7	5.7	7.1	5.8
25-yr	Tier 1/Tier 2/Tier 3	6.5	7.5	7.4	6.4	8.2	6.9	8.8	7.0
50-yr	Tier 1/Tier 2/Tier 3	7.4	8.7	8.4	7.4	9.3	7.7	10	7.8
100-yr	Tier 2/Tier 3	8.3	10.3	9.5	8.4	10.5	8.7	11.3	8.7
500-yr	Tier 3	11.4	14.6	13.1	12.3	14.5	12.0	15.5	11.9

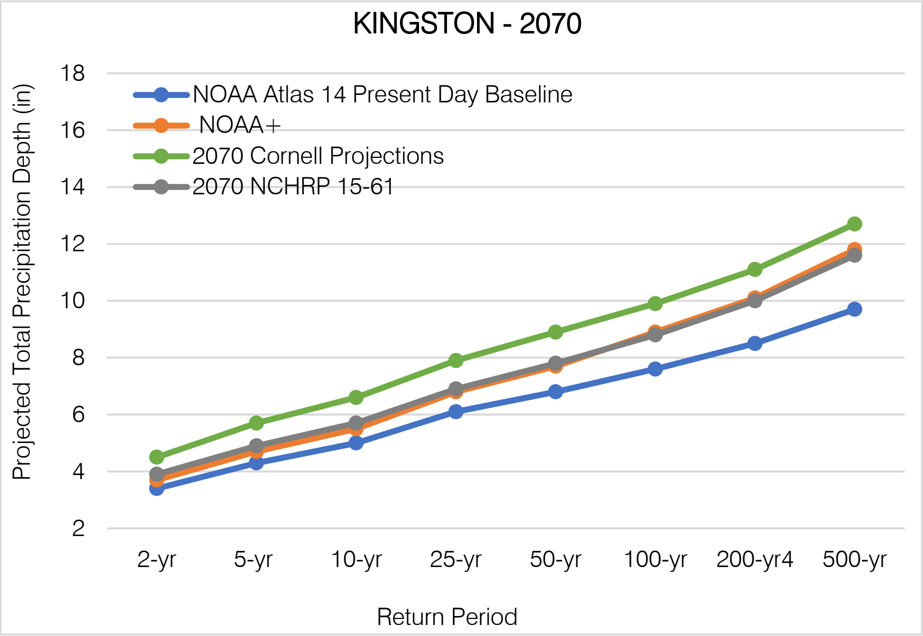
1. Baseline: Median values from NOAA Atlas14 total precipitation depth
2. NOAA+: 90% of the upper bound of the 90% Confidence Interval of NOAA Atlas 14 total precipitation depth; for Tier 1 projects only
3. NCHRP 15-61: Site specific analysis for dams and flood control structures; For Tier 3 projects only

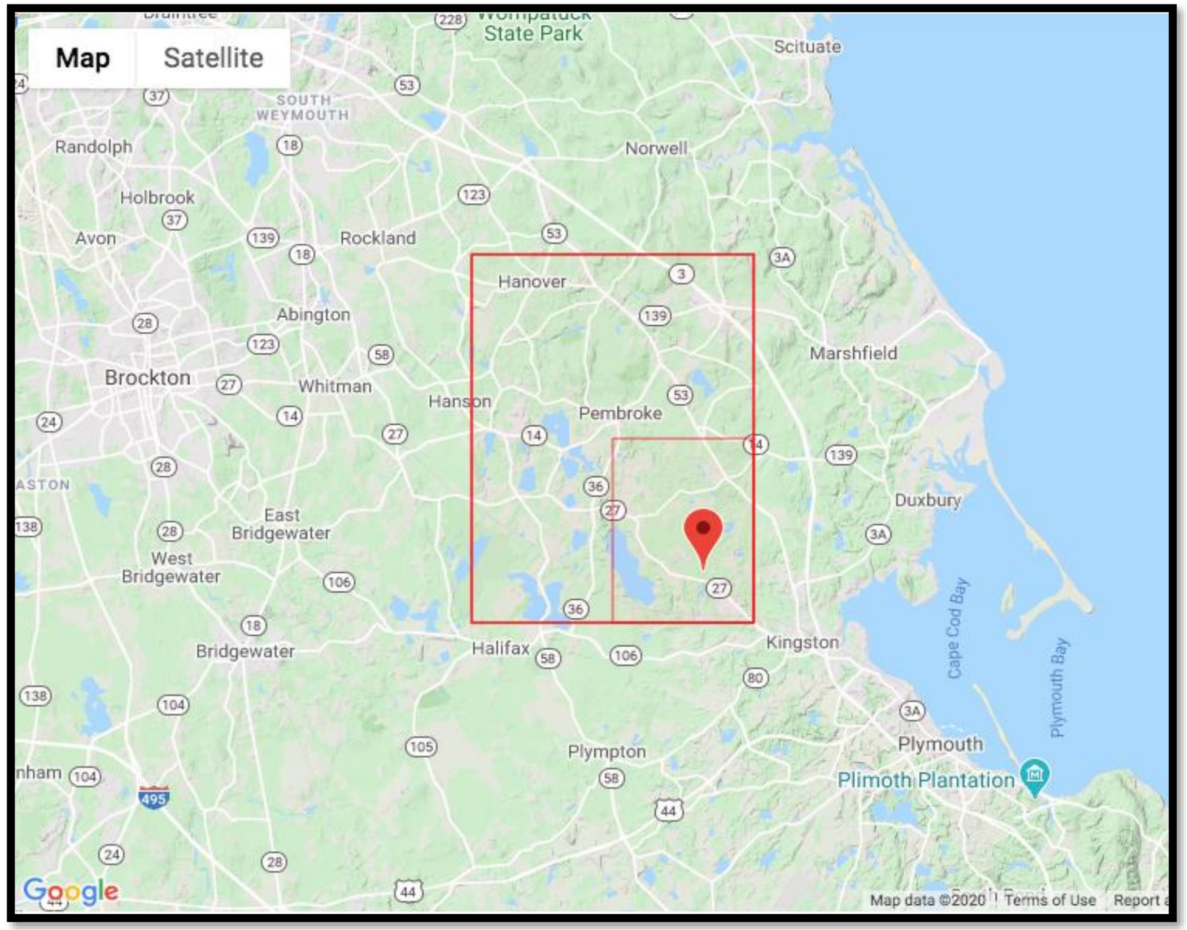
▨ The Tool (V1.2) does not give the highlighted return periods for any asset that receives a Tier 1 designation and/or a "Dams and Flood Control Structures" asset type that receives a Tier 3 designation.

Kingston







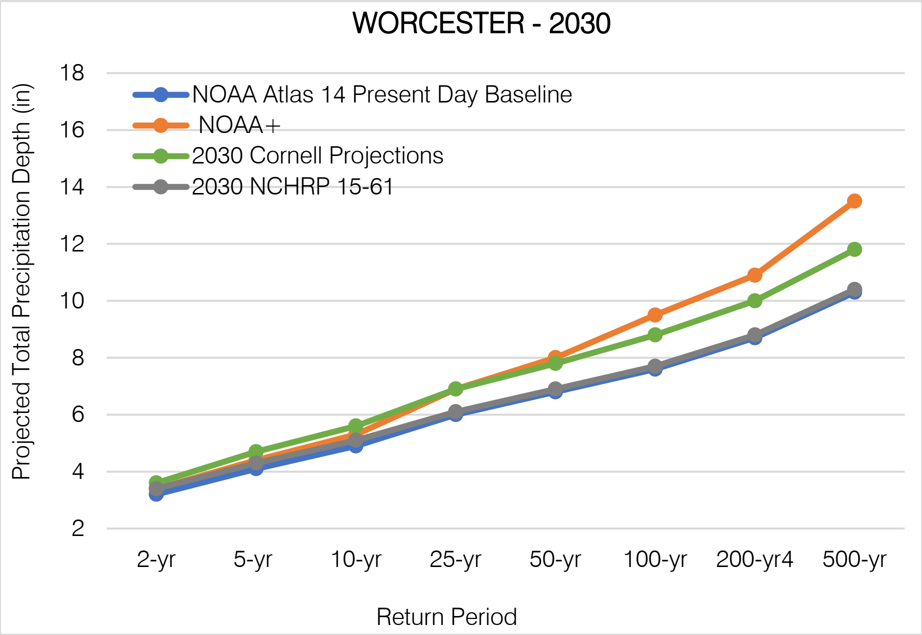


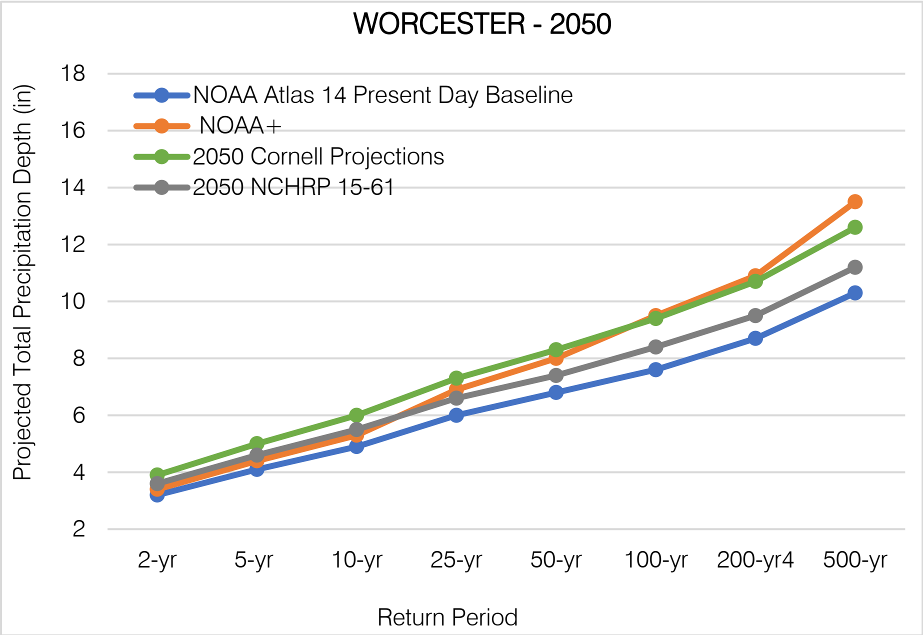
KINGSTON Projected Total Precipitation Depths for 24-hr Design Storms (inches)									
Return period	Potential Tier Designation for Assets from the Tool	NOAA Atlas 14 Present Day Baseline[1]	NOAA+[2]	2030 Cornell Projections	2030 NCHRP 15-61[3]	2050 Cornell Projections	2050 NCHRP 15-61[3]	2070 Cornell Projections	2070 NCHRP 15-61[3]
2-yr	Tier 1	3.4	3.7	3.9	3.7	4.2	3.8	4.5	3.9
5-yr	Tier 1	4.3	4.7	4.9	4.5	5.3	4.8	5.7	4.9
10-yr	Tier 1/Tier 2	5	5.5	5.8	5.2	6.2	5.6	6.6	5.7
25-yr	Tier 1/Tier 2/Tier 3	6.1	6.8	6.9	6.1	7.4	6.8	7.9	6.9
50-yr	Tier 1/Tier 2/Tier 3	6.8	7.7	7.8	6.8	8.3	7.7	8.9	7.8
100-yr	Tier 2/Tier 3	7.6	8.9	8.7	7.5	9.3	8.6	9.9	8.8
500-yr	Tier 3	9.7	11.8	11.1	9.5	11.9	11.4	12.7	11.6

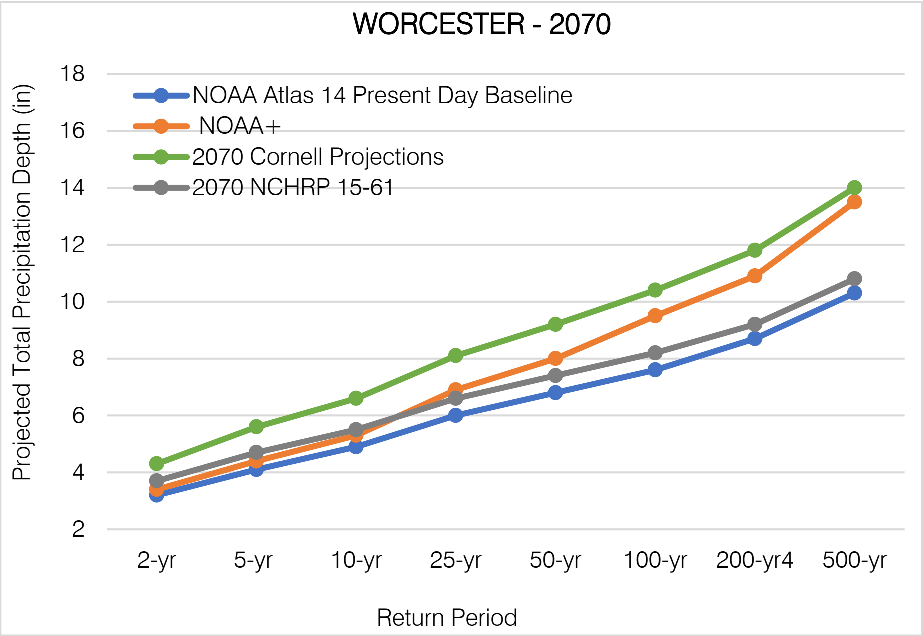
1. Baseline: Median values from NOAA Atlas14 total precipitation depth
2. NOAA+: 90% of the upper bound of the 90% Confidence Interval of NOAA Atlas 14 total precipitation depth; for Tier 1 projects only
3. NCHRP 15-61: Site specific analysis for dams and flood control structures; For Tier 3 projects only

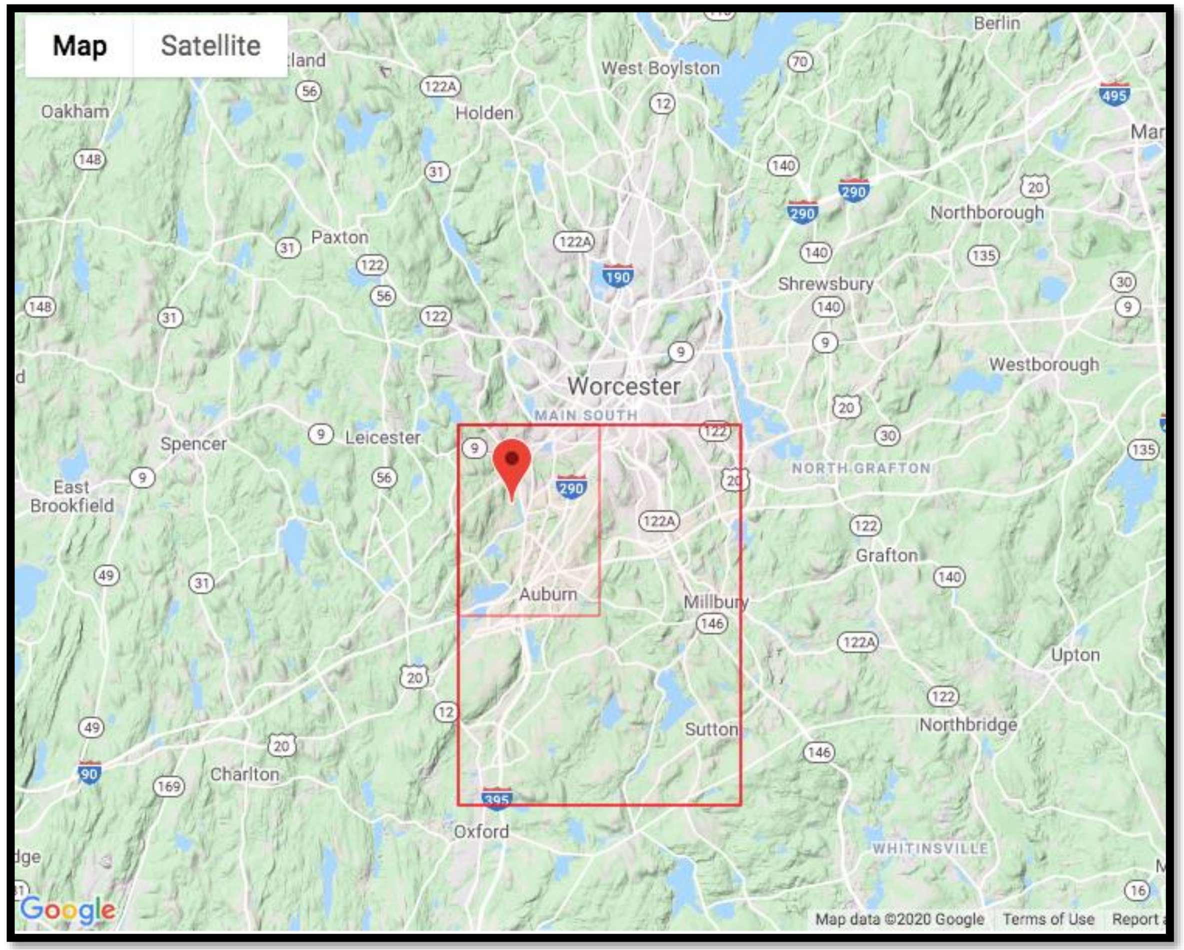
▨ The Tool (V1.2) does not give the highlighted return periods for any asset that receives a Tier 1 designation and/or a "Dams and Flood Control Structures" asset type that receives a Tier 3 designation.

Worcester







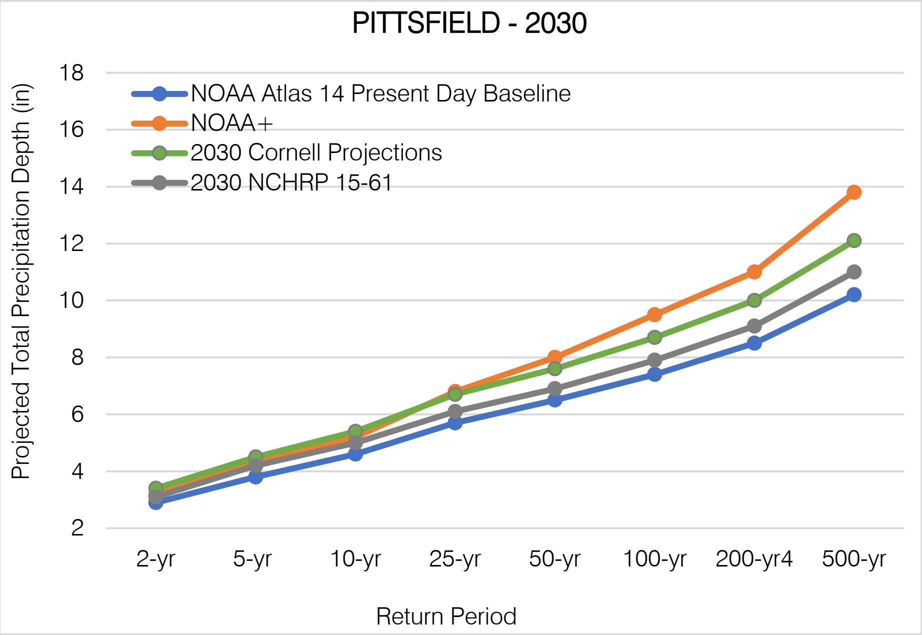


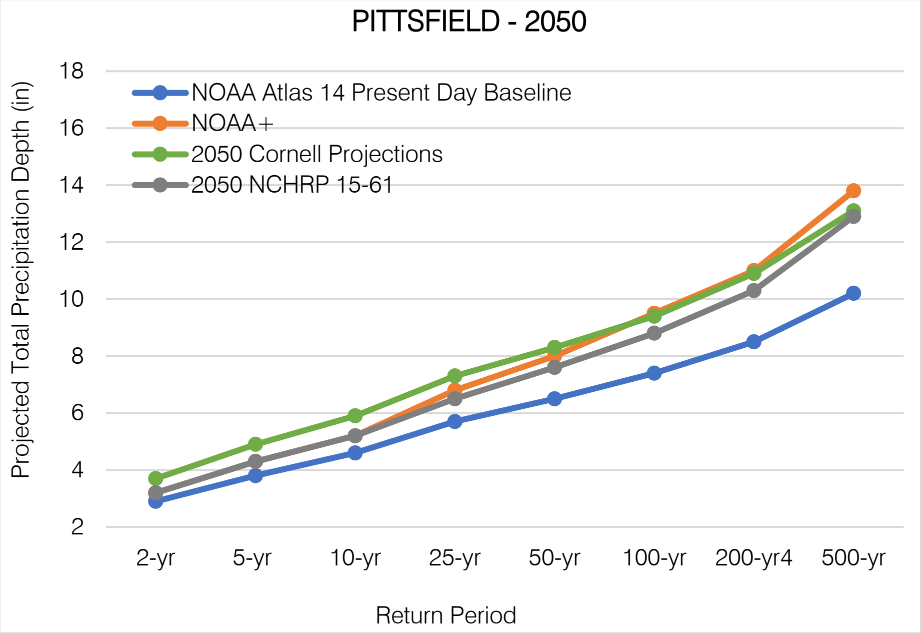
WORCESTER									
Projected Total Precipitation Depths for 24-hr Design Storms (inches)									
Return period	Potential Tier Designation for Assets from the Tool	NOAA Atlas 14 Present Day Baseline[1]	NOAA+[2]	2030 Cornell Projections	2030 NCHRP 15-61[3]	2050 Cornell Projections	2050 NCHRP 15-61[3]	2070 Cornell Projections	2070 NCHRP 15-61[3]
2-yr	Tier 1	3.2	3.4	3.6	3.4	3.9	3.6	4.3	3.7
5-yr	Tier 1	4.1	4.4	4.7	4.3	5.0	4.6	5.6	4.7
10-yr	Tier 1/Tier 2	4.9	5.3	5.6	5.1	6.0	5.5	6.6	5.5
25-yr	Tier 1/Tier 2/Tier 3	6.0	6.9	6.9	6.1	7.3	6.6	8.1	6.6
50-yr	Tier 1/Tier 2/Tier 3	6.8	8.0	7.8	6.9	8.3	7.4	9.2	7.4
100-yr	Tier 2/Tier 3	7.6	9.5	8.8	7.7	9.4	8.4	10.4	8.2
500-yr	Tier 3	10.3	13.5	11.8	10.4	12.6	11.2	14.0	10.8

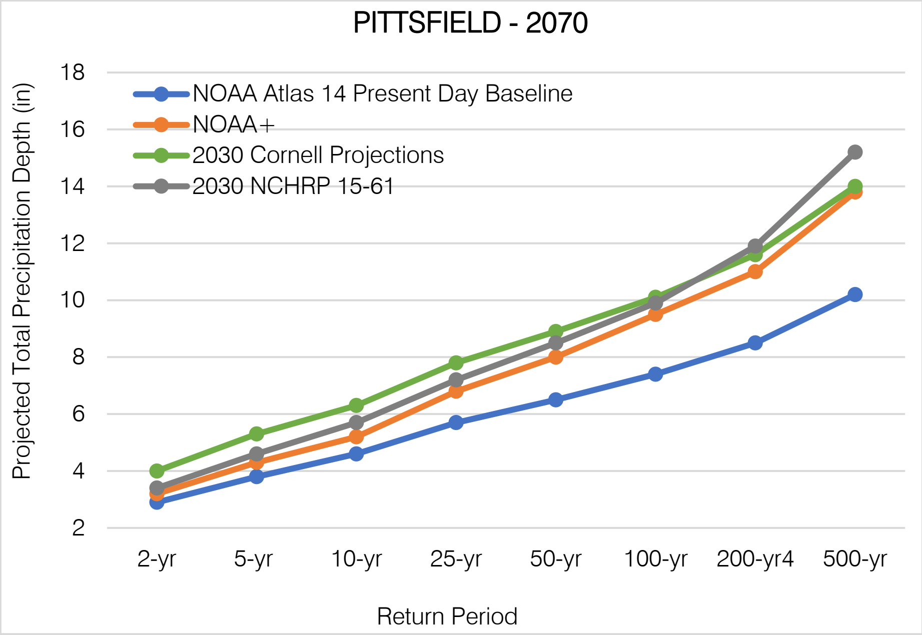
1. Baseline: Median values from NOAA Atlas14 total precipitation depth
2. NOAA+: 90% of the upper bound of the 90% Confidence Interval of NOAA Atlas 14 total precipitation depth; for Tier 1 projects only
3. NCHRP 15-61: Site specific analysis for dams and flood control structures; For Tier 3 projects only

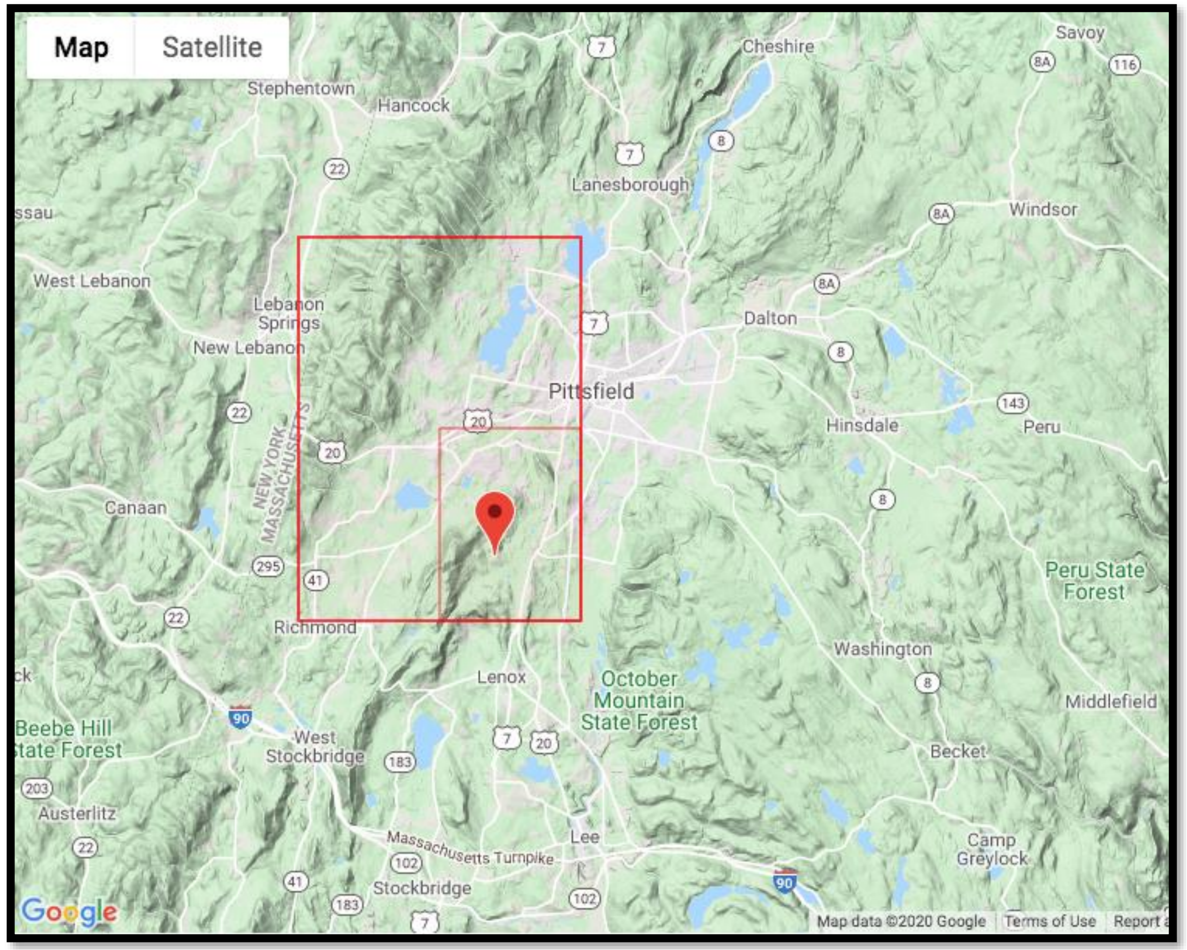
▨	The Tool (V1.2) does not give the highlighted return periods for any asset that receives a Tier 1 designation and/or a "Dams and Flood Control Structures" asset type that receives a Tier 3 designation.

Pittsfield







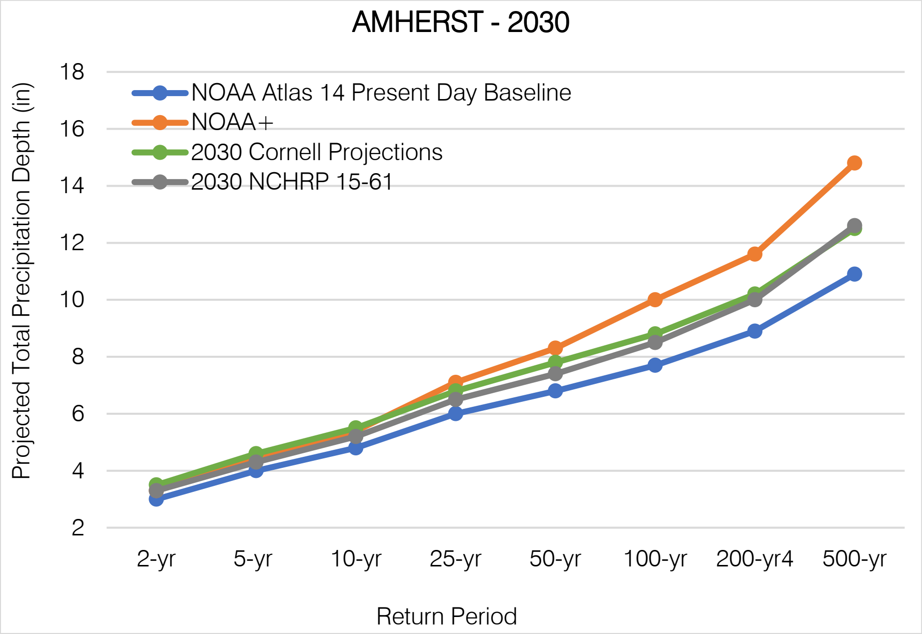


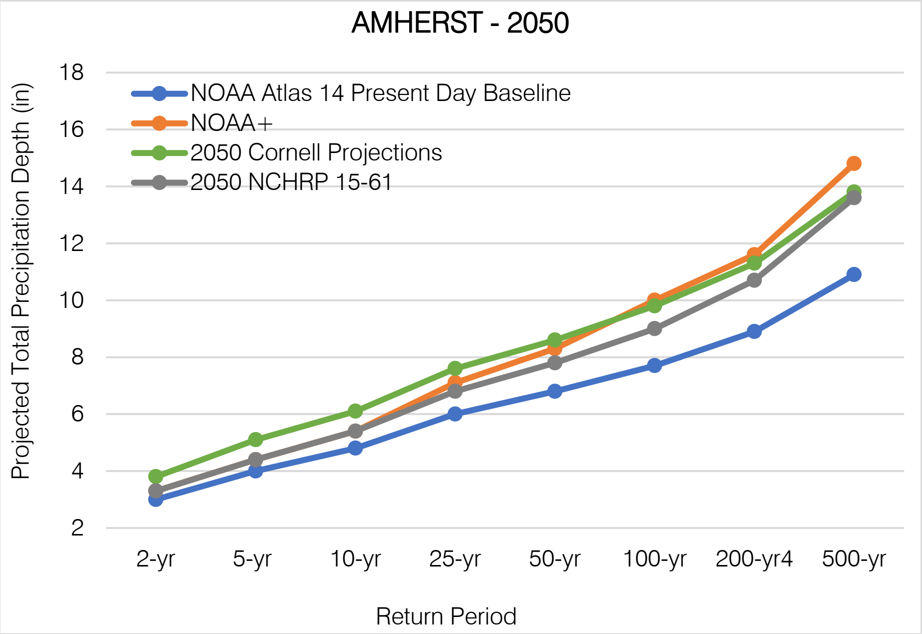
PITTSFIELD Projected Total Precipitation Depths for 24-hr Design Storms (inches)									
Return period	Potential Tier Designation for Assets from the Tool	NOAA Atlas 14 Present Day Baseline[1]	NOAA+[2]	2030 Cornell Projections	2030 NCHRP 15-61[3]	2050 Cornell Projections	2050 NCHRP 15-61[3]	2070 Cornell Projections	2070 NCHRP 15-61[3]
2-yr	Tier 1	2.9	3.2	3.4	3.1	3.7	3.2	4	3.4
5-yr	Tier 1	3.8	4.3	4.5	4.2	4.9	4.3	5.3	4.6
10-yr	Tier 1/Tier 2	4.6	5.2	5.4	5	5.9	5.2	6.3	5.7
25-yr	Tier 1/Tier 2/Tier 3	5.7	6.8	6.7	6.1	7.3	6.5	7.8	7.2
50-yr	Tier 1/Tier 2/Tier 3	6.5	8	7.6	6.9	8.3	7.6	8.9	8.5
100-yr	Tier 2/Tier 3	7.4	9.5	8.7	7.9	9.4	8.8	10.1	9.9
500-yr	Tier 3	10.2	13.8	12.1	11.0	13.1	12.9	14	15.2

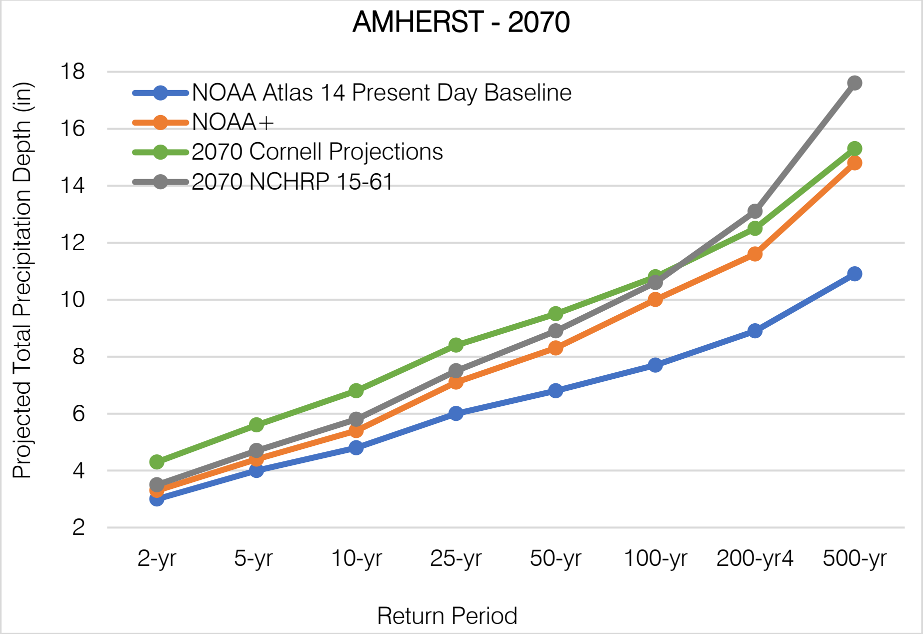
1. Baseline: Median values from NOAA Atlas14 total precipitation depth
2. NOAA+: 90% of the upper bound of the 90% Confidence Interval of NOAA Atlas 14 total precipitation depth; for Tier 1 projects only
3. NCHRP 15-61: Site specific analysis for dams and flood control structures; For Tier 3 projects only

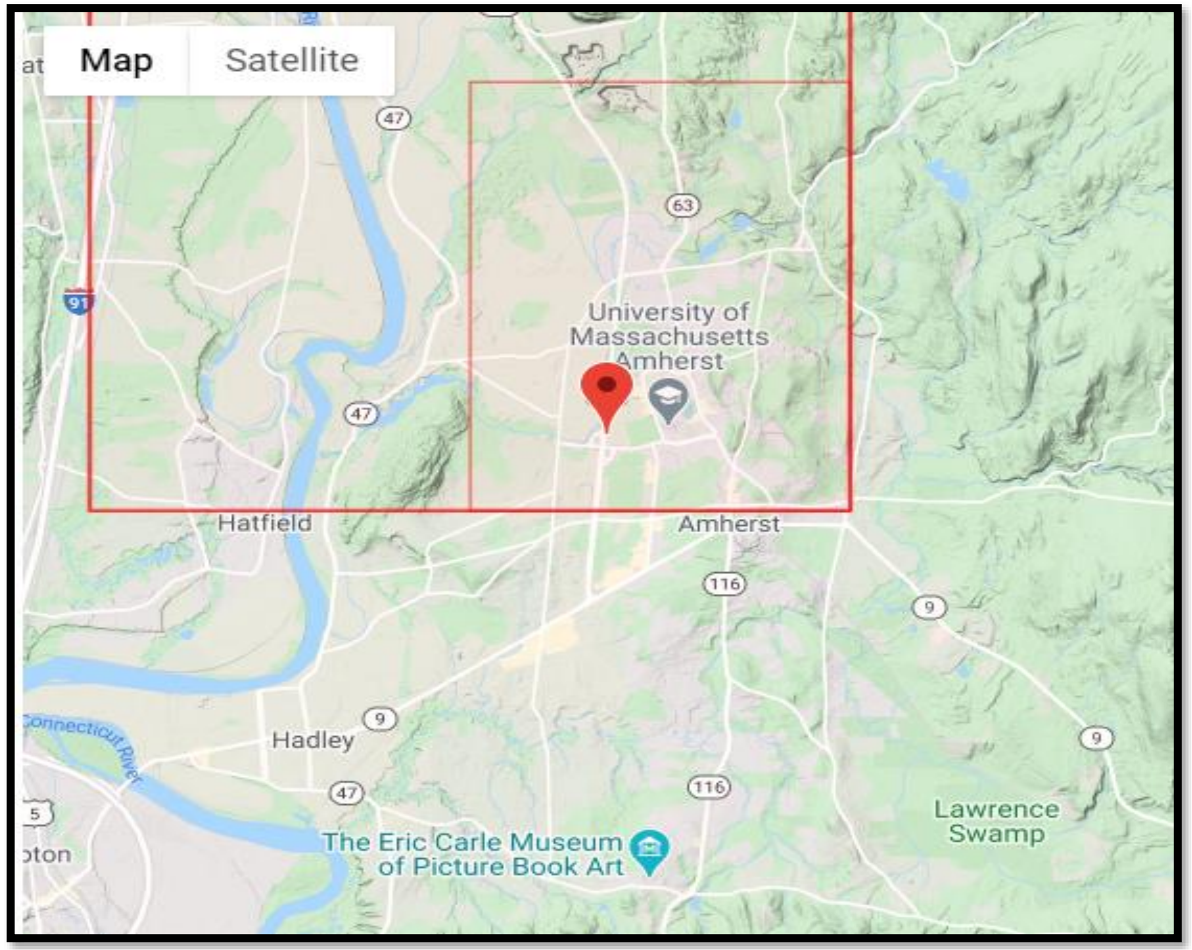
▨ The Tool (V1.2) does not give the highlighted return periods for any asset that receives a Tier 1 designation and/or a “Dams and Flood Control Structures” asset type that receives a Tier 3 designation.

Amherst









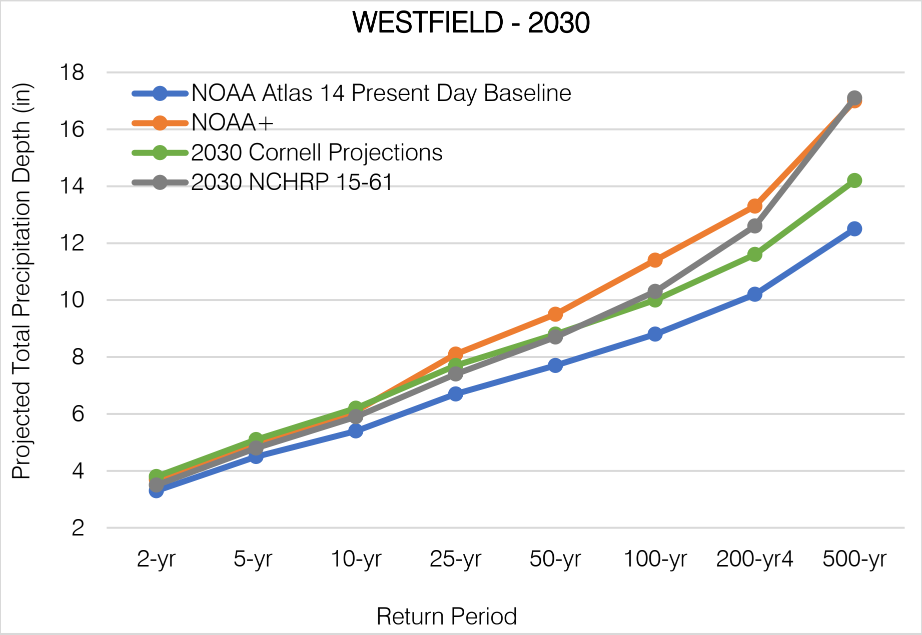
AMHERST
Projected Total Precipitation Depths for 24-hr Design Storms (inches)

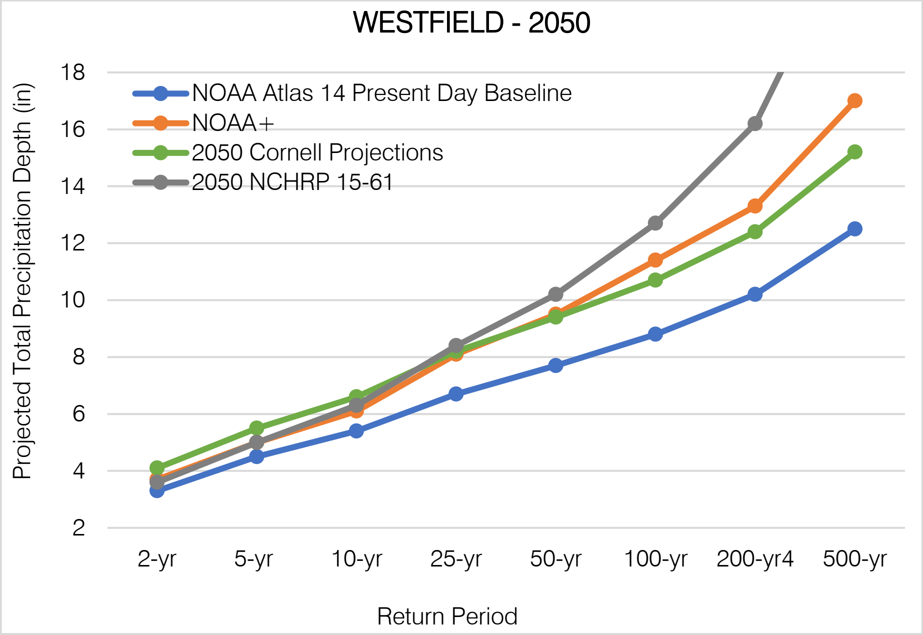
Return period	Potential Tier Designation for Assets from the Tool	NOAA Atlas 14 Present Day Baseline[1]	NOAA+[2]	2030 Cornell Projections	2030 NCHRP 15-61[3]	2050 Cornell Projections	2050 NCHRP 15-61[3]	2070 Cornell Projections	2070 NCHRP 15-61[3]
2-yr	Tier 1	3.0	3.3	3.5	3.3	3.8	3.3	4.3	3.5
5-yr	Tier 1	4.0	4.4	4.6	4.3	5.1	4.4	5.6	4.7
10-yr	Tier 1/Tier 2	4.8	5.4	5.5	5.2	6.1	5.4	6.8	5.8
25-yr	Tier 1/Tier 2/Tier 3	6.0	7.1	6.8	6.5	7.6	6.8	8.4	7.5
50-yr	Tier 1/Tier 2/Tier 3	6.8	8.3	7.8	7.4	8.6	7.8	9.5	8.9
100-yr	Tier 2/Tier 3	7.7	10.0	8.8	8.5	9.8	9.0	10.8	10.6
500-yr	Tier 3	10.9	14.8	12.5	12.6	13.8	13.6	15.3	17.6

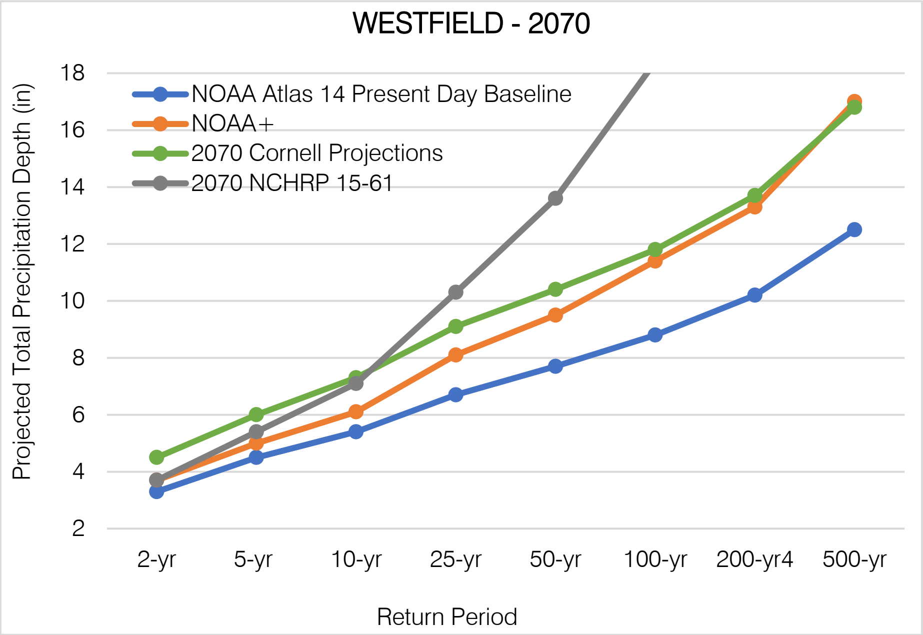
1. Baseline: Median values from NOAA Atlas14 total precipitation depth
2. NOAA+: 90% of the upper bound of the 90% Confidence Interval of NOAA Atlas 14 total precipitation depth; for Tier 1 projects only
3. NCHRP 15-61: Site specific analysis for dams and flood control structures; For Tier 3 projects only

▨ The Tool (V1.2) does not give the highlighted return periods for any asset that receives a Tier 1 designation and/or a "Dams and Flood Control Structures" asset type that receives a Tier 3 designation.

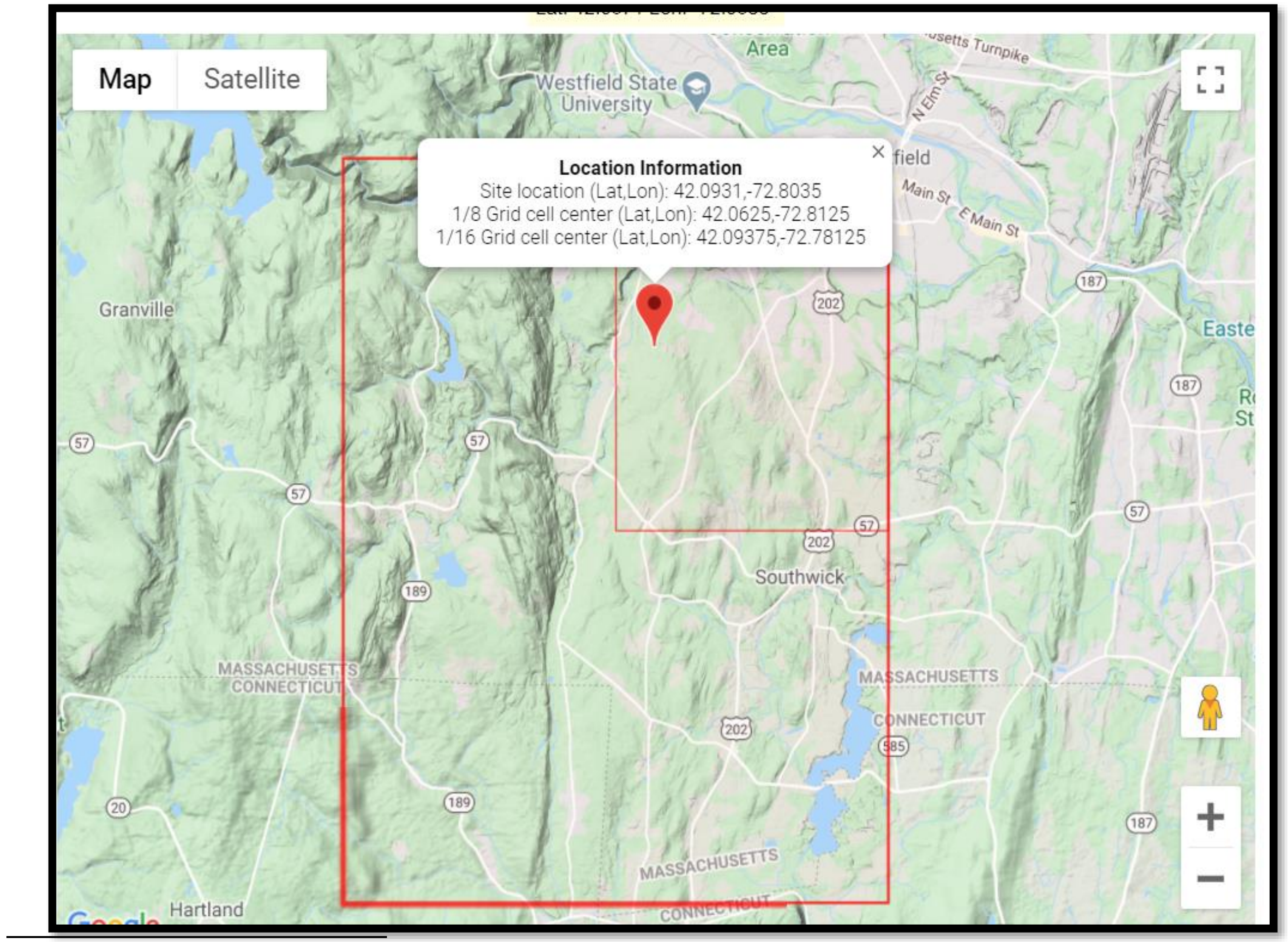
Westfield







1



Location Information
Site location (Lat,Lon): 42.0931,-72.8035
1/8 Grid cell center (Lat,Lon): 42.0625,-72.8125
1/16 Grid cell center (Lat,Lon): 42.09375,-72.78125

1

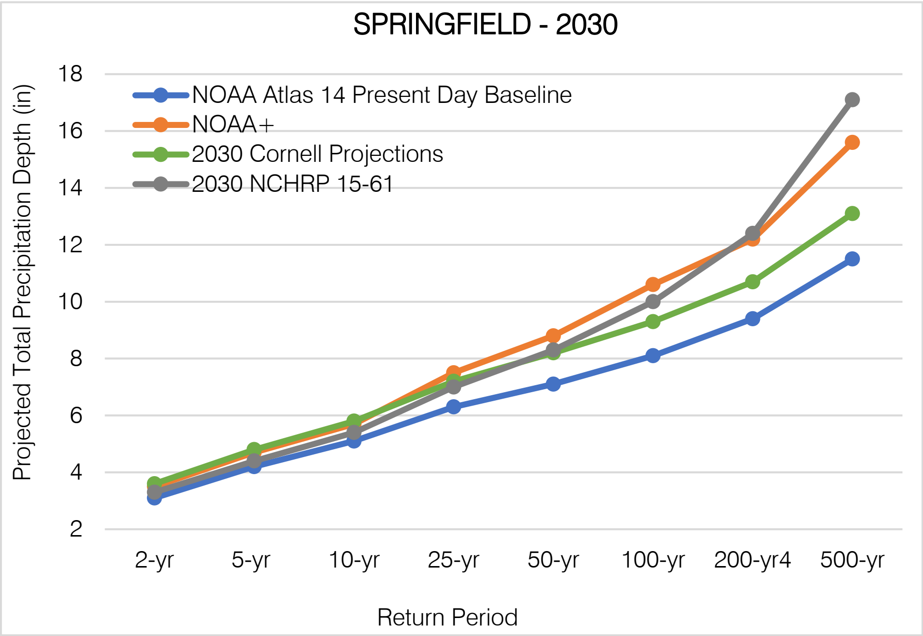
WESTFIELD
Projected Total Precipitation Depths for 24-hr Design Storms (inches)

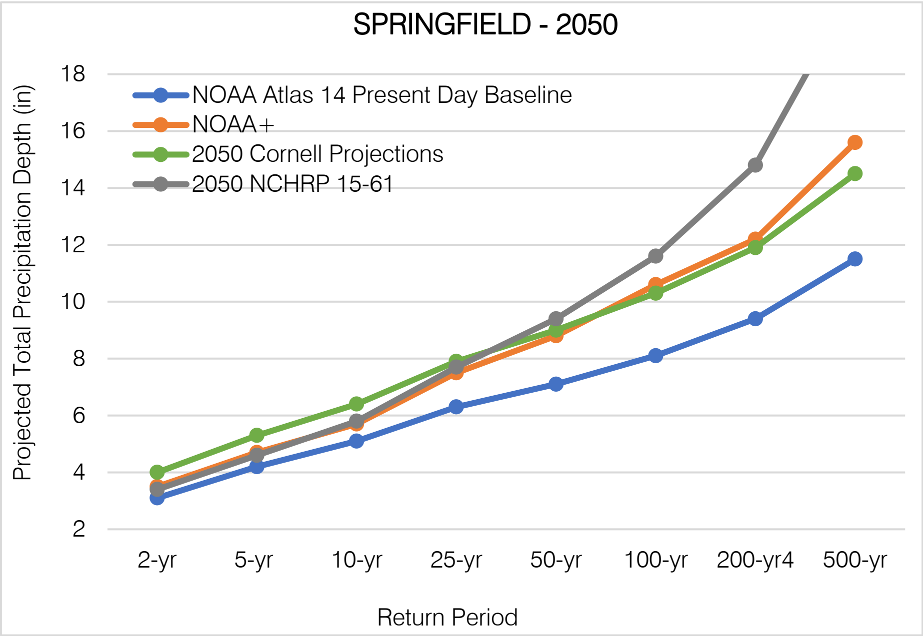
Return period	Potential Tier Designation for Assets from the Tool	NOAA Atlas 14 Present Day Baseline[1]	NOAA+[2]	2030 Cornell Projections	2030 NCHRP 15-61[3]	2050 Cornell Projections	2050 NCHRP 15-61[3]	2070 Cornell Projections	2070 NCHRP 15-61[3]
2-yr	Tier 1	3.3	3.7	3.8	3.5	4.1	3.6	4.5	3.7
5-yr	Tier 1	4.5	5	5.1	4.8	5.5	5	6	5.4
10-yr	Tier 1/Tier 2	5.4	6.1	6.2	5.9	6.6	6.3	7.3	7.1
25-yr	Tier 1/Tier 2/Tier 3	6.7	8.1	7.7	7.4	8.2	8.4	9.1	10.3
50-yr	Tier 1/Tier 2/Tier 3	7.7	9.5	8.8	8.7	9.4	10.2	10.4	13.6
100-yr	Tier 2/Tier 3	8.8	11.4	10	10.3	10.7	12.7	11.8	18.4
500-yr	Tier 3	12.5	17	14.2	17.1	15.2	23.3	16.8	42.4

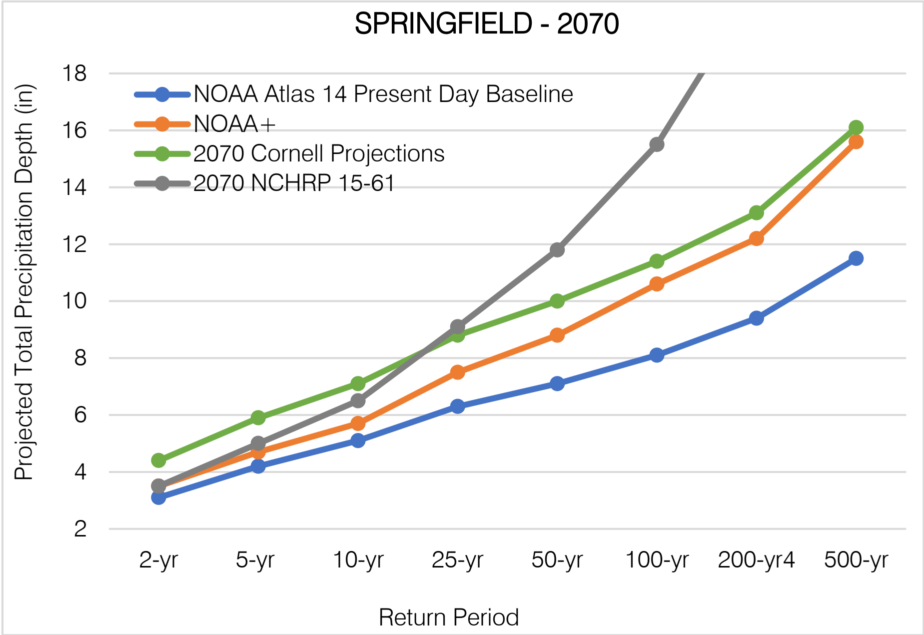
1. Baseline: Median values from NOAA Atlas14 total precipitation depth
2. NOAA+: 90% of the upper bound of the 90% Confidence Interval of NOAA Atlas 14 total precipitation depth; for Tier 1 projects only
3. NCHRP 15-61: Site specific analysis for dams and flood control structures; For Tier 3 projects only

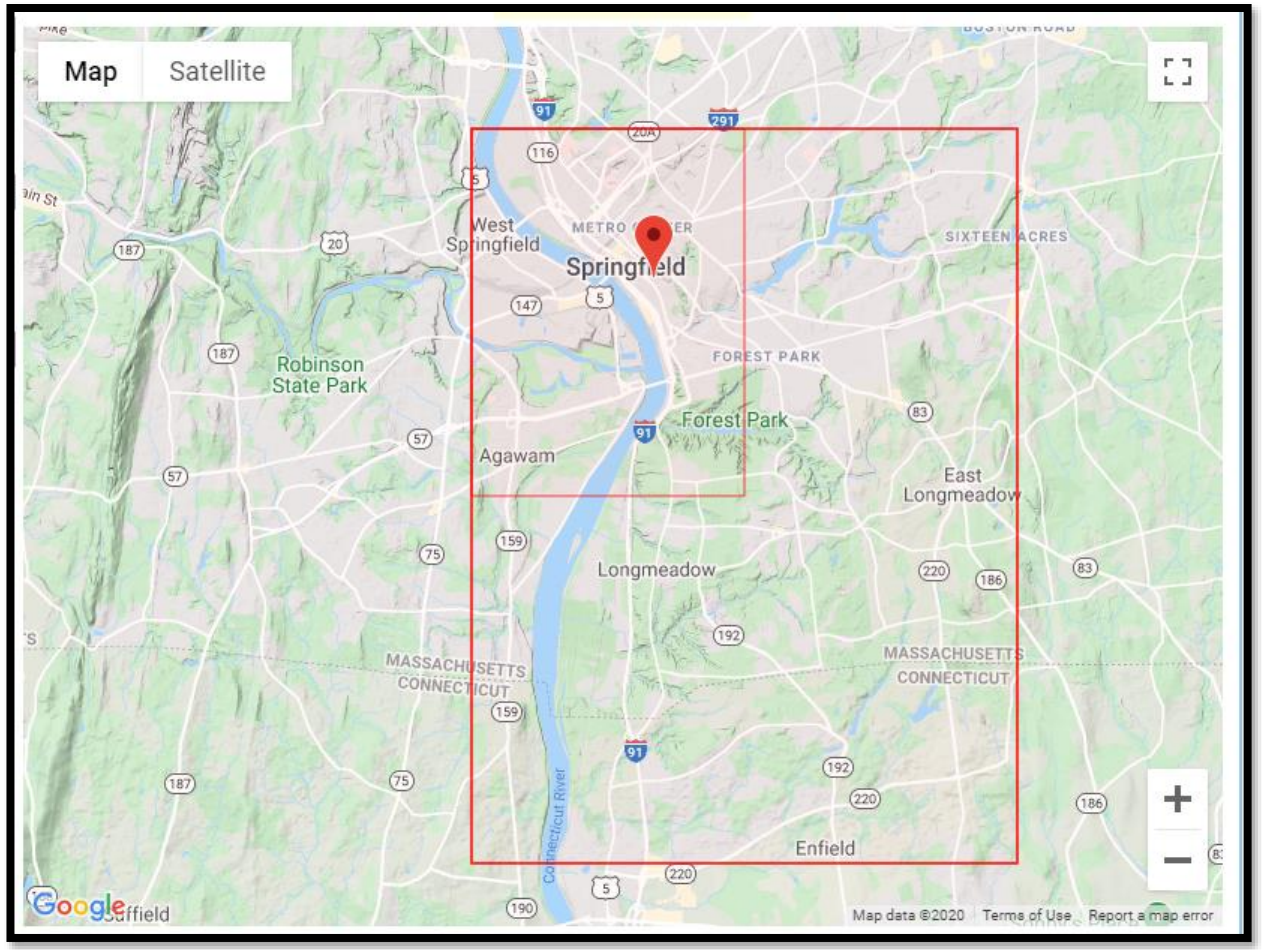
▨	The Tool (V1.2) does not give the highlighted return periods for any asset that receives a Tier 1 designation and/or a “Dams and Flood Control Structures” asset type that receives a Tier 3 designation.

Springfield









SPRINGFIELD
Projected Total Precipitation Depths for 24-hr Design Storms (inches)

Return period	Potential Tier Designation for Assets from the Tool	NOAA Atlas 14 Present Day Baseline[1]	NOAA+[2]	2030 Cornell Projections	2030 NCHRP 15-61[3]	2050 Cornell Projections	2050 NCHRP 15-61[3]	2070 Cornell Projections	2070 NCHRP 15-61[3]
2-yr	Tier 1	3.1	3.5	3.6	3.3	4	3.4	4.4	3.5
5-yr	Tier 1	4.2	4.7	4.8	4.4	5.3	4.6	5.9	5
10-yr	Tier 1/Tier 2	5.1	5.7	5.8	5.4	6.4	5.8	7.1	6.5
25-yr	Tier 1/Tier 2/Tier 3	6.3	7.5	7.2	7.0	7.9	7.7	8.8	9.1
50-yr	Tier 1/Tier 2/Tier 3	7.1	8.8	8.2	8.3	9	9.4	10	11.8
100-yr	Tier 2/Tier 3	8.1	10.6	9.3	10	10.3	11.6	11.4	15.5
500-yr	Tier 3	11.5	15.6	13.1	17.1	14.5	21.1	16.1	33.2

1. Baseline: Median values from NOAA Atlas14 total precipitation depth
2. NOAA+: 90% of the upper bound of the 90% Confidence Interval of NOAA Atlas 14 total precipitation depth; for Tier 1 projects only
3. NCHRP 15-61: Site specific analysis for dams and flood control structures; For Tier 3 projects only

▨ The Tool (V1.2) does not give the highlighted return periods for any asset that receives a Tier 1 designation and/or a "Dams and Flood Control Structures" asset type that receives a Tier 3 designation.

Data Comparison:

BOSTON (Location: Moakley Park)							
Return Period	Potential Tier Designation for Assets from the Tool	% difference NOAA+ vs 2030 Cornell	% difference NOAA+ vs 2050 Cornell	% difference NOAA+ vs 2070 Cornell	% difference 2030 Cornell vs NCHRP	% difference 2050 Cornell vs NCHRP	% difference 2070 Cornell vs NCHRP
2-yr	Tier 1	8%	13%	23%	8%	8%	14%
5-yr	Tier 1	6%	12%	19%	8%	6%	9%
10-yr	Tier 1/Tier 2	5%	11%	20%	5%	3%	7%
25-yr	Tier 1/Tier 2/Tier 3	0%	6%	15%	6%	0%	5%
50-yr	Tier 1/Tier 2/Tier 3	-4%	3%	13%	2%	-3%	1%
100-yr	Tier 2/Tier 3	-8%	0%	9%	1%	-7%	-3%
500-yr	Tier 3	-13%	-6%	5%	-6%	-20%	-16%

All the percent difference analyses were done compared to Cornell Projections. **Positive** percent difference means Cornell projections are higher, and **negative** percent difference means Cornell projections are lower

▒	**The Tool does not recommend these return periods**
🟩	**Values are similar to Cornell (±5%)**
🟨	**Cornell values are lower (negative values and >5% difference)**
🟧	**Cornell values are higher (positive values and >5% difference)**

CAMBRIDGE							
Return Period	Potential Tier Designation for Assets from the Tool	% difference NOAA+ vs 2030 Cornell	% difference NOAA+ vs 2050 Cornell	% difference NOAA+ vs 2070 Cornell	% difference 2030 Cornell vs NCHRP	% difference 2050 Cornell vs NCHRP	% difference 2070 Cornell vs NCHRP
2-yr	Tier 1	3%	10%	18%	8%	10%	14%
5-yr	Tier 1	4%	11%	19%	8%	8%	12%
10-yr	Tier 1/Tier 2	3%	11%	19%	8%	6%	10%
25-yr	Tier 1/Tier 2/Tier 3	-1%	5%	14%	8%	3%	7%
50-yr	Tier 1/Tier 2/Tier 3	-4%	2%	12%	7%	-1%	4%
100-yr	Tier 2/Tier 3	-10%	-2%	8%	4%	-5%	0%
500-yr	Tier 3	-15%	-7%	3%	-3%	-19%	-18%

NEWBURYPORT							
Return Period	Potential Tier Designation for Assets from the Tool	% difference NOAA+ vs 2030 Cornell	% difference NOAA+ vs 2050 Cornell	% difference NOAA+ vs 2070 Cornell	% difference 2030 Cornell vs NCHRP	% difference 2050 Cornell vs NCHRP	% difference 2070 Cornell vs NCHRP
2-yr	Tier 1	5%	14%	20%	8%	12%	16%
5-yr	Tier 1	4%	14%	19%	10%	14%	17%
10-yr	Tier 1/Tier 2	3%	13%	18%	12%	15%	18%
25-yr	Tier 1/Tier 2/Tier 3	-1%	9%	15%	14%	16%	20%
50-yr	Tier 1/Tier 2/Tier 3	-4%	6%	13%	12%	17%	22%
100-yr	Tier 2/Tier 3	-8%	2%	9%	12%	17%	23%
500-yr	Tier 3	-11%	-1%	6%	6%	17%	23%

KINGSTON

Return Period	Potential Tier Designation for Assets from the Tool	% difference NOAA+ vs 2030 Cornell	% difference NOAA+ vs 2050 Cornell	% difference NOAA+ vs 2070 Cornell	% difference 2030 Cornell vs NCHRP	% difference 2050 Cornell vs NCHRP	% difference 2070 Cornell vs NCHRP
2-yr	Tier 1	5%	12%	18%	5%	10%	13%
5-yr	Tier 1	4%	11%	18%	8%	9%	14%
10-yr	Tier 1/Tier 2	5%	11%	17%	10%	10%	14%
25-yr	Tier 1/Tier 2/Tier 3	1%	8%	14%	12%	8%	13%
50-yr	Tier 1/Tier 2/Tier 3	1%	7%	13%	13%	7%	12%
100-yr	Tier 2/Tier 3	-2%	4%	10%	14%	8%	11%
500-yr	Tier 3	-6%	1%	7%	14%	4%	9%

PITTSFIELD

Return Period	Potential Tier Designation for Assets from the Tool	% difference NOAA+ vs 2030 Cornell	% difference NOAA+ vs 2050 Cornell	% difference NOAA+ vs 2070 Cornell	% difference 2030 Cornell vs NCHRP	% difference 2050 Cornell vs NCHRP	% difference 2070 Cornell vs NCHRP
2-yr	Tier 1	6%	13%	21%	6%	8%	14%
5-yr	Tier 1	6%	12%	21%	9%	8%	16%
10-yr	Tier 1/Tier 2	5%	12%	20%	9%	8%	17%
25-yr	Tier 1/Tier 2/Tier 3	0%	5%	15%	12%	10%	19%
50-yr	Tier 1/Tier 2/Tier 3	-3%	4%	13%	12%	11%	20%
100-yr	Tier 2/Tier 3	-8%	-1%	9%	13%	11%	21%
500-yr	Tier 3	-14%	-7%	4%	12%	11%	23%

WORCESTER

Return Period	Potential Tier Designation for Assets from the Tool	% difference NOAA+ vs 2030 Cornell	% difference NOAA+ vs 2050 Cornell	% difference NOAA+ vs 2070 Cornell	% difference 2030 Cornell vs NCHRP	% difference 2050 Cornell vs NCHRP	% difference 2070 Cornell vs NCHRP
2-yr	Tier 1	6%	14%	20%	9%	14%	15%
5-yr	Tier 1	4%	12%	19%	7%	12%	13%
10-yr	Tier 1/Tier 2	4%	12%	17%	7%	12%	10%
25-yr	Tier 1/Tier 2/Tier 3	-1%	7%	13%	9%	11%	8%
50-yr	Tier 1/Tier 2/Tier 3	-5%	4%	10%	9%	8%	4%
100-yr	Tier 2/Tier 3	-9%	-1%	6%	9%	6%	2%
500-yr	Tier 3	-14%	-5%	1%	9%	2%	-9%

AMHERST

Return Period	Potential Tier Designation for Assets from the Tool	% difference NOAA+ vs 2030 Cornell	% difference NOAA+ vs 2050 Cornell	% difference NOAA+ vs 2070 Cornell	% difference 2030 Cornell vs NCHRP	% difference 2050 Cornell vs NCHRP	% difference 2070 Cornell vs NCHRP
2-yr	Tier 1	6%	13%	23%	6%	13%	19%
5-yr	Tier 1	4%	14%	21%	7%	14%	16%
10-yr	Tier 1/Tier 2	2%	11%	21%	5%	11%	15%
25-yr	Tier 1/Tier 2/Tier 3	-4%	7%	15%	4%	11%	11%
50-yr	Tier 1/Tier 2/Tier 3	-6%	3%	13%	5%	9%	6%
100-yr	Tier 2/Tier 3	-14%	-2%	7%	3%	8%	2%
500-yr	Tier 3	-18%	-7%	3%	-1%	1%	-15%

WESTFIELD

Return Period	Potential Tier Designation for Assets from the Tool	% difference NOAA+ vs 2030 Cornell	% difference NOAA+ vs 2050 Cornell	% difference NOAA+ vs 2070 Cornell	% difference 2030 Cornell vs NCHRP	% difference 2050 Cornell vs NCHRP	% difference 2070 Cornell vs NCHRP
2-yr	Tier 1	3%	10%	18%	8%	12%	18%
5-yr	Tier 1	2%	9%	17%	6%	9%	10%
10-yr	Tier 1/Tier 2	2%	8%	16%	5%	5%	3%
25-yr	Tier 1/Tier 2/Tier 3	-5%	1%	11%	4%	-2%	-13%
50-yr	Tier 1/Tier 2/Tier 3	-8%	-1%	9%	1%	-9%	-31%
100-yr	Tier 2/Tier 3	-14%	-7%	3%	-3%	-19%	-56%
500-yr	Tier 3	-20%	-12%	-1%	-20%	-53%	-152%

SPRINGFIELD

Return Period	Potential Tier Designation for Assets from the Tool	% difference NOAA+ vs 2030 Cornell	% difference NOAA+ vs 2050 Cornell	% difference NOAA+ vs 2070 Cornell	% difference 2030 Cornell vs NCHRP	% difference 2050 Cornell vs NCHRP	% difference 2070 Cornell vs NCHRP
2-yr	Tier 1	3%	13%	20%	8%	15%	20%
5-yr	Tier 1	2%	11%	20%	8%	13%	15%
10-yr	Tier 1/Tier 2	2%	11%	20%	7%	9%	8%
25-yr	Tier 1/Tier 2/Tier 3	-4%	5%	15%	3%	3%	-3%
50-yr	Tier 1/Tier 2/Tier 3	-7%	2%	12%	-1%	-4%	-18%
100-yr	Tier 2/Tier 3	-14%	-3%	7%	-8%	-13%	-36%
500-yr	Tier 3	-19%	-8%	3%	-31%	-46%	-106%

Attachment 4-C– COMPILED TIERED ESTIMATION METHOD PDFS

CLIMATE RESILIENCE DESIGN STANDARDS

TIERED METHODS TO CALCULATE DESIGN CRITERIA VALUES

Version 1.4
DECEMBER 2024

CLIMATE RESILIENCE DESIGN STANDARDS

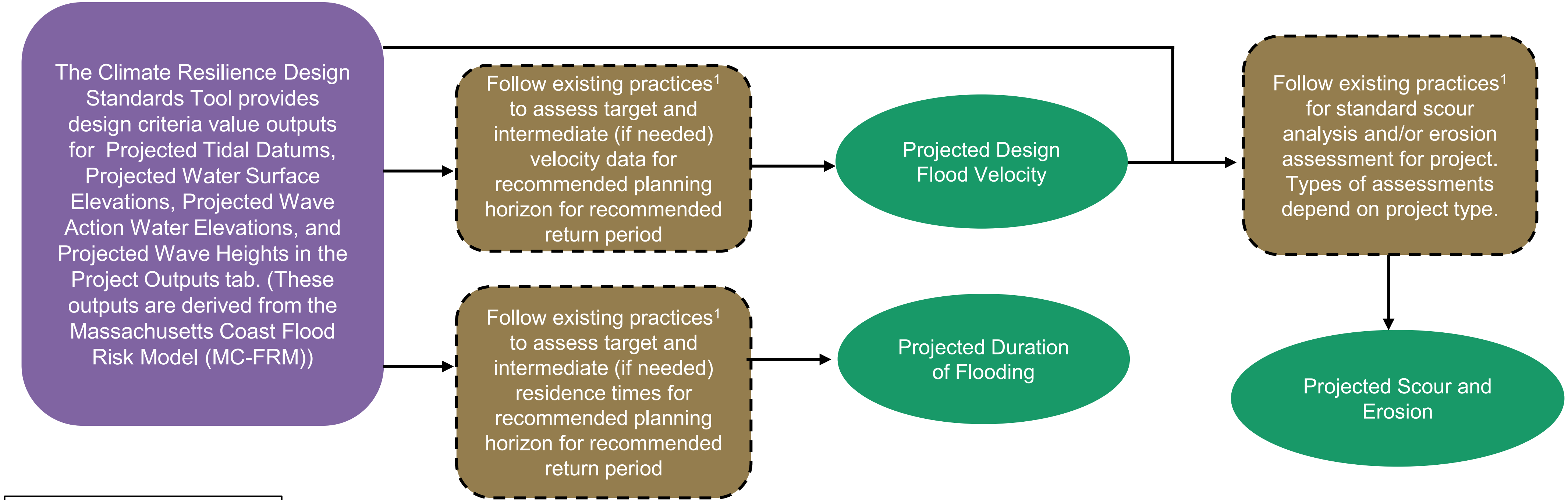
PROJECTED SEA LEVEL RISE / STORM SURGE DESIGN CRITERIA METHODS

ALL TIERS

Version 1.4
DECEMBER 2024

Method to Assess
Projected Sea Level Rise / Storm Surge Design Criteria

Given Standards Output from Tool: Planning Horizon (2030, 2050, 2070); Return Period [Annual Exceedance Probability] (20-yr [5%], 50-yr [2%], 100-yr [1%], 200-yr [0.5%], 500-yr [0.2%], 1000-yr [0.1%])



The Climate Resilience Design Standards Tool provides design criteria value outputs for Projected Tidal Datums, Projected Water Surface Elevations, Projected Wave Elevations, Projected Wave Action Water Elevations, and Projected Wave Heights in the Project Outputs tab. (These outputs are derived from the Massachusetts Coast Flood Risk Model (MC-FRM))

Follow existing practices[1] to assess target and intermediate (if needed) velocity data for recommended planning horizon for recommended return period

Projected Design Flood Velocity

Follow existing practices[1] for standard scour analysis and/or erosion assessment for project. Types of assessments depend on project type.

Projected Scour and Erosion

Follow existing practices[1] to assess target and intermediate (if needed) residence times for recommended planning horizon for recommended return period

Projected Duration of Flooding

Legends
Tool Output ▭
Calculation steps ▭
Design Criteria ⬭
Existing practice ⬚

1. Consult a professional coastal engineer or scientist/modeler to estimate projected Duration of Flooding, Design Flood Velocity, and Scour & Erosion based on the recommended Standards and outputs provided through this Tool.

CLIMATE RESILIENCE DESIGN STANDARDS

PROJECTED TOTAL PRECIPITATION DEPTH DESIGN CRITERIA

TIERED METHODOLOGY

Tier 3 Dams and Flood Control Structure Projects – Pages 2-15

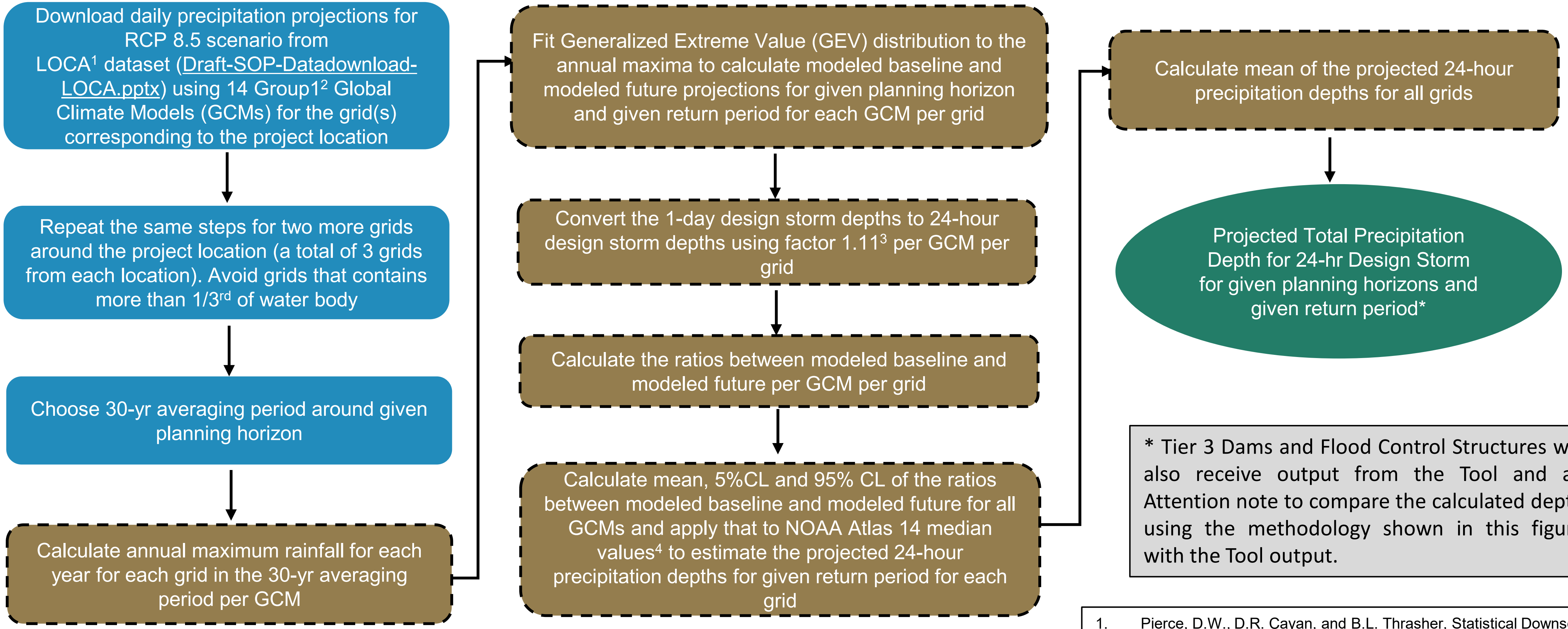
Tier 1 Projects – Pages 16-17

Version 1.4

DECEMBER 2024

Tiered Methodology to Assess Projected Total Precipitation Depth for 24-hr Design Storm
Tier 3 - Dams and Flood Control Structures*

Given Standards Output from Tool: Planning Horizon (2030, 2050, 2070); Return Period (5-yr, 10-yr, 25-yr, 50-yr, 100-yr, 200-yr, 500-yr)



Download daily precipitation projections for RCP 8.5 scenario from LOCA[1] dataset (Draft-SOP-Datadownload-LOCA.pptx) using 14 Group1[2] Global Climate Models (GCMs) for the grid(s) corresponding to the project location

Repeat the same steps for two more grids around the project location (a total of 3 grids from each location). Avoid grids that contains more than 1/3rd of water body

Choose 30-yr averaging period around given planning horizon

Calculate annual maximum rainfall for each year for each grid in the 30-yr averaging period per GCM

Fit Generalized Extreme Value (GEV) distribution to the annual maxima to calculate modeled baseline and modeled future projections for given planning horizon and given return period for each GCM per grid

Convert the 1-day design storm depths to 24-hour design storm depths using factor 1.11[3] per GCM per grid

Calculate the ratios between modeled baseline and modeled future per GCM per grid

Calculate mean, 5%CL and 95% CL of the ratios between modeled baseline and modeled future for all GCMs and apply that to NOAA Atlas 14 median values[4] to estimate the projected 24-hour precipitation depths for given return period for each grid

Calculate mean of the projected 24-hour precipitation depths for all grids

Projected Total Precipitation Depth for 24-hr Design Storm for given planning horizons and given return period*

* Tier 3 Dams and Flood Control Structures will also receive output from the Tool and an Attention note to compare the calculated depth using the methodology shown in this figure with the Tool output.

1. Pierce, D.W., D.R. Cayan, and B.L. Thrasher, Statistical Downscaling Using Localized Constructed Analogs (LOCA). Journal of Hydrometeorology, 2014. 15(6): p. 2558-2585
2. Applying Climate Change Information to Hydrologic and Coastal Design of Transportation Infrastructure (NCHRP Project 15-61- Final Report) by Kilgore et al., 2019
3. NOAA Atlas 14 Precipitation Frequency Estimates: Northeastern States; NOAA Atlas 14, Volume 10, Version 3

Legends

Data Gathering	▭
Calculation steps	▭
Design Criteria	⬭
Existing practice	⬚

VERSION 1.4 METHODS
December 2024

Tiered Methodology to Assess Projected Total Precipitation Depth for 24-hr Design Storm

Tier 3 - Dams and Flood Control Structures (Step 0: Download LOCA Dataset)

- **Go to https://gdo-dcp.ucllnl.org/ to download data from LOCA**
- **Go to page "Projection: Subset Request"**

STEP 1
Go to sub-tab "Page 1. Temporal & Spatial Extent"

Step 0.1.1: "Time Step and Period", select daily period from Jan-1950 through Dec-2099

Step 0.1.2: "Domain", select "NLDAS"

Step 0.1.3: Select "Location" method and either enter the latitude, longitude pair OR specify interactively within the map based on Project Location. If the selected grid includes more than 1/3rd water body, also download data from the adjacent grid.

STEP 2
Go to sub-tab "Page 2. Products, Variables, Projections"

Step 0.2.4: "Select Projection Sets", check "LOCA-CMIP5-Climate-daily"

Step 0.2.5: Under "Products" select both "1/16 degree" boxes. For "Variables", check "Precipitation Rate (mm/dd)"

Step 0.2.6: Under "Emissions Scenarios, Climate Models and Runs", check boxes associated with Group 1 GCMs per NHCRP15-61 report[1], as shown in the Step 2.6 example slide. For each model, select emission scenario RCP8.5 for precipitation.

STEP 3
Go to sub-tab "Page 3. Analysis, Format, and Notification"

Step 0.3.7: "Analysis", keep dial set to "No Analysis"

Step 0.3.8: **"**Output Format", choose "ASCII text, comma-delimited (csv)"

Step 0.3.9: "Notification when Processing is Complete", enter your email address twice.

Finally, check your user type, application type, and applicable resource area(s) as appropriate.

STEP 4
Data request and data download

Step 0.4.1: Press button "Submit Request" on top left

Step 0.4.2: A popup box will appear with details of the submission. Press "Submit". Press "Ok".

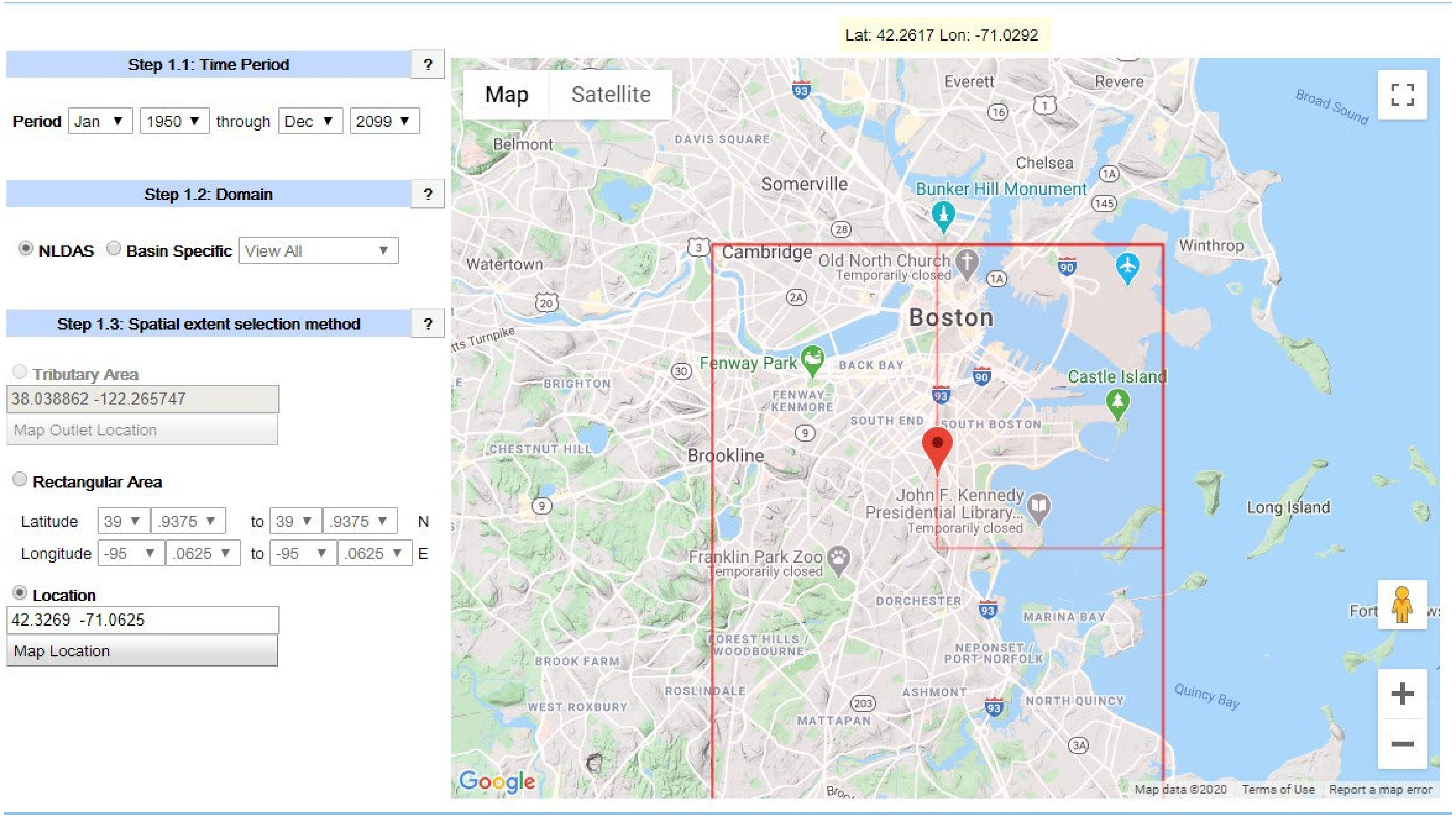
Step 0.4.3: Click on the link that arrives in the email a few hours later to get to an ftp directory of files produced for your job request

Step 0.4.5: Click folder "Loca5" and download the .csv file for the climate projection data and .txt files for data related information

REFERENCES
1. Applying Climate Change Information to Hydrologic and Coastal Design of Transportation Infrastructure (NCHRP Project 15-61- Final Report) by Kilgore et al., 2019

VERSION 1.4 METHODS
December 2024

Download LOCA Dataset (Example: Project Area and Time Selection)
Moakley Park, South Boston, MA



Step 1.1: Time Period ?

Period Jan ▼ 1950 ▼ through Dec ▼ 2099 ▼

Step 1.2: Domain ?

● **NLDAS** ○ **Basin Specific** View All ▼

Step 1.3: Spatial extent selection method ?

○ Tributary Area

38.038862 -122.265747

Map Outlet Location

○ **Rectangular Area**

Latitude	39 ▼ .9375 ▼	to	39 ▼ .9375 ▼	N
Longitude	-95 ▼ .0625 ▼	to	-95 ▼ .0625 ▼	E

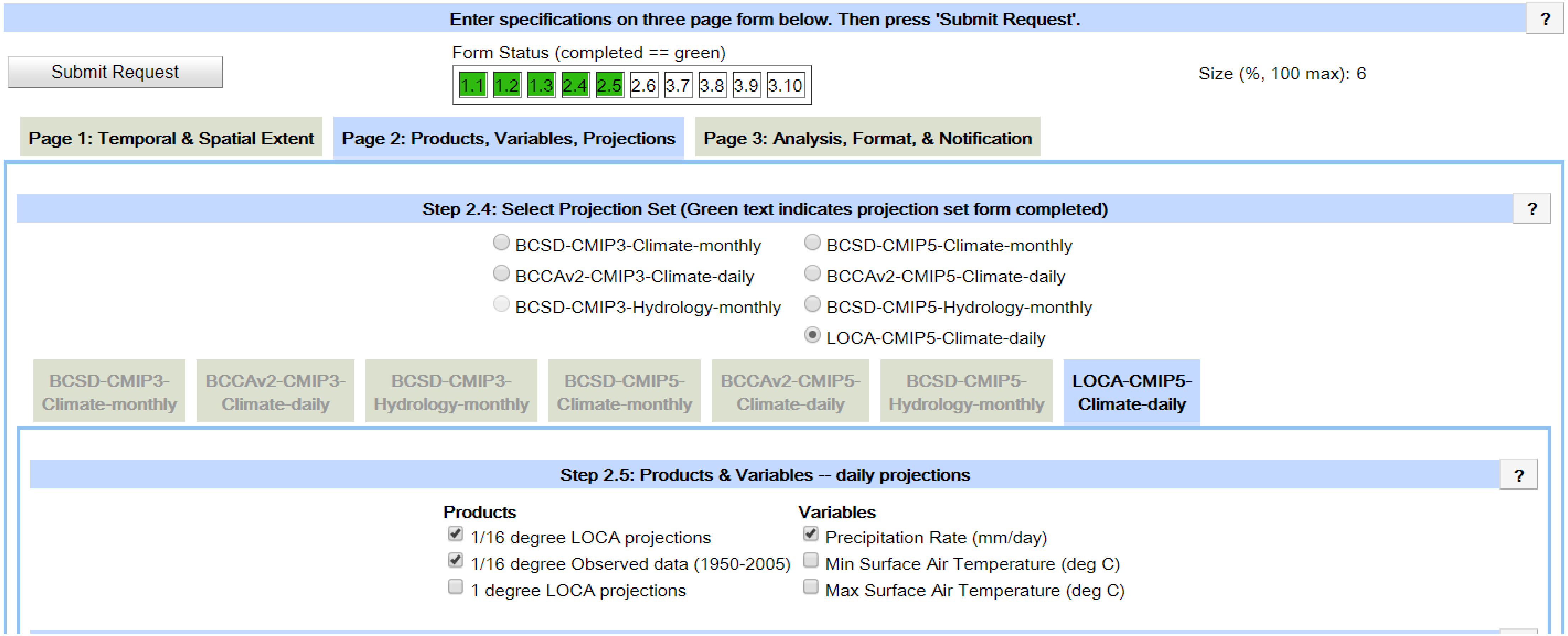
● **Location**

42.3269 -71.0625

Map Location

Lat: 42.2617 Lon: -71.0292

Download LOCA Dataset (Example: Projection Set and Variables Selection)
Moakley Park, South Boston, MA



Enter specifications on three page form below. Then press 'Submit Request'.

Form Status (completed == green)

🟩 1.1	🟩 1.2	🟩 1.3	🟩 2.4	🟩 2.5	2.6	3.7	3.8	3.9	3.10

Size (%, 100 max): 6

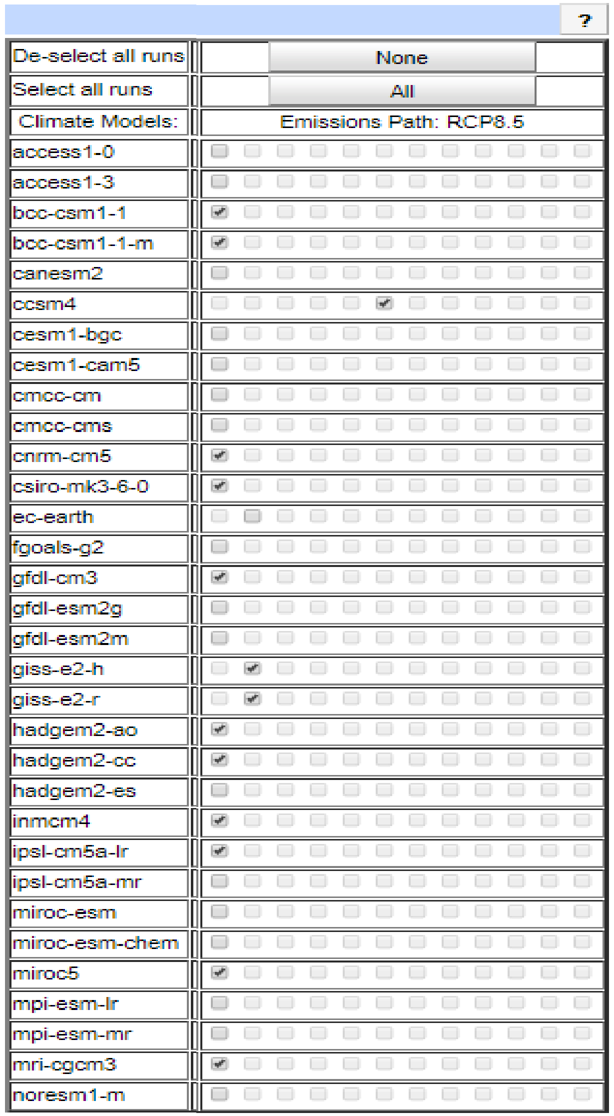
Step 2.4: Select Projection Set (Green text indicates projection set form completed)

○ BCSD-CMIP3-Climate-monthly	○ BCSD-CMIP5-Climate-monthly
○ BCCAv2-CMIP3-Climate-daily	○ BCCAv2-CMIP5-Climate-daily
○ BCSD-CMIP3-Hydrology-monthly	○ BCSD-CMIP5-Hydrology-monthly
	● LOCA-CMIP5-Climate-daily

Step 2.5: Products & Variables -- daily projections

Products	Variables
☑ 1/16 degree LOCA projections	☑ Precipitation Rate (mm/day)
☑ 1/16 degree Observed data (1950-2005)	☐ Min Surface Air Temperature (deg C)
☐ 1 degree LOCA projections	☐ Max Surface Air Temperature (deg C)

Download LOCA Dataset (Example: Group1* GCM Selections for Emission Scenario RCP8.5) Moakley Park, South Boston, MA



De-select all runs	None											
Select all runs	All											
Climate Models:	Emissions Path: RCP8.5											
access1-0	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
access1-3	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
bcc-csm1-1	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
bcc-csm1-1-m	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
canesm2	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
ccsm4	☐	☐	☐	☐	☐	☑	☐	☐	☐	☐	☐	☐
cesm1-bgc	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
cesm1-cam5	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
cmcc-cm	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
cmcc-cms	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
cnrm-cm5	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
csiro-mk3-6-0	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
ec-earth	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
fgoals-g2	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
gfdl-cm3	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
gfdl-esm2g	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
gfdl-esm2m	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
giss-e2-h	☐	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
giss-e2-r	☐	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
hadgem2-ao	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
hadgem2-cc	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
hadgem2-es	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
inmcm4	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
ipsl-cm5a-lr	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
ipsl-cm5a-mr	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
miroc-esm	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
miroc-esm-chem	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
miroc5	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
mpi-esm-lr	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
mpi-esm-mr	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
mri-cgcm3	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
noresm1-m	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

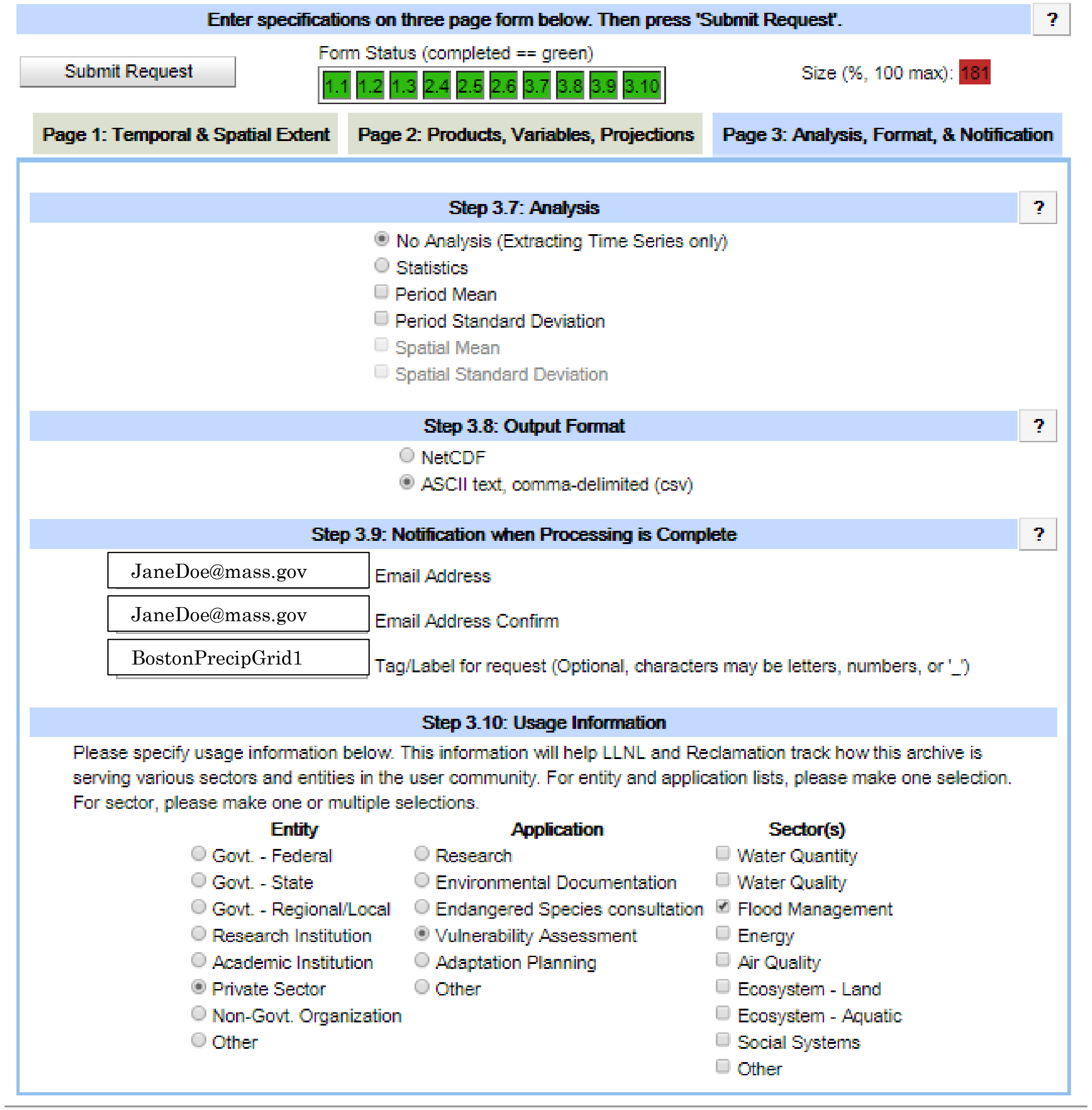
Check the Following Boxes under RCP8.5:

- ✓ bcc-csm-1
- ✓ bcc-csm-1-m
- ✓ ccsm4
- ✓ cnrm-cm5
- ✓ csiro-mk3-6-0
- ✓ gfdl-cm3
- ✓ giss-e2-h
- ✓ giss-e2-r
- ✓ hadgem2-ao
- ✓ hadgem2-cc
- ✓ inmcm4
- ✓ ipsl-cm5a-lr
- ✓ miroc5
- ✓ mri-cgcm3

VERSION 1.4 METHODS
December 2024

* Applying Climate Change Information to Hydrologic and Coastal Design of Transportation Infrastructure (NCHRP Project 15-61- Final Report) by Kilgore et al., 2019

Download LOCA Dataset (Example: Type of Analysis, Output Format, and Others)
Moakley Park, South Boston, MA



Enter specifications on three page form below. Then press 'Submit Request'.

Form Status (completed == green)

1.1 1.2 1.3 2.4 2.5 2.6 3.7 3.8 3.9 3.10

Size (%, 100 max): 181

Step 3.7: Analysis

● No Analysis (Extracting Time Series only)
○ Statistics
☐ Period Mean
☐ Period Standard Deviation
☐ Spatial Mean
☐ Spatial Standard Deviation

Step 3.8: Output Format

○ NetCDF
● ASCII text, comma-delimited (csv)

Step 3.9: Notification when Processing is Complete

JaneDoe@mass.gov Email Address
JaneDoe@mass.gov Email Address Confirm
BostonPrecipGrid1 Tag/Label for request (Optional, characters may be letters, numbers, or '_')

Step 3.10: Usage Information

Please specify usage information below. This information will help LLNL and Reclamation track how this archive is serving various sectors and entities in the user community. For entity and application lists, please make one selection. For sector, please make one or multiple selections.

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○ Research
○ Environmental Documentation
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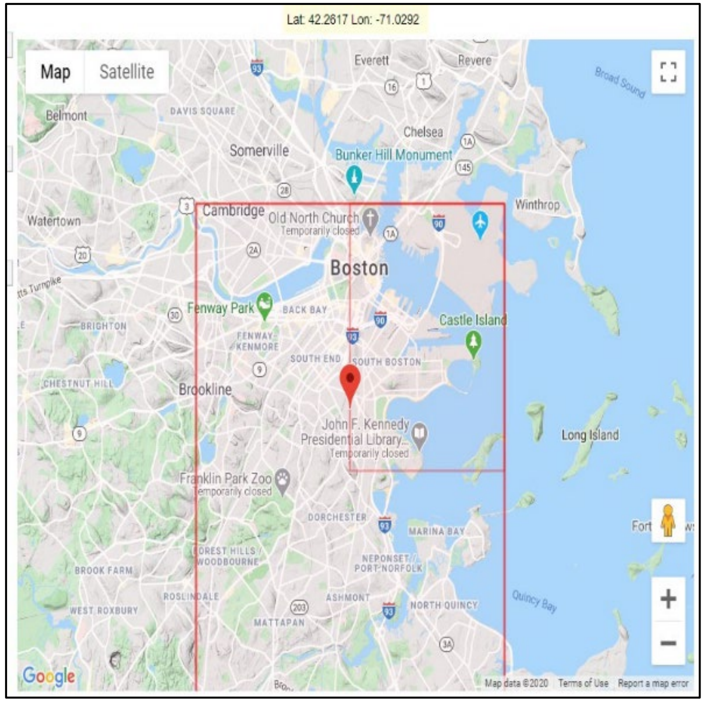
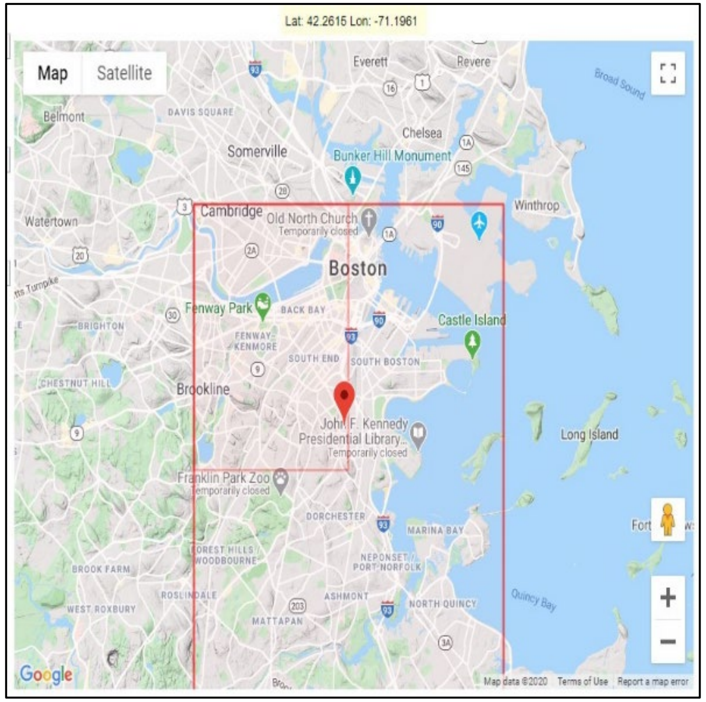
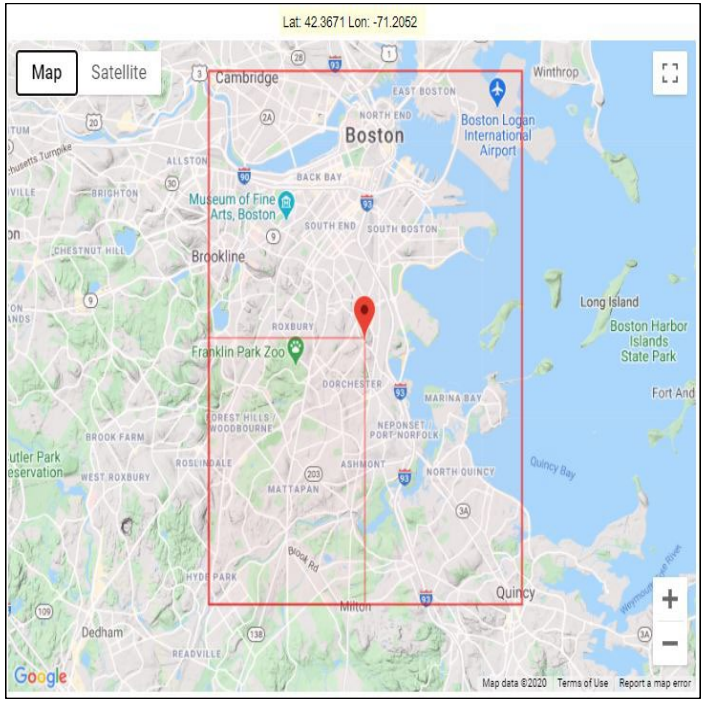
☐ Ecosystem - Land
☐ Ecosystem - Aquatic
☐ Social Systems
☐ Other

Tiered Methodology to Assess Projected Total Precipitation Depth for 24-hr Design Storm
Tier 3 - Dams and Flood Control Structures
(Step 1 Example: Select 2 More Grids Around Project Location to Download LOCA Datasets) Moakley Park, South Boston, MA

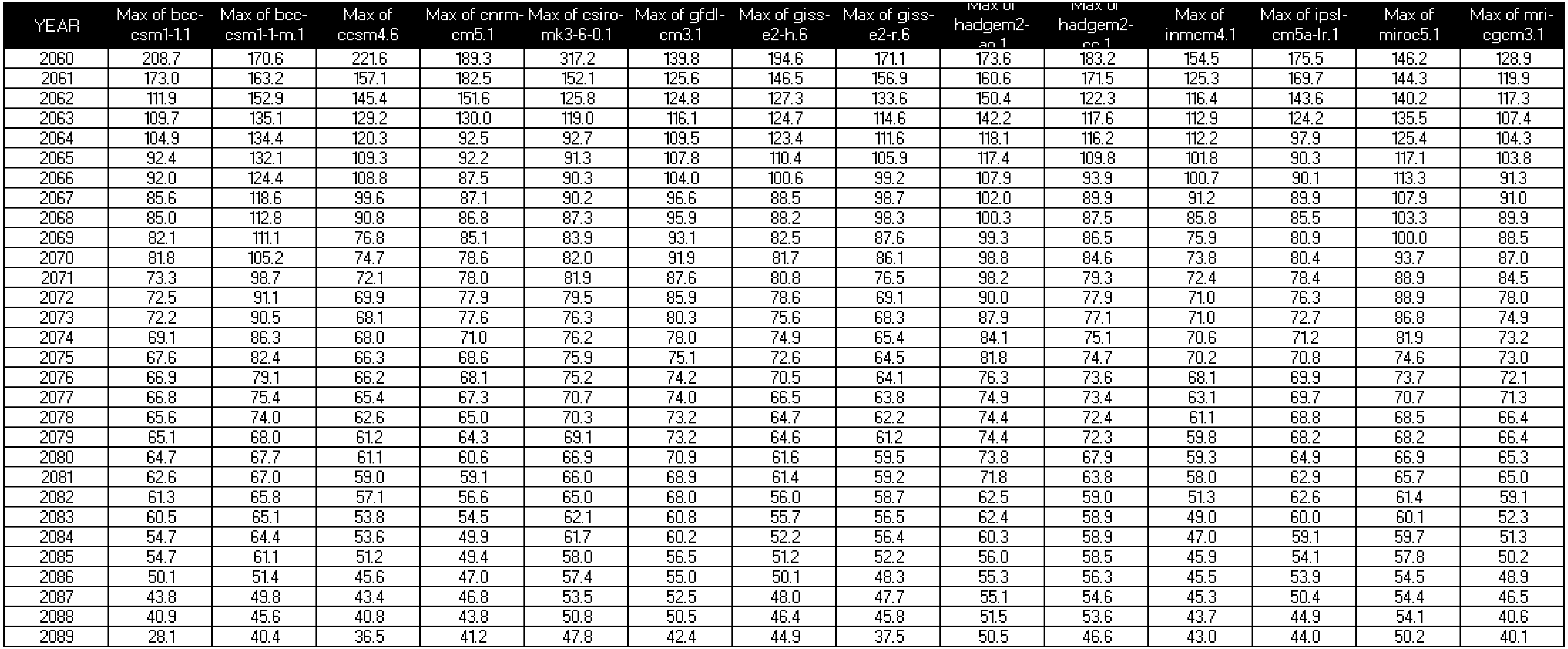






Tiered Methodology to Assess Projected Total Precipitation Depth for 24-hr Design Storm
Tier 3 - Dams and Flood Control Structures

(Step 2 – 3 Example: Calculating Annual Maximum for each GCM for each Grid for RCP 8.5 in the 30 Year Span Surrounding Each Planning Horizon*) Moakley Park, South Boston, MA



YEAR	Max of bcc-csm1-1.1	Max of bcc-csm1-1-m.1	Max of ccsm4.6	Max of cnrm-cm5.1	Max of csiro-mk3-6-0.1	Max of gfdl-cm3.1	Max of giss-e2-h.6	Max of giss-e2-r.6	Max of hadgem2-ao.1	Max of hadgem2-cc.1	Max of inmcm4.1	Max of ipsl-cm5a-lr.1	Max of miroc5.1	Max of mri-cgcm3.1
2060	208.7	170.6	221.6	189.3	317.2	139.8	194.6	171.1	173.6	183.2	154.5	175.5	146.2	128.9
2061	173.0	163.2	157.1	182.5	152.1	125.6	146.5	156.9	160.6	171.5	125.3	169.7	144.3	119.9
2062	111.9	152.9	145.4	151.6	125.8	124.8	127.3	133.6	150.4	122.3	116.4	143.6	140.2	117.3
2063	109.7	135.1	129.2	130.0	119.0	116.1	124.7	114.6	142.2	117.6	112.9	124.2	135.5	107.4
2064	104.9	134.4	120.3	92.5	92.7	109.5	123.4	111.6	118.1	116.2	112.2	97.9	125.4	104.3
2065	92.4	132.1	109.3	92.2	91.3	107.8	110.4	105.9	117.4	109.8	101.8	90.3	117.1	103.8
2066	92.0	124.4	108.8	87.5	90.3	104.0	100.6	99.2	107.9	93.9	100.7	90.1	113.3	91.3
2067	85.6	118.6	99.6	87.1	90.2	96.6	88.5	98.7	102.0	89.9	91.2	89.9	107.9	91.0
2068	85.0	112.8	90.8	86.8	87.3	95.9	88.2	98.3	100.3	87.5	85.8	85.5	103.3	89.9
2069	82.1	111.1	76.8	85.1	83.9	93.1	82.5	87.6	99.3	86.5	75.9	80.9	100.0	88.5
2070	81.8	105.2	74.7	78.6	82.0	91.9	81.7	86.1	98.8	84.6	73.8	80.4	93.7	87.0
2071	73.3	98.7	72.1	78.0	81.9	87.6	80.8	76.5	98.2	79.3	72.4	78.4	88.9	84.5
2072	72.5	91.1	69.9	77.9	79.5	85.9	78.6	69.1	90.0	77.9	71.0	76.3	88.9	78.0
2073	72.2	90.5	68.1	77.6	76.3	80.3	75.6	68.3	87.9	77.1	71.0	72.7	86.8	74.9
2074	69.1	86.3	68.0	71.0	76.2	78.0	74.9	65.4	84.1	75.1	70.6	71.2	81.9	73.2
2075	67.6	82.4	66.3	68.6	75.9	75.1	72.6	64.5	81.8	74.7	70.2	70.8	74.6	73.0
2076	66.9	79.1	66.2	68.1	75.2	74.2	70.5	64.1	76.3	73.6	68.1	69.9	73.7	72.1
2077	66.8	75.4	65.4	67.3	70.7	74.0	66.5	63.8	74.9	73.4	63.1	69.7	70.7	71.3
2078	65.6	74.0	62.6	65.0	70.3	73.2	64.7	62.2	74.4	72.4	61.1	68.8	68.5	66.4
2079	65.1	68.0	61.2	64.3	69.1	73.2	64.6	61.2	74.4	72.3	59.8	68.2	68.2	66.4
2080	64.7	67.7	61.1	60.6	66.9	70.9	61.6	59.5	73.8	67.9	59.3	64.9	66.9	65.3
2081	62.6	67.0	59.0	59.1	66.0	68.9	61.4	59.2	71.8	63.8	58.0	62.9	65.7	65.0
2082	61.3	65.8	57.1	56.6	65.0	68.0	56.0	58.7	62.5	59.0	51.3	62.6	61.4	59.1
2083	60.5	65.1	53.8	54.5	62.1	60.8	55.7	56.5	62.4	58.9	49.0	60.0	60.1	52.3
2084	54.7	64.4	53.6	49.9	61.7	60.2	52.2	56.4	60.3	58.9	47.0	59.1	59.7	51.3
2085	54.7	61.1	51.2	49.4	58.0	56.5	51.2	52.2	56.0	58.5	45.9	54.1	57.8	50.2
2086	50.1	51.4	45.6	47.0	57.4	55.0	50.1	48.3	55.3	56.3	45.5	53.9	54.5	48.9
2087	43.8	49.8	43.4	46.8	53.5	52.5	48.0	47.7	55.1	54.6	45.3	50.4	54.4	46.5
2088	40.9	45.6	40.8	43.8	50.8	50.5	46.4	45.8	51.5	53.6	43.7	44.9	54.1	40.6
2089	28.1	40.4	36.5	41.2	47.8	42.4	44.9	37.5	50.5	46.6	43.0	44.0	50.2	40.1

*This chart shows annual maximums for the 2070s planning horizon only.

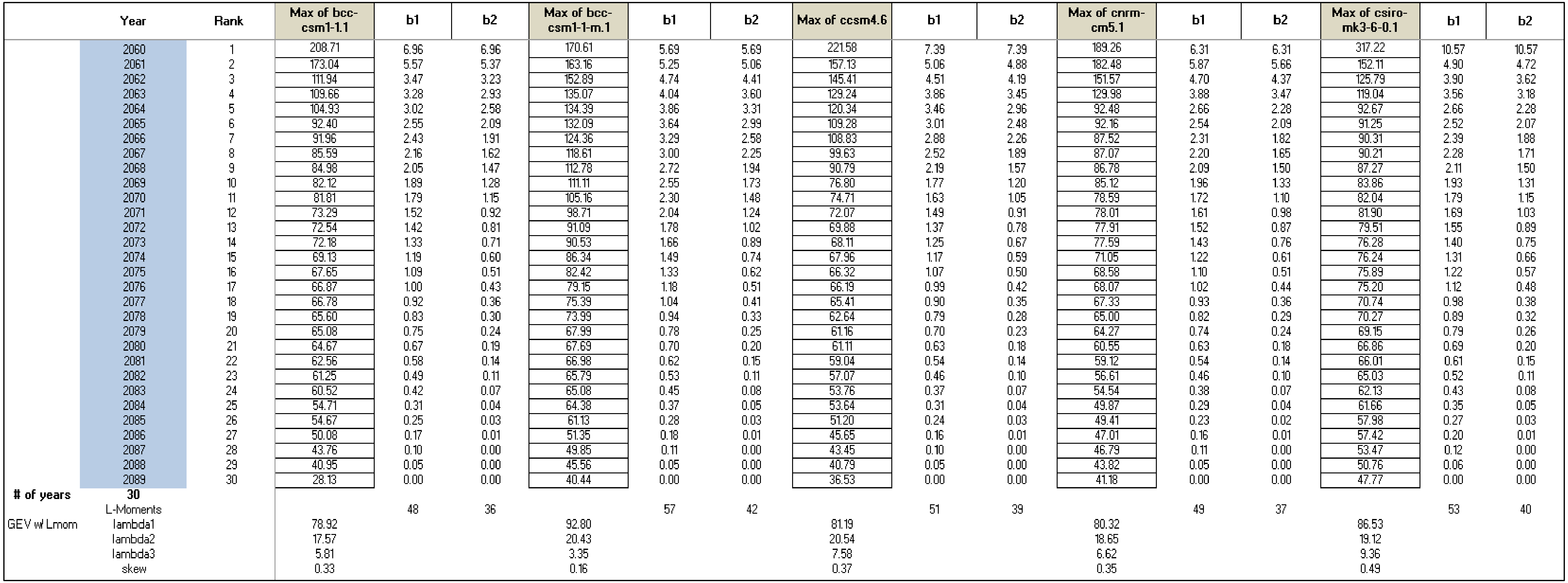
VERSION 1.4 METHODS
December 2024

Tiered Methodology to Assess Projected Total Precipitation Depth for 24-hr Design Storm

Tier 3 - Dams and Flood Control Structures

(Step 4 Example: Fitting GEV Distribution on annual maxima of each grid for each GCM*)

Moakley Park, South Boston, MA



	Year	Rank	Max of bcc-csm1-1.1	b1	b2	Max of bcc-csm1-1-m.1	b1	b2	Max of ccsm4.6	b1	b2	Max of cnrm-cm5.1	b1	b2	Max of csiro-mk3-6-0.1	b1	b2
	2060	1	208.71	6.96	6.96	170.61	5.69	5.69	221.58	7.39	7.39	189.26	6.31	6.31	317.22	10.57	10.57
	2061	2	173.04	5.57	5.37	163.16	5.25	5.06	157.13	5.06	4.88	182.48	5.87	5.66	152.11	4.90	4.72
	2062	3	111.94	3.47	3.23	152.89	4.74	4.41	145.41	4.51	4.19	151.57	4.70	4.37	125.79	3.90	3.62
	2063	4	109.66	3.28	2.93	135.07	4.04	3.60	129.24	3.86	3.45	129.98	3.88	3.47	119.04	3.56	3.18
	2064	5	104.93	3.02	2.58	134.39	3.86	3.31	120.34	3.46	2.96	92.48	2.66	2.28	92.67	2.66	2.28
	2065	6	92.40	2.55	2.09	132.09	3.64	2.99	109.28	3.01	2.48	92.16	2.54	2.09	91.25	2.52	2.07
	2066	7	91.96	2.43	1.91	124.36	3.29	2.58	108.83	2.88	2.26	87.52	2.31	1.82	90.31	2.39	1.88
	2067	8	85.59	2.16	1.62	118.61	3.00	2.25	99.63	2.52	1.89	87.07	2.20	1.65	90.21	2.28	1.71
	2068	9	84.98	2.05	1.47	112.78	2.72	1.94	90.79	2.19	1.57	86.78	2.09	1.50	87.27	2.11	1.50
	2069	10	82.12	1.89	1.28	111.11	2.55	1.73	76.80	1.77	1.20	85.12	1.96	1.33	83.86	1.93	1.31
	2070	11	81.81	1.79	1.15	105.16	2.30	1.48	74.71	1.63	1.05	78.59	1.72	1.10	82.04	1.79	1.15
	2071	12	73.29	1.52	0.92	98.71	2.04	1.24	72.07	1.49	0.91	78.01	1.61	0.98	81.90	1.69	1.03
	2072	13	72.54	1.42	0.81	91.09	1.78	1.02	69.88	1.37	0.78	77.91	1.52	0.87	79.51	1.55	0.89
	2073	14	72.18	1.33	0.71	90.53	1.66	0.89	68.11	1.25	0.67	77.59	1.43	0.76	76.28	1.40	0.75
	2074	15	69.13	1.19	0.60	86.34	1.49	0.74	67.96	1.17	0.59	71.05	1.22	0.61	76.24	1.31	0.66
	2075	16	67.65	1.09	0.51	82.42	1.33	0.62	66.32	1.07	0.50	68.58	1.10	0.51	75.89	1.22	0.57
	2076	17	66.87	1.00	0.43	79.15	1.18	0.51	66.19	0.99	0.42	68.07	1.02	0.44	75.20	1.12	0.48
	2077	18	66.78	0.92	0.36	75.39	1.04	0.41	65.41	0.90	0.35	67.33	0.93	0.36	70.74	0.98	0.38
	2078	19	65.60	0.83	0.30	73.99	0.94	0.33	62.64	0.79	0.28	65.00	0.82	0.29	70.27	0.89	0.32
	2079	20	65.08	0.75	0.24	67.99	0.78	0.25	61.16	0.70	0.23	64.27	0.74	0.24	69.15	0.79	0.26
	2080	21	64.67	0.67	0.19	67.69	0.70	0.20	61.11	0.63	0.18	60.55	0.63	0.18	66.86	0.69	0.20
	2081	22	62.56	0.58	0.14	66.98	0.62	0.15	59.04	0.54	0.14	59.12	0.54	0.14	66.01	0.61	0.15
	2082	23	61.25	0.49	0.11	65.79	0.53	0.11	57.07	0.46	0.10	56.61	0.46	0.10	65.03	0.52	0.11
	2083	24	60.52	0.42	0.07	65.08	0.45	0.08	53.76	0.37	0.07	54.54	0.38	0.07	62.13	0.43	0.08
	2084	25	54.71	0.31	0.04	64.38	0.37	0.05	53.64	0.31	0.04	49.87	0.29	0.04	61.66	0.35	0.05
	2085	26	54.67	0.25	0.03	61.13	0.28	0.03	51.20	0.24	0.03	49.41	0.23	0.02	57.98	0.27	0.03
	2086	27	50.08	0.17	0.01	51.35	0.18	0.01	45.65	0.16	0.01	47.01	0.16	0.01	57.42	0.20	0.01
	2087	28	43.76	0.10	0.00	49.85	0.11	0.00	43.45	0.10	0.00	46.79	0.11	0.00	53.47	0.12	0.00
	2088	29	40.95	0.05	0.00	45.56	0.05	0.00	40.79	0.05	0.00	43.82	0.05	0.00	50.76	0.06	0.00
	2089	30	28.13	0.00	0.00	40.44	0.00	0.00	36.53	0.00	0.00	41.18	0.00	0.00	47.77	0.00	0.00
# of years	**30**																
	L-Moments			48	36		57	42		51	39		49	37		53	40
GEV w/ Lmom	lambda1		78.92			92.80			81.19			80.32			86.53		
	lambda2		17.57			20.43			20.54			18.65			19.12		
	lambda3		5.81			3.35			7.58			6.62			9.36		
	skew		0.33			0.16			0.37			0.35			0.49		

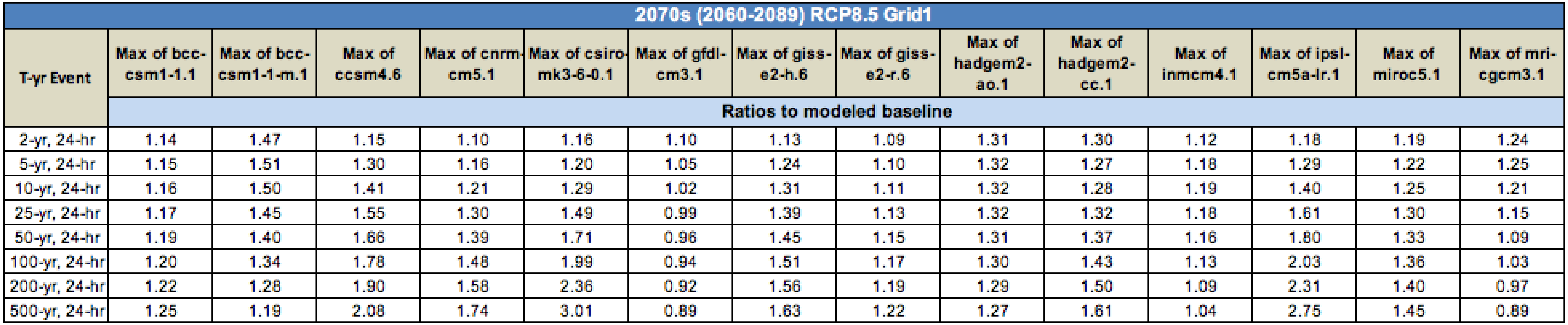
*This chart shows fitting a GEV Distribution on annual maxima of the 2070s planning horizon only.

Tiered Methodology to Assess Projected Total Precipitation Depth for 24-hr Design Storm

Tier 3 - Dams and Flood Control Structures

(Step 5 - 6 Example: Calculate ratios between baseline and future for each GCM for each grid*)

Moakley Park, South Boston, MA



2070s (2060-2089) RCP8.5 Grid1														
T-yr Event	Max of bcc-csm1-1.1	Max of bcc-csm1-1-m.1	Max of ccsm4.6	Max of cnrm-cm5.1	Max of csiro-mk3-6-0.1	Max of gfdl-cm3.1	Max of giss-e2-h.6	Max of giss-e2-r.6	Max of hadgem2-ao.1	Max of hadgem2-cc.1	Max of inmcm4.1	Max of ipsl-cm5a-lr.1	Max of miroc5.1	Max of mri-cgcm3.1
	Ratios to modeled baseline													
2-yr, 24-hr	1.14	1.47	1.15	1.10	1.16	1.10	1.13	1.09	1.31	1.30	1.12	1.18	1.19	1.24
5-yr, 24-hr	1.15	1.51	1.30	1.16	1.20	1.05	1.24	1.10	1.32	1.27	1.18	1.29	1.22	1.25
10-yr, 24-hr	1.16	1.50	1.41	1.21	1.29	1.02	1.31	1.11	1.32	1.28	1.19	1.40	1.25	1.21
25-yr, 24-hr	1.17	1.45	1.55	1.30	1.49	0.99	1.39	1.13	1.32	1.32	1.18	1.61	1.30	1.15
50-yr, 24-hr	1.19	1.40	1.66	1.39	1.71	0.96	1.45	1.15	1.31	1.37	1.16	1.80	1.33	1.09
100-yr, 24-hr	1.20	1.34	1.78	1.48	1.99	0.94	1.51	1.17	1.30	1.43	1.13	2.03	1.36	1.03
200-yr, 24-hr	1.22	1.28	1.90	1.58	2.36	0.92	1.56	1.19	1.29	1.50	1.09	2.31	1.40	0.97
500-yr, 24-hr	1.25	1.19	2.08	1.74	3.01	0.89	1.63	1.22	1.27	1.61	1.04	2.75	1.45	0.89

Future design depth / baseline design depth = ratio

2070s example for 10-yr, 24-hr:
5.267 in. / 4.557 in. = 1.16

*This chart shows ratios for the 2070 planning horizon only.

Tiered Methodology to Assess Projected Total Precipitation Depth for 24-hr Design Storm

Tier 3 - Dams and Flood Control Structures

(Step 7 Example: Calculating mean of the ratios for all GCMs and adding ratios to NOAA Atlas 14 Values*)

Moakley Park, South Boston, MA

2070s (2060-2089) RCP8.5 Grid1											
Return Period	**NOAA 14 Precip. (in.)**	**NOAA 14 Precip. 5% CI (in.)**	**NOAA 14 Precip. 95% CI (in.)**	**No. of Models**	**Mean of ratios**	**Std Dev. of ratios**	**5% CL of ratios**	**95% CL of ratios**	**Projected Precip. (in.)**	**Projected Precip. 5% CI (in.)**	**Projected Precip. 95% CI (in.)**
2-yr	3.3	2.8	3.8	14	1.19	0.11	1.15	1.24	3.9	3.7	4.0
5-yr	4.3	3.6	5.1	14	1.23	0.11	1.18	1.28	5.3	5.1	5.5
10-yr	5.1	4.3	6.1	14	1.26	0.13	1.21	1.32	6.5	6.2	6.7
25-yr	6.3	5.1	8.0	14	1.31	0.18	1.23	1.39	8.2	7.8	8.7
50-yr	7.2	5.6	9.3	14	1.35	0.24	1.25	1.46	9.7	8.9	10.4
100-yr	8.1	6.1	11.0	14	1.41	0.33	1.26	1.55	11.4	10.2	12.6
200-yr	9.3	6.4	12.8	14	1.47	0.45	1.27	1.67	13.6	11.8	15.4
500-yr	11.1	7.3	15.9	14	1.57	0.65	1.29	1.86	17.5	14.3	20.6

*This chart shows NOAA Atlas 14 values and projected total precipitation depths for 24-hr design storms for the 2070 planning horizon using an ensemble of 14 GCMs from LOCA dataset following NCHRP 15-61 methodology.

Tiered Methodology to Assess Projected Total Precipitation Depth for 24-hr Design Storm

Tier 3 - Dams and Flood Control Structures

(Step 8 Example: Calculating mean of the projected 24-hour precipitation depths for all grids*)

Moakley Park, South Boston, MA

2070s (2060-2089) RCP8.5 Average of the Grids			
Return Period	**Projected Precip. (in.)**	**Projected Precip. 5% CI (in.)**	**Projected Precip. 95% CI (in.)**
2-yr	3.8	3.6	4.0
5-yr	5.2	4.9	5.4
10-yr	6.4	6.1	6.7
25-yr	8.1	7.6	8.6
50-yr	9.5	8.8	10.3
100-yr	11.2	10.1	12.4
200-yr	13.5	11.6	15.3
500-yr	17.4	14.1	20.6

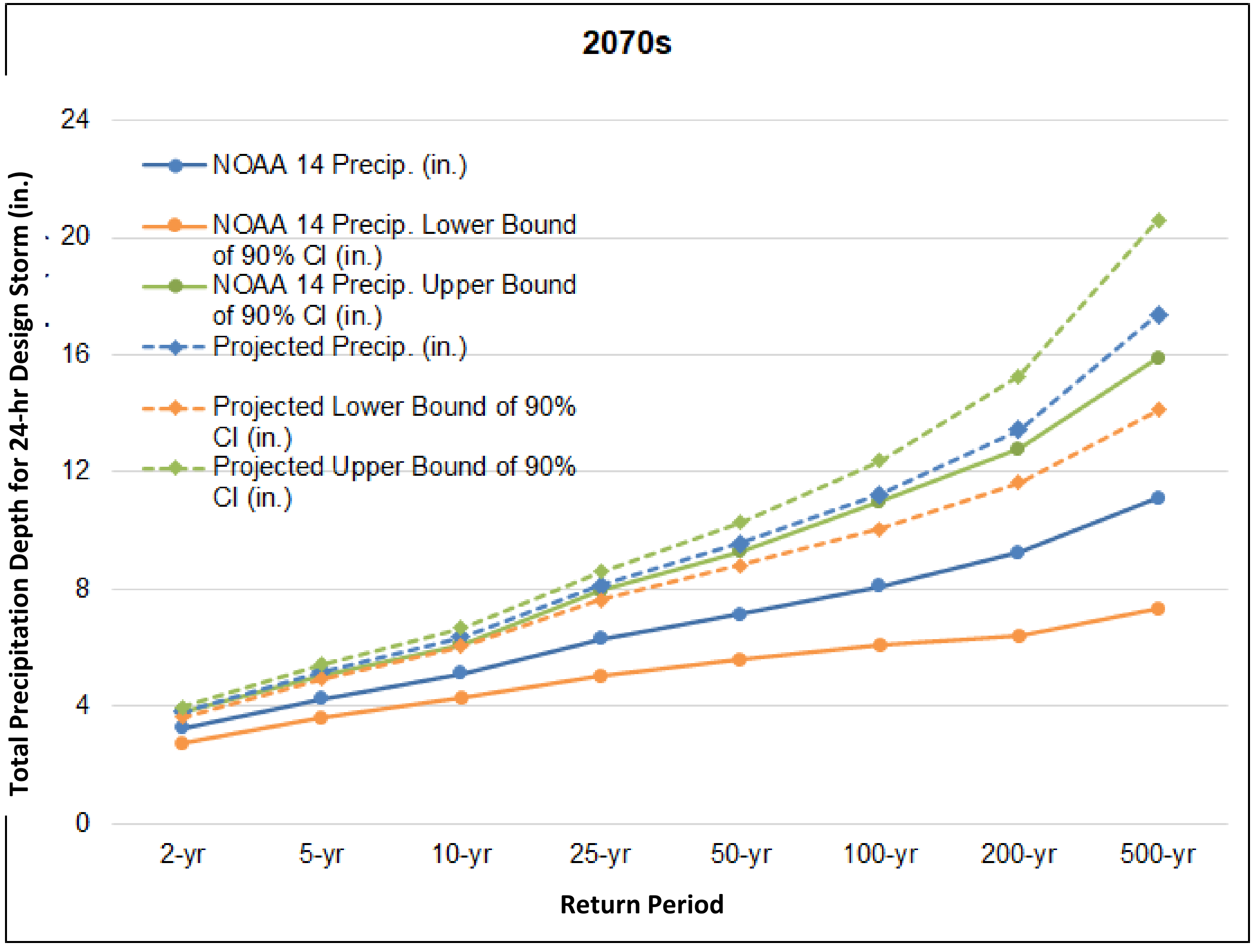
*This chart shows mean of the projected total precipitation depth for 24-hr design storms for the 2070 planning horizon using an ensemble of 14 GCMs from LOCA dataset following NCHRP 15-61 methodology.

Tiered Methodology to Assess Projected Total Precipitation Depth for 24-hr Design Storm

Tier 3 - Dams and Flood Control Structures

(Step 9 Example: Comparing the projected precipitation quantiles with NOAA Atlas 14 historical estimates*)

Moakley Park, South Boston, MA



*This figure shows comparison between projected precipitation quantiles with NOAA Atlas 14 historical estimates for the 2070s planning horizon only.

Tiered Methodology to Assess Projected Total Precipitation Depth for 24-hr Design Storm

Tier 3 - Dams and Flood Control Structures

(Step 11 Example: 24-hr design storm hyetographs for peak intensity for given planning horizon and design storm*)

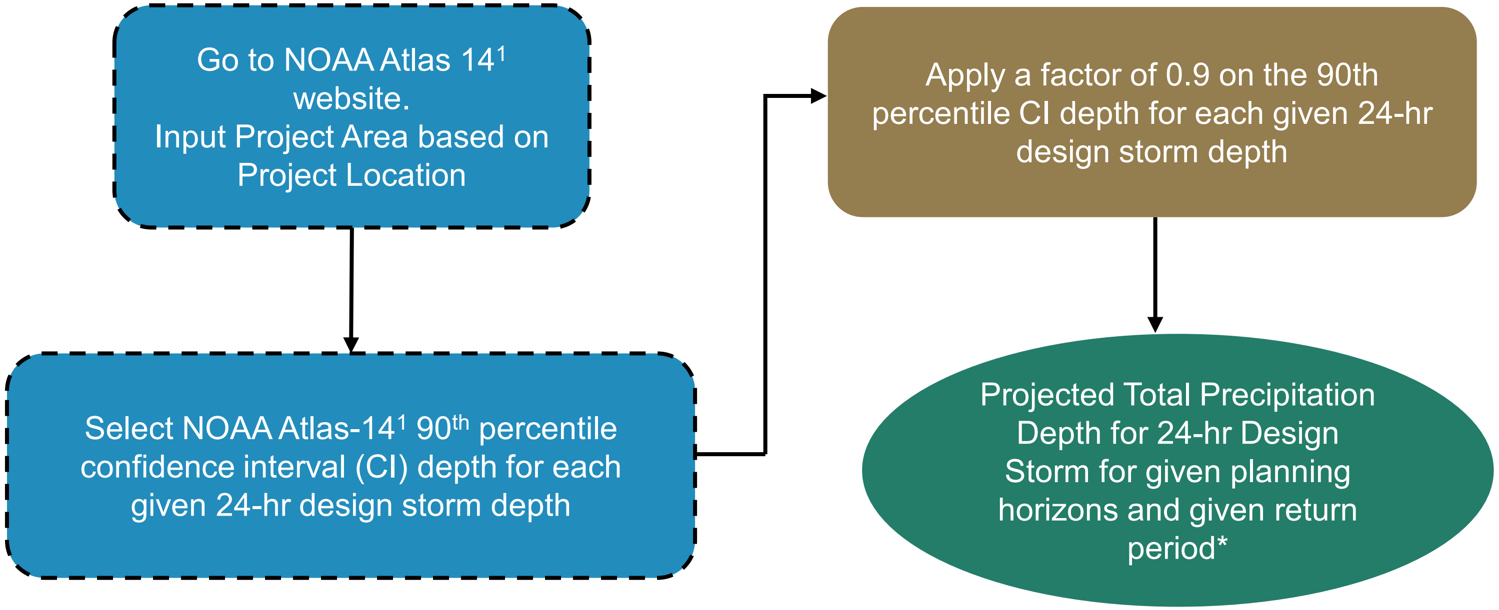
Moakley Park, South Boston, MA

Return Period	NOAA Atlas 14 Present Baseline - 24hr (in)	Tier 3 Projected Total Precip Depth 2070 Values - 24hr (in)
2-yr	3.3	3.8
5-yr	4.3	5.2
10-yr	5.1	6.4
25-yr	6.3	8.1
50-yr	7.2	9.5
100-yr	8.1	11.2
200-yr	9.3	13.5
500-yr	11.1	17.4

*This chart shows mean of the projected total precipitation depth for 24-hr design storms for the 2070 planning horizon using an ensemble of 14 GCMs from LOCA dataset following NCHRP 15-61 methodology.

Tiered Methodology to Assess Projected Total Precipitation Depth for 24-hr Design Storm Tier 1 Projects*

Given Standards Output from Tool: Planning Horizon (2030, 2050, 2070); Return Period (5-yr, 10-yr, 25-yr, 50-yr, 100-yr, 200-yr, 500-yr)



Go to NOAA Atlas 14[1] website.
Input Project Area based on Project Location

Select NOAA Atlas-14[1] 90th percentile confidence interval (CI) depth for each given 24-hr design storm depth

Apply a factor of 0.9 on the 90th percentile CI depth for each given 24-hr design storm depth

Projected Total Precipitation Depth for 24-hr Design Storm for given planning horizons and given return period*

Legends

Data Gathering	▭
Calculation steps	▭
Design Criteria	⬭
Existing practice	⬚

* Tier 1 Projects will also receive output from the Tool and an Attention note to compare the calculated depth using the methodology shown in this figure with the Tool output.

1. NOAA Atlas 14 Precipitation Frequency Estimates: Northeastern States; NOAA Atlas 14, Volume 10, Version 3

Tiered Methodology to Assess Projected Total Precipitation Depth for 24-hr Design Storm

Tier 1 Projects (24-hr design storm depths for recommended return periods)

Moakley Park, South Boston, MA

Return Period	NOAA Atlas 14 Present Baseline - 24hr (in)	NOAA Atlas 14 Present Baseline - 24hr (90th percentile) (in)	Tier 1 90% of 90th percentile of NOAA baseline (in)
2-yr	3.3	3.8	3.4
5-yr	4.3	5.1	4.6
10-yr	5.1	6.1	5.5
25-yr	6.3	8.0	7.2
50-yr	7.2	9.3	8.4
100-yr	8.1	11.0	9.9
200-yr	9.3	12.8	11.5
500-yr	11.1	15.9	14.3

CLIMATE RESILIENCE DESIGN STANDARDS

PROJECTED PEAK INTENSITY DESIGN CRITERIA METHODS

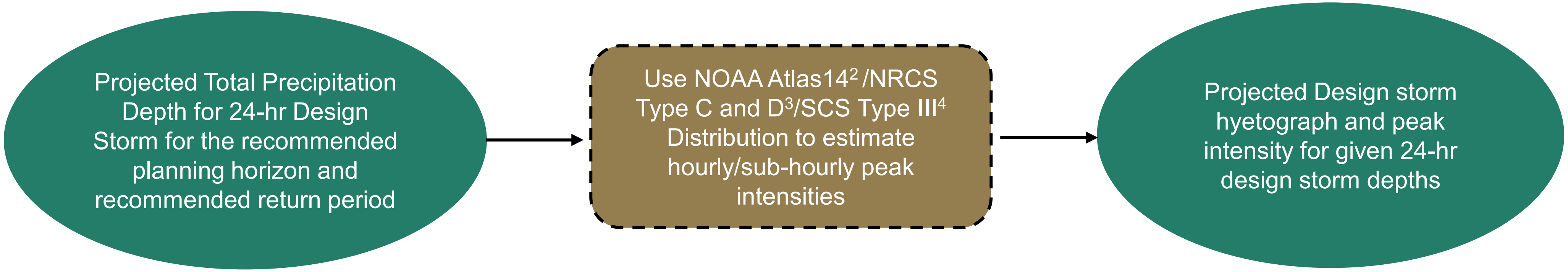
All Tiers

Version 1.4

DECEMBER 2024

Tiered Method to Assess Projected Peak Intensity for All Tiers

Given Standards Output from Tool: Projected Total Precipitation Depth for 24-Hr Design Storm for recommended Planning Horizon (2030, 2050, 2070); Return Period (5-yr, 10-yr, 25-yr, 50-yr, 100-yr, 200-yr, 500-yr)



Projected Total Precipitation Depth for 24-hr Design Storm for the recommended planning horizon and recommended return period

Use NOAA Atlas14[2] /NRCS Type C and D[3]/SCS Type III[4] Distribution to estimate hourly/sub-hourly peak intensities

Projected Design storm hyetograph and peak intensity for given 24-hr design storm depths

Legends

Calculation steps ▭
Design Criteria ⬭
Existing practice ⬚

VERSION 1.4 METHODS
December 2024

1. NOAA Atlas 14 Precipitation Frequency Estimates: Northeastern States; NOAA Atlas 14, Volume 10, Version 3
2. Engineering Field Handbook Chapter 2: Estimating Runoff and Peak Discharges: Massachusetts EFH-2 Supplement Number: MA-EFH2. https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1097125.pdf
3. HEC-HMS Technical Reference Manual – SCS Storm; https://www.hec.usace.army.mil/confluence/hmsdocs/hmstrm/precipitation/scs-storm

Tiered Methodology to Assess Projected Peak Intensity

Example: 24-hr design storm hyetographs for projected peak intensity for given planning horizon and design storm*, Moakley Park, South Boston, MA using SCS Type III Distribution

Return Period	NOAA Atlas 14 Present Baseline - 24hr (in)	Projected Total Precip Depth 2070 Values - 24hr (in)
2-yr	3.3	3.8
5-yr	4.3	5.2
10-yr	5.1	6.4
25-yr	6.3	8.1
50-yr	7.2	9.5
100-yr	8.1	11.2
200-yr	9.3	13.5
500-yr	11.1	17.4

*These charts show 24-hr design storm hyetographs for peak intensity for the 2070s planning horizon only

10yr - 24 hr 2070s		6.4 in	
Duration (hr)	Ratio	Cumulative depth (in.)	Hourly peak intensity (in./hr)
0	0	0	0
1	0.01	0.06	0.06
2	0.02	0.13	0.06
3	0.03	0.19	0.07
4	0.04	0.27	0.08
5	0.06	0.36	0.09
6	0.07	0.45	0.10
7	0.09	0.57	0.12
8	0.11	0.72	0.15
9	0.15	0.92	0.20
10	0.19	1.19	0.27
11	0.25	1.58	0.38
12	0.50	3.15	1.58
13	0.75	4.73	1.58
14	0.81	5.11	0.38
15	0.85	5.38	0.27
16	0.89	5.58	0.20
17	0.91	5.73	0.15
18	0.93	5.85	0.12
19	0.94	5.94	0.10
20	0.96	6.03	0.09
21	0.97	6.11	0.08
22	0.98	6.18	0.07
23	0.99	6.24	0.06
24	1	6.30	0.06

CLIMATE RESILIENCE DESIGN STANDARDS

PROJECTED RIVERINE DESIGN CRITERIA
TIERED METHODS

Tier 3 & 2 Projects – Page 2

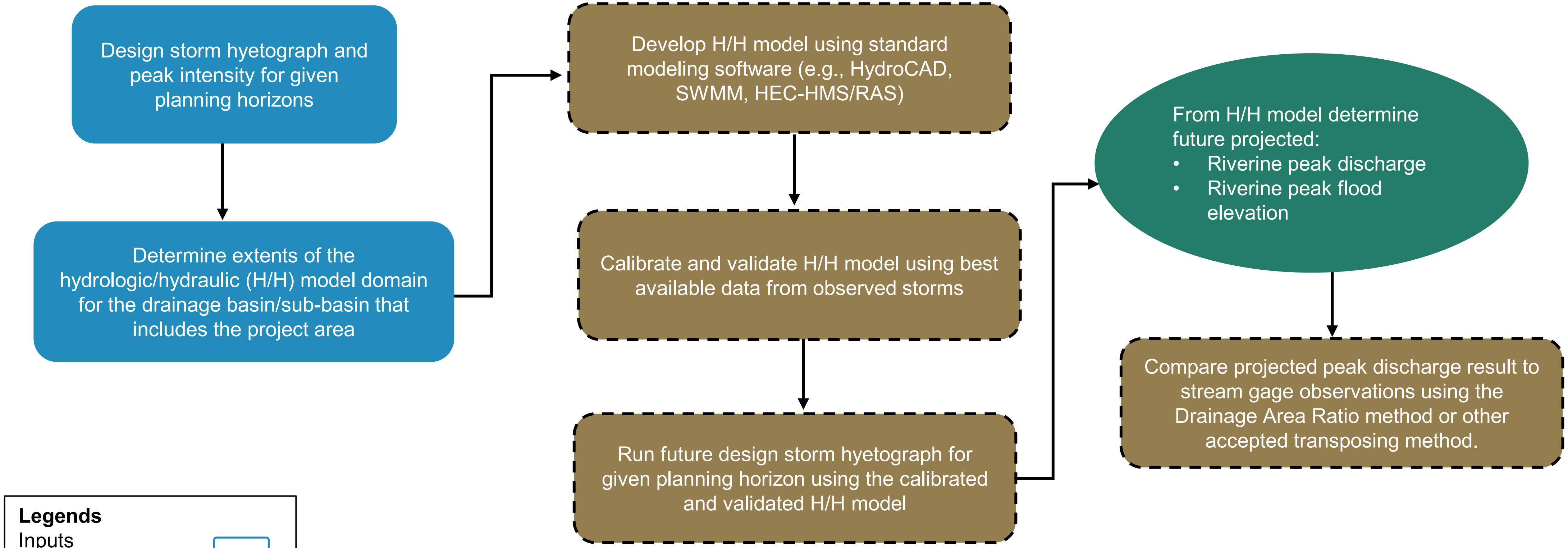
Tier 1 Projects – Page 3

Version 1.4

DECEMBER 2024

Tiered Method to Assess Projected Riverine Peak Discharge Criteria For Tier 3/Tier 2 Projects

Given Standards Output from Tool: Projected 24-hour Design Storm for Recommended Planning Horizon (2030, 2050, 2070); Recurrence Interval (5-yr, 10-yr, 25-yr, 50-yr, 100-yr, 200-yr, 500-yr)



Design storm hyetograph and peak intensity for given planning horizons

Determine extents of the hydrologic/hydraulic (H/H) model domain for the drainage basin/sub-basin that includes the project area

Develop H/H model using standard modeling software (e.g., HydroCAD, SWMM, HEC-HMS/RAS)

Calibrate and validate H/H model using best available data from observed storms

Run future design storm hyetograph for given planning horizon using the calibrated and validated H/H model

From H/H model determine future projected:
- Riverine peak discharge
- Riverine peak flood elevation

Compare projected peak discharge result to stream gage observations using the Drainage Area Ratio method or other accepted transposing method.

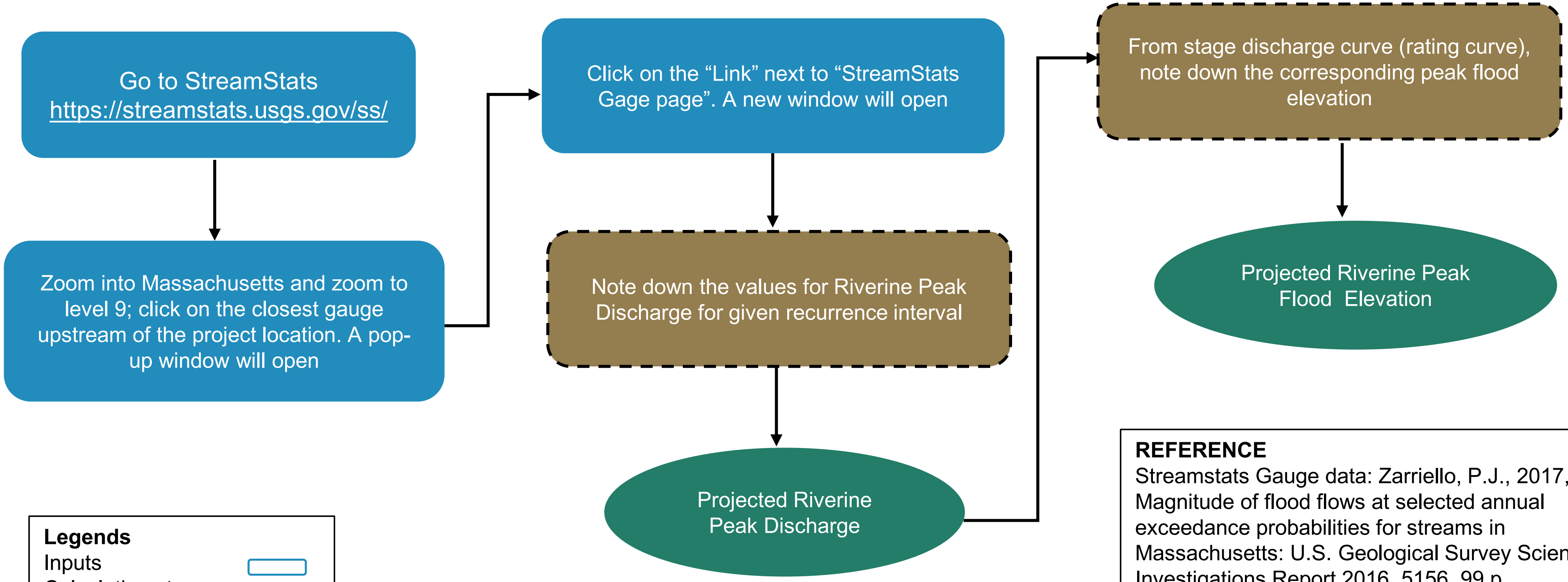
Legends

Inputs	▭
Calculation steps	▭
Outputs	⬭
Existing practice	⬚

VERSION 1.4 METHODS
December 2024

Tiered Method to Assess Projected Riverine Peak Discharge Criteria For Tier 1 Projects

Given Standards Output from Tool: Projected 24-hour Design Storm for Recommended Planning Horizon (2030, 2050, 2070); Recurrence Interval (5-yr, 10-yr, 25-yr, 50-yr, 100-yr, 200-yr, 500-yr)



Go to StreamStats
https://streamstats.usgs.gov/ss/

Zoom into Massachusetts and zoom to level 9; click on the closest gauge upstream of the project location. A pop-up window will open

Click on the “Link” next to “StreamStats Gage page”. A new window will open

Note down the values for Riverine Peak Discharge for given recurrence interval

Projected Riverine Peak Discharge

From stage discharge curve (rating curve), note down the corresponding peak flood elevation

Projected Riverine Peak Flood Elevation

REFERENCE
Streamstats Gauge data: Zarriello, P.J., 2017, Magnitude of flood flows at selected annual exceedance probabilities for streams in Massachusetts: U.S. Geological Survey Scientific Investigations Report 2016, 5156, 99 p.

Legends
Inputs ▭
Calculation steps ▭
Outputs ⬭
Existing practice ⬚

VERSION 1.4 METHODS
December 2024

CLIMATE RESILIENCE DESIGN STANDARDS

PROJECTED HEAT INDEX DESIGN CRITERIA TIERED METHODS

Tier 3 Projects – Pages 2-9

Tier 2 & 1 Projects – Page 10

Version 1.4

DECEMBER 2024

Tiered Method to Assess Projected Heat Index
Tier 3 Projects (Highest Level of Effort)

Given from Standards Output: Average Temperature for recommended Planning Horizon (2030, 2050, 2070); Percentile (50th, 90th)

Step 0: Download data from MACA[1] dataset for the following parameters for RCP8.5 using Group 1[2] GCMs

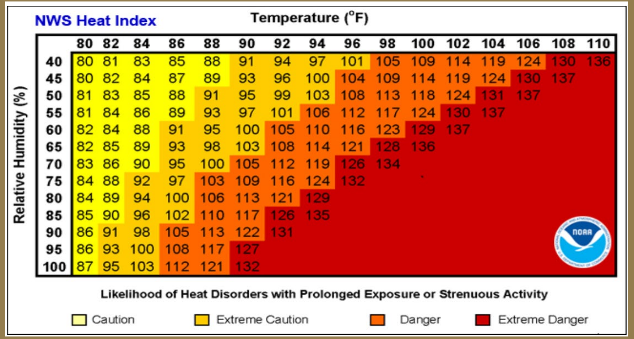
- rhsmax (Maximum Rel. Humidity)

Step 1: Choose 30-yr averaging period around the given planning horizon

Step 3a: Calculate average relative humidity of each year per GCM, for the given planning horizon

Step 3b: Projected 50th, and 90th average temperature for the recommended planning horizon and recommended return period

Step 4: Estimate heat index for given planning horizon using the equation from NOAA[3], also visualized in the following table from NOAA[4]



NWS Heat Index

Temperature (°F)

Relative Humidity (%)	80	82	84	86	88	90	92	94	96	98	100	102	104	106	108	110
40	80	81	83	85	88	91	94	97	101	105	109	114	119	124	130	136
45	80	82	84	87	89	93	96	100	104	109	114	119	124	130	137	
50	81	83	85	88	91	95	99	103	108	113	118	124	131	137		
55	81	84	86	89	93	97	101	106	112	117	124	130	137			
60	82	84	88	91	95	100	105	110	116	123	129	137				
65	82	85	89	93	98	103	108	114	121	128	136					
70	83	86	90	95	100	105	112	119	126	134						
75	84	88	92	97	103	109	116	124	132							
80	84	89	94	100	106	113	121	129								
85	85	90	96	102	110	117	126	135								
90	86	91	98	105	113	122	131									
95	86	93	100	108	117	127										
100	87	95	103	112	121	132										

Likelihood of Heat Disorders with Prolonged Exposure or Strenuous Activity

🟨 Caution 🟨 Extreme Caution 🟧 Danger 🟥 Extreme Danger

Step 5: Calculate the 50th and 90th percentiles of heat index per GCM per year for the 30-yr averaging period around given planning horizon

Step 6: Calculate the average of all GCMs for each of the 50th and 90th percentiles for projected heat index for the 30-yr averaging period around the given planning horizon

Step 6: Projected heat index for given planning horizon

Legends

Data Gathering ▭

Calculation steps ▭

Design Criteria ⬭

REFERENCES

1. Abatzoglou J.T. and Brown T.J. A comparison of statistical downscaling methods suited for wildfire applications, International Journal of Climatology (2012), 32, 772-780
2. Applying Climate Change Information to Hydrologic and Coastal Design of Transportation Infrastructure (NCHRP Project 15-61-Final Report) by Kilgore et al., 2019
3. National Oceanic and Atmospheric Administration (NOAA). 2014. The Heat Index Equation. https://www.wpc.ncep.noaa.gov/html/heatindex_equation.shtml
4. National Oceanic and Atmospheric Administration (NOAA).n.d. Heat Index. https://www.weather.gov/safety/heat-index

Tiered Method to Assess Projected Heat Index - Tier 3 Projects
(Step 0: Complete MACA data download)

- **Go to https://climate.northwestknowledge.net/MACA/data_portal.php to download data from Multivariate Adaptive Constructed Analogs (MACA) data portal**

STEP 1
Domain selection

STEP 2
Products, Time frequency, Variables selection

STEP 2 (..cont.)
Model, Emission Scenarios, Time periods selection

STEP 3
Data download

Step 0.1.1: Select “Rectangular Subset” from “Domain” dropdown list

Step 0.1.2: A rectangle will appear on the interactive map. Move the rectangle and place it around the project area. Increase or decrease the size of the rectangle based on the area you want to cover around the location. Make sure that water body does not cover more than 1/3rd of your grid.

Step 0.1.3: Select “files of URLs for downloading data” from “Download Format” dropdown list

Step 0.2.1: “MACA Product” : “MACAv2-METDATA”

Step 0.2.2: “Time Frequency” : “daily”

Step 0.2.3: “Variables” : Check boxes for the climate parameters relevant to the project for examples,

- “rhsmax (Maximum Relative Humidity)”

Step 0.2.4: “CMIP5 Models” : Check boxes for all the Group 1 models from NCHRP report[1]

Step 0.2.5: “CMIP5 Scenarios/Time Periods” : Check boxes for the following parameters for

- “**RCP8.5**” : “future RCP8.5 (2006-2099)”

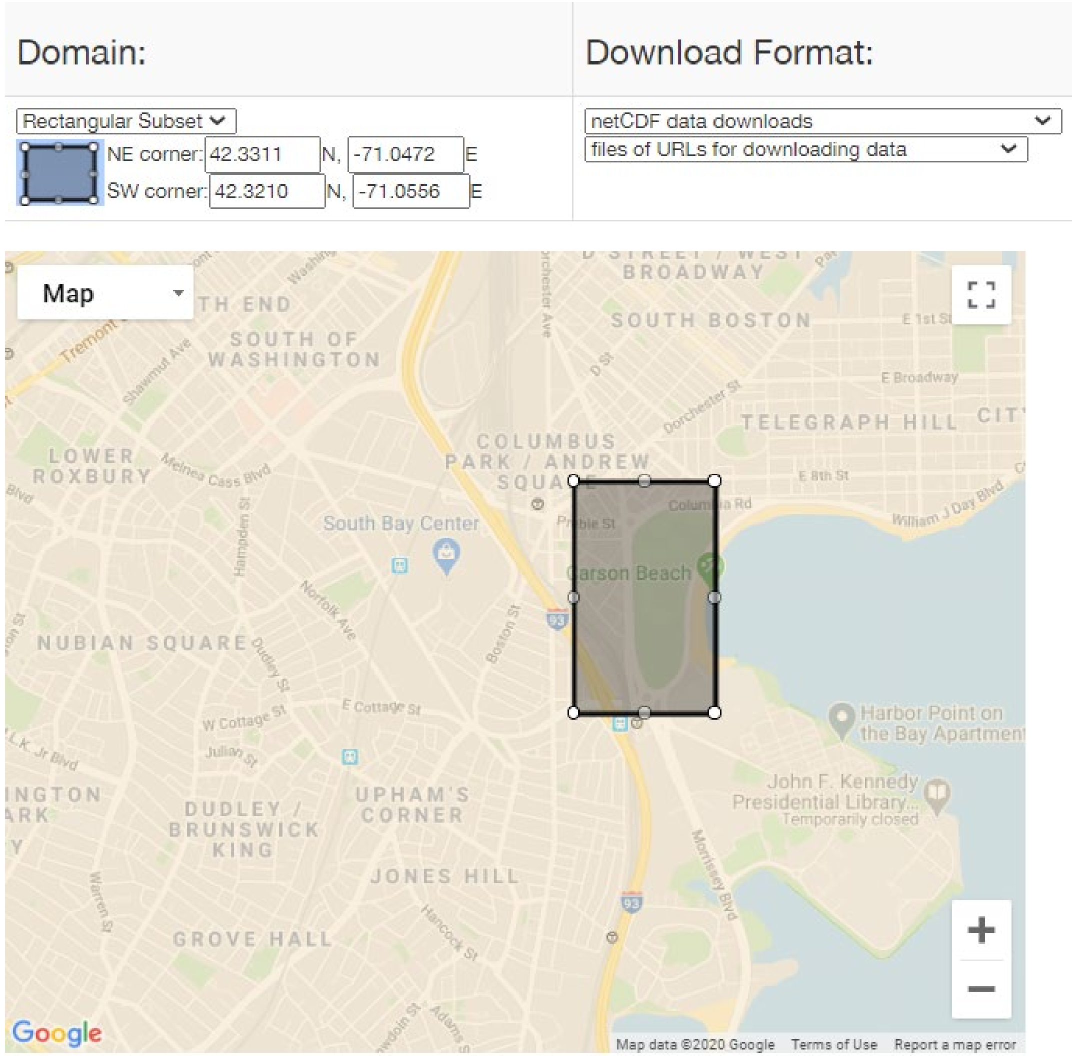
Step 0.3.1: Press button “Download file“ on top right

Step 0.3.2: Open the text file to extract the downloaded data

Step 0.3.3: Climate projection files are downloaded as Netcdf files. Convert the files in your preferred file format for climate projection analysis

REFERENCES
1. Applying Climate Change Information to Hydrologic and Coastal Design of Transportation Infrastructure (NCHRP Project 15-61- Final Report) by Kilgore et al., 2019

Download MACA Dataset
(Example: Project Area, and Download Format Selection)



Domain:

Rectangular Subset

NE corner: 42.3311 N, -71.0472 E

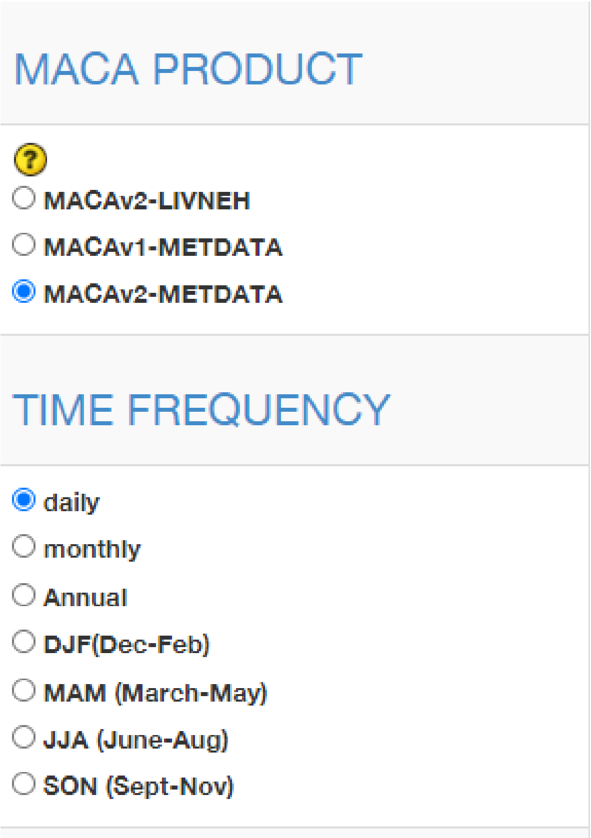
SW corner: 42.3210 N, -71.0556 E

Download Format:

netCDF data downloads

files of URLs for downloading data

Download MACA Dataset
(Example: Product, Time Frequency, and Variables Selection)

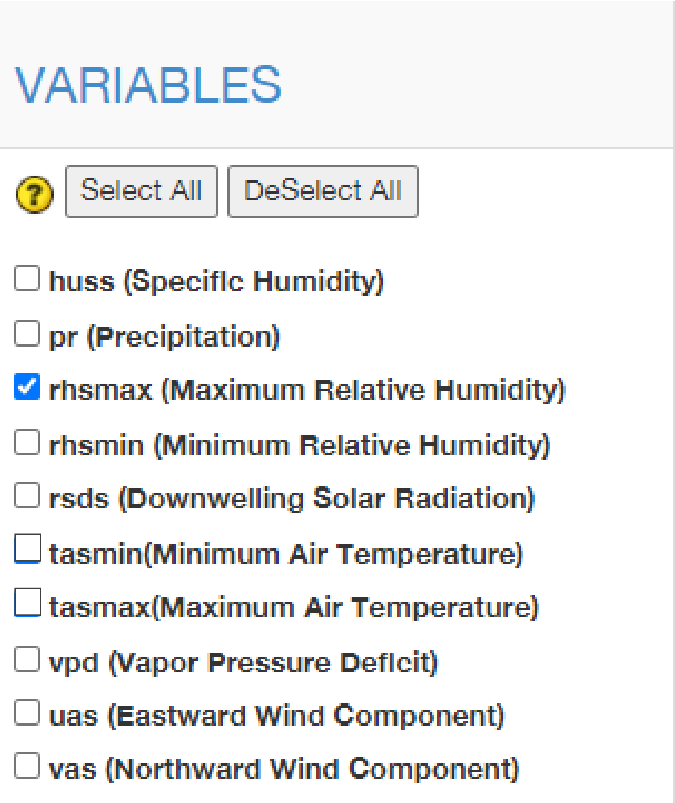


MACA PRODUCT

○ MACAv2-LIVNEH
○ MACAv1-METDATA
● MACAv2-METDATA

TIME FREQUENCY

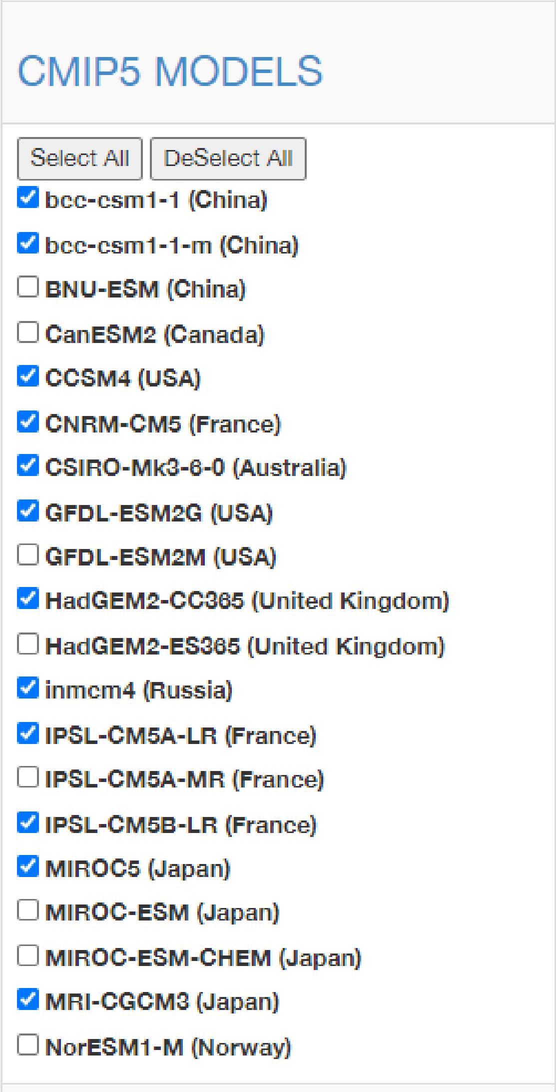
● daily
○ monthly
○ Annual
○ DJF(Dec-Feb)
○ MAM (March-May)
○ JJA (June-Aug)
○ SON (Sept-Nov)



VARIABLES

☐ huss (Specific Humidity)
☐ pr (Precipitation)
☑ rhsmax (Maximum Relative Humidity)
☐ rhsmin (Minimum Relative Humidity)
☐ rsds (Downwelling Solar Radiation)
☐ tasmin(Minimum Air Temperature)
☐ tasmax(Maximum Air Temperature)
☐ vpd (Vapor Pressure Deficit)
☐ uas (Eastward Wind Component)
☐ vas (Northward Wind Component)

Download MACA Dataset (Example: Group1[1] GCM Selections)



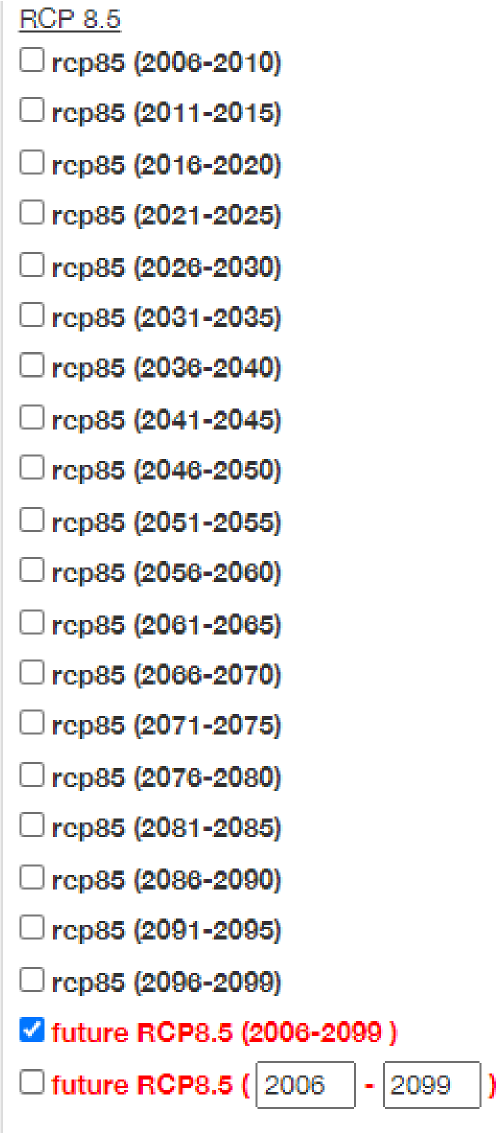
CMIP5 MODELS

- ☑ bcc-csm1-1 (China)
- ☑ bcc-csm1-1-m (China)
- ☐ BNU-ESM (China)
- ☐ CanESM2 (Canada)
- ☑ CCSM4 (USA)
- ☑ CNRM-CM5 (France)
- ☑ CSIRO-Mk3-6-0 (Australia)
- ☑ GFDL-ESM2G (USA)
- ☐ GFDL-ESM2M (USA)
- ☑ HadGEM2-CC365 (United Kingdom)
- ☐ HadGEM2-ES365 (United Kingdom)
- ☑ inmcm4 (Russia)
- ☑ IPSL-CM5A-LR (France)
- ☐ IPSL-CM5A-MR (France)
- ☑ IPSL-CM5B-LR (France)
- ☑ MIROC5 (Japan)
- ☐ MIROC-ESM (Japan)
- ☐ MIROC-ESM-CHEM (Japan)
- ☑ MRI-CGCM3 (Japan)
- ☐ NorESM1-M (Norway)

REFERENCES

1. Applying Climate Change Information to Hydrologic and Coastal Design of Transportation Infrastructure (NCHRP Project 15-61- Final Report) by Kilgore et al., 2019

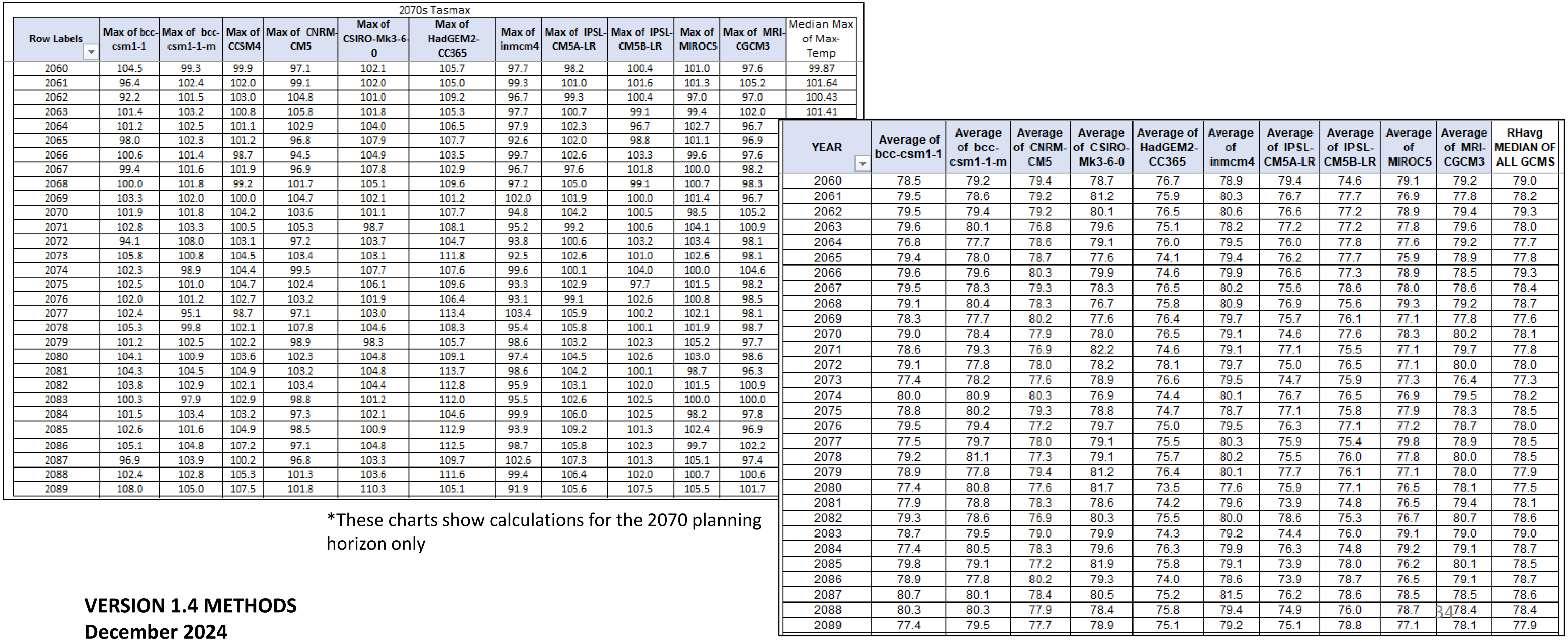
Download MACA Dataset (Example: Emission Scenario (RCP8.5) and Time Selection)



RCP 8.5

☐ rcp85 (2006-2010)
☐ rcp85 (2011-2015)
☐ rcp85 (2016-2020)
☐ rcp85 (2021-2025)
☐ rcp85 (2026-2030)
☐ rcp85 (2031-2035)
☐ rcp85 (2036-2040)
☐ rcp85 (2041-2045)
☐ rcp85 (2046-2050)
☐ rcp85 (2051-2055)
☐ rcp85 (2056-2060)
☐ rcp85 (2061-2065)
☐ rcp85 (2066-2070)
☐ rcp85 (2071-2075)
☐ rcp85 (2076-2080)
☐ rcp85 (2081-2085)
☐ rcp85 (2086-2090)
☐ rcp85 (2091-2095)
☐ rcp85 (2096-2099)
☑ future RCP8.5 (2006-2099)
☐ future RCP8.5 (2006 - 2099)

Tiered Method to
Assess Projected Heat Index - Tier 3 Projects
(Step 3 Example: Calculate the median max. temp. and median avg. rel. Humidity*)
Moakley Park, South Boston, MA



2070s Tasmax

Row Labels	Max of bcc-csm1-1	Max of bcc-csm1-1-m	Max of CCSM4	Max of CNRM-CM5	Max of CSIRO-Mk3-6-0	Max of HadGEM2-CC365	Max of inmcm4	Max of IPSL-CM5A-LR	Max of IPSL-CM5B-LR	Max of MIROC5	Max of MRI-CGCM3	Median Max of Max-Temp
2060	104.5	99.3	99.9	97.1	102.1	105.7	97.7	98.2	100.4	101.0	97.6	99.87
2061	96.4	102.4	102.0	99.1	102.0	105.0	99.3	101.0	101.6	101.3	105.2	101.64
2062	92.2	101.5	103.0	104.8	101.0	109.2	96.7	99.3	100.4	97.0	97.0	100.43
2063	101.4	103.2	100.8	105.8	101.8	105.3	97.7	100.7	99.1	99.4	102.0	101.41
2064	101.2	102.5	101.1	102.9	104.0	106.5	97.9	102.3	96.7	102.7	96.7	
2065	98.0	102.3	101.2	96.8	107.9	107.7	92.6	102.0	98.8	101.1	96.9	
2066	100.6	101.4	98.7	94.5	104.9	103.5	99.7	102.6	103.3	99.6	97.6	
2067	99.4	101.6	101.9	96.9	107.8	102.9	96.7	97.6	101.8	100.0	98.2	
2068	100.0	101.8	99.2	101.7	105.1	109.6	97.2	105.0	99.1	100.7	98.3	
2069	103.3	102.0	100.0	104.7	102.1	101.2	102.0	101.9	100.0	101.4	96.7	
2070	101.9	101.8	104.2	103.6	101.1	107.7	94.8	104.2	100.5	98.5	105.2	
2071	102.8	103.3	100.5	105.3	98.7	108.1	95.2	99.2	100.6	104.1	100.9	
2072	94.1	108.0	103.1	97.2	103.7	104.7	93.8	100.6	103.2	103.4	98.1	
2073	105.8	100.8	104.5	103.4	103.1	111.8	92.5	102.6	101.0	102.6	98.1	
2074	102.3	98.9	104.4	99.5	107.7	107.6	99.6	100.1	104.0	100.0	104.6	
2075	102.5	101.0	104.7	102.4	106.1	109.6	93.3	102.9	97.7	101.5	98.2	
2076	102.0	101.2	102.7	103.2	101.9	106.4	93.1	99.1	102.6	100.8	98.5	
2077	102.4	95.1	98.7	97.1	103.0	113.4	103.4	105.9	100.2	102.1	98.1	
2078	105.3	99.8	102.1	107.8	104.6	108.3	95.4	105.8	100.1	101.9	98.7	
2079	101.2	102.5	102.2	98.9	98.3	105.7	98.6	103.2	102.3	105.2	97.7	
2080	104.1	100.9	103.6	102.3	104.8	109.1	97.4	104.5	102.6	103.0	98.6	
2081	104.3	104.5	104.9	103.2	104.8	113.7	98.6	104.2	100.1	98.7	96.3	
2082	103.8	102.9	102.1	103.4	104.4	112.8	95.9	103.1	102.0	101.5	100.9	
2083	100.3	97.9	102.9	98.8	101.2	112.0	95.5	102.6	102.5	100.0	100.0	
2084	101.5	103.4	103.2	97.3	102.1	104.6	99.9	106.0	102.5	98.2	97.8	
2085	102.6	101.6	104.9	98.5	100.9	112.9	93.9	109.2	101.3	102.4	96.9	
2086	105.1	104.8	107.2	97.1	104.8	112.5	98.7	105.8	102.3	99.7	102.2	
2087	96.9	103.9	100.2	96.8	103.3	109.7	102.6	107.3	101.3	105.1	97.4	
2088	102.4	102.8	105.3	101.3	103.6	111.6	99.4	106.4	102.0	100.7	100.6	
2089	108.0	105.0	107.5	101.8	110.3	105.1	91.9	105.6	107.5	105.5	101.7	

YEAR	Average of bcc-csm1-1	Average of bcc-csm1-1-m	Average of CNRM-CM5	Average of CSIRO-Mk3-6-0	Average of HadGEM2-CC365	Average of inmcm4	Average of IPSL-CM5A-LR	Average of IPSL-CM5B-LR	Average of MIROC5	Average of MRI-CGCM3	RHavg MEDIAN OF ALL GCMS
2060	78.5	79.2	79.4	78.7	76.7	78.9	79.4	74.6	79.1	79.2	79.0
2061	79.5	78.6	79.2	81.2	75.9	80.3	76.7	77.7	76.9	77.8	78.2
2062	79.5	79.4	79.2	80.1	76.5	80.6	76.6	77.2	78.9	79.4	79.3
2063	79.6	80.1	76.8	79.6	75.1	78.2	77.2	77.2	77.8	79.6	78.0
2064	76.8	77.7	78.6	79.1	76.0	79.5	76.0	77.8	77.6	79.2	77.7
2065	79.4	78.0	78.7	77.6	74.1	79.4	76.2	77.7	75.9	78.9	77.8
2066	79.6	79.6	80.3	79.9	74.6	79.9	76.6	77.3	78.9	78.5	79.3
2067	79.5	78.3	79.3	78.3	76.5	80.2	75.6	78.6	78.0	78.6	78.4
2068	79.1	80.4	78.3	76.7	75.8	80.9	76.9	75.6	79.3	79.2	78.7
2069	78.3	77.7	80.2	77.6	76.4	79.7	75.7	76.1	77.1	77.8	77.6
2070	79.0	78.4	77.9	78.0	76.5	79.1	74.6	77.6	78.3	80.2	78.1
2071	78.6	79.3	76.9	82.2	74.6	79.1	77.1	75.5	77.1	79.7	77.8
2072	79.1	77.8	78.0	78.2	78.1	79.7	75.0	76.5	77.1	80.0	78.0
2073	77.4	78.2	77.6	78.9	76.6	79.5	74.7	75.9	77.3	76.4	77.3
2074	80.0	80.9	80.3	76.9	74.4	80.1	76.7	76.5	76.9	79.5	78.2
2075	78.8	80.2	79.3	78.8	74.7	78.7	77.1	75.8	77.9	78.3	78.5
2076	79.5	79.4	77.2	79.7	75.0	79.5	76.3	77.1	77.2	78.7	78.0
2077	77.5	79.7	78.0	79.1	75.5	80.3	75.9	75.4	79.8	78.9	78.5
2078	79.2	81.1	77.3	79.1	75.7	80.2	75.5	76.0	77.8	80.0	78.5
2079	78.9	77.8	79.4	81.2	76.4	80.1	77.7	76.1	77.1	78.0	77.9
2080	77.4	80.8	77.6	81.7	73.5	77.6	75.9	77.1	76.5	78.1	77.5
2081	77.9	78.8	78.3	78.6	74.2	79.6	73.9	74.8	76.5	79.4	78.1
2082	79.3	78.6	76.9	80.3	75.5	80.0	78.6	75.3	76.7	80.7	78.6
2083	78.7	79.5	79.0	79.9	74.3	79.2	74.4	76.0	79.1	79.0	79.0
2084	77.4	80.5	78.3	79.6	76.3	79.9	76.3	74.8	79.2	79.1	78.7
2085	79.8	79.1	77.2	81.9	75.8	79.1	73.9	78.0	76.2	80.1	78.5
2086	78.9	77.8	80.2	79.3	74.0	78.6	73.9	78.7	76.5	79.1	78.7
2087	80.7	80.1	78.4	80.5	75.2	81.5	76.2	78.6	78.5	78.5	78.6
2088	80.3	80.3	77.9	78.4	75.8	79.4	74.9	76.0	78.7	78.4	78.4
2089	77.4	79.5	77.7	78.9	75.1	79.2	75.1	78.8	77.1	78.1	77.9

*These charts show calculations for the 2070 planning horizon only

VERSION 1.4 METHODS
December 2024

Tiered Method to
Assess Projected Heat Index - Tier 3 Projects
(Step 4: Calculate heat index per year based on the NOAA Heat Index Eqn.)*
Example: Moakley Park, Boston

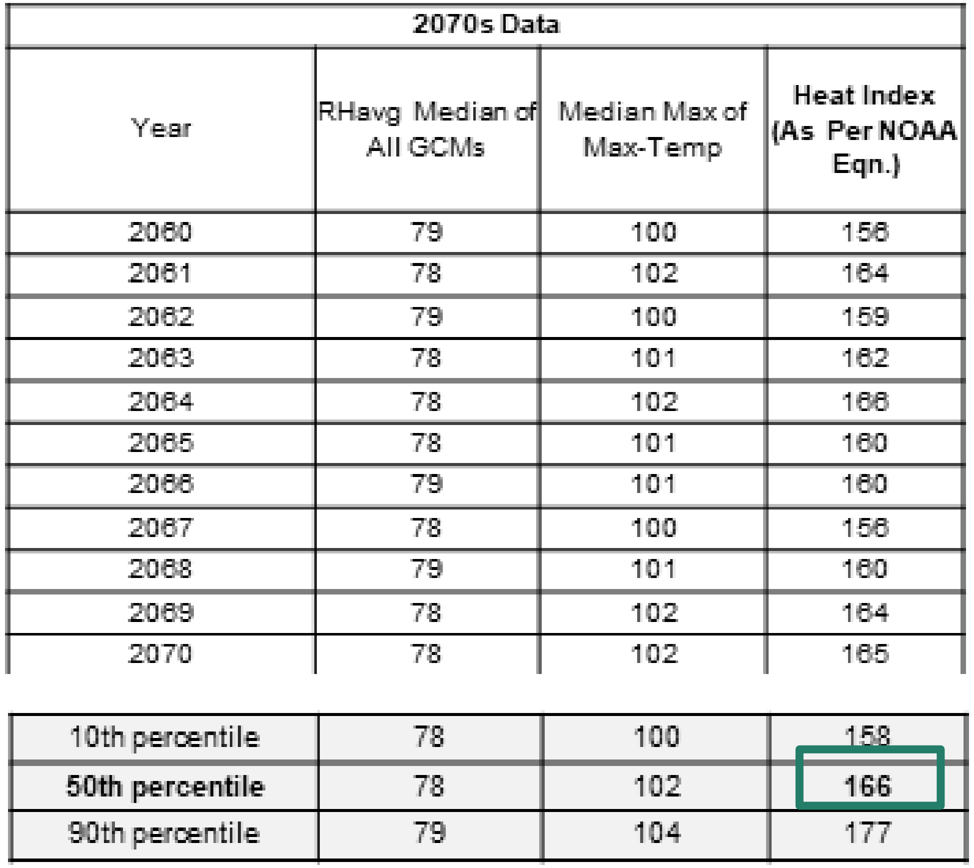
$$HI = -42.379 + 2.04901523*T + 10.14333127*RH - .22475541*T*RH - .00683783*T*T - .05481717*RH*RH + .00122874*T*T*RH + .00085282*T*RH*RH - .00000199*T*T*RH*RH$$

where,

HI = Heat Index

T = Temperature (tasmax)

RI = Relative Humidity (average rhsmax)



2070s Data			
Year	RHavg Median of All GCMs	Median Max of Max-Temp	Heat Index (As Per NOAA Eqn.)
2060	79	100	156
2061	78	102	164
2062	79	100	159
2063	78	101	162
2064	78	102	166
2065	78	101	160
2066	79	101	160
2067	78	100	156
2068	79	101	160
2069	78	102	164
2070	78	102	165
10th percentile	78	100	158
50th percentile	78	102	166
90th percentile	79	104	177

*This chart shows calculations for the 2070 planning horizon only

Tiered Method to Assess Projected Heat Index
Tier 2 and Tier 1 Projects

Given from Standards Output: Average Temperature for recommended Planning Horizon (2030, 2050, 2070); Percentile (50th, 90th)

Step 1: Use baseline value of the historical average heat index

Step 2: Apply percent increase[5] to historical average values based on given planning horizon

Planning Horizons	Increase
Mid-Century (2030s, 2050s)	13%
Late-Century (2070s, 2090s)	36%

Step 3: Projected heat index for given planning horizon

Legends

Data Gathering	▭
Calculation steps	▭
Design Criteria	⬭

REFERENCES

5. Percent Increase data based on Climate Change Vulnerability Assessment (November 2015) report for City of Cambridge, MA (Table 2, pp. 23)

Attachment 4-D– COMPILED DESIGN CRITERIA GUIDANCE LANGUAGE

RESILIENTMASS ACTION TEAM (RMAT)

CLIMATE RESILIENCE DESIGN STANDARDS & GUIDANCE

COMPILED DESIGN CRITERIA GUIDANCE LANGUAGE

DATE: DECEMBER 2024

VERSION 1.4

CONTRACT NUMBER:
ENV 19 CC 02
OWNER:
Massachusetts Executive Office of Energy and Environmental Affairs (EEA)
IN PARTNERSHIP WITH:
Massachusetts Emergency Management Agency (MEMA)
CONSULTANT TEAM:
Weston & Sampson, Woods Hole Group, Dr. Jennifer Jacobs
BSC Group (EEA IT Vendor & Tool Developer)

Table of Contents

GUIDANCE LANGUAGE FOR SEA LEVEL RISE / STORM SURGE DESIGN CRITERIA

Projected Tidal Datums

Definition

A tidal datum is a standard vertical elevation reference defined by certain phases of the tide. Tidal datums are often the reference for shoreline or coastal property boundaries where an elevation related to local sea level is needed. Projected tidal datums can be used to identify the elevation of tide levels along a shoreline in the future based on sea level rise. The following are some of the most common tidal datums (https://tidesandcurrents.noaa.gov/datum_options.html) that are extracted from the Massachusetts Coast Flood Risk Model (MC-FRM):

- Mean Higher High Water (MHHW)
- Mean High Water (MHW)
- Mean Tide Level (MTL)
- Mean Low Water (MLW)
- Mean Lower Low Water (MLLW)

Projected Tidal Datum Values

The projected Tidal Datum Elevations vary across the coastline based on a variety of factors and may vary at a given site.

Asset Name	Recommended Planning Horizon	Projected Tidal Datum Elevation (ft-NAVD88)				
		MHHW	MHW	MTL	MLW	MLLW
Test						

Standards and/or Projected Values will be presented here, if available

How Tidal Datums may inform Planning

Identify if the asset (function, access, operability, etc.) may be impacted considering the range of projected Tidal Datums (from MLLW to MHHW) over the useful life of the asset. Based on those projected values, consider if there are opportunities on the site to establish a migration zone for the shoreline and associated coastal resources to move inland to higher ground as sea levels rise. Buildings and infrastructure assets that are not intended to be exposed to tidal fluctuations (like seawalls, dams, and tide gates) should consider relocation or elevation at a minimum above the future target MHHW as planning advances to early design.

How Tidal Datum may inform Early Design

Additional site investigations are recommended to evaluate and inform design of assets that are affected by projected Tidal Datums (e.g., shoreline restoration projects). Consider current, intermediate, and target Tidal Datums and how the asset may respond to different projected Tidal Datums given actual site conditions. Note: there may be assets that are not directly exposed to the future shoreline that are affected by projected Tidal Datums (e.g., stormwater infrastructure could be impacted by rising tidal levels).

How Tidal Datums may inform Project Evaluation

Consider how the project's design narrative and drawings address current, intermediate, and/or target projected Tidal Datums for the overall site and individual assets. Projects should identify if opportunities for living shorelines, natural resource restoration, and/or a migration zone for tidal datums were considered in plans and design. Current and projected Tidal Datums should be indicated on project drawings.

Limitations for Projected Tidal Datums, Standards, and Guidance

The recommended Standards for Tidal Datums are based on the user drawn polygon and relationships as defined in the Supporting Documents. The projected Tidal Datum values provided through the Tool are based on the Massachusetts Coast Flood Risk Model (MC-FRM) outputs as of 9/13/2021, which included GIS-based data for three planning horizons (2030, 2050, 2070). These values are projections based on assumptions as defined in the model and the LiDAR used at the time. For additional information on the MC-FRM, review the additional resources provided on the Start Here page.

The projected values, Standards, and Guidance provided within this Tool may be used to inform plans and designs, but they do not provide guarantees for future conditions or resilience. The projected values are not to be considered final or appropriate for construction documents without supporting engineering analyses. The guidance provided within this Tool is intended to be general and users are encouraged to do their own due diligence. The geographic extents of projected Tidal Datums are based on the MC-FRM outputs as of 9/13/21, and Tidal Datums are recommended to be evaluated if a project location is exposed to coastal flooding, even if no projected values are available through the Tool.

Projected Water Surface Elevation

Definition

Projected Water Surface Elevation is the projected elevation for a specific future flood event, considering storm surge, tides, and wave setup. Wave setup, as included in water surface elevation, is defined by FEMA as “an increase in the total stillwater elevation against a barrier (dunes, bluffs, or structures) caused by breaking waves.” (https://www.fema.gov/sites/default/files/2020-02/Coastal_Wave_Setup_Guidance_Nov_2015.pdf).

Projected Water Surface Elevation Values:

The projected modeled elevations may vary across large sites due to variations in the site’s physical features (e.g., topography), so the elevations are presented as a maximum, minimum, and area weighted average values in the table below. The area weighted average represents the most typical value corresponding to the projected Water Surface Elevation of the project site.

Asset Name	Recommended Planning Horizon	Recommended Return Period	Projected Water Surface Elevation (ft-NAVD88)		
			Minimum	Maximum	Area Weighted Average [I]
Test	Standards and/or Projected Values will be presented here, if available				

How Water Surface Elevation may inform Planning

Consider the range of the projected Water Surface Elevation within the project area by clicking the “Projected Water Surface Elevation Maps” tab, which will appear for the asset with the least frequent return period recommended through the Tool. Three maps are provided that illustrate the projected Water Surface Elevation and extent of flooding for the planning horizon and return period indicated. If the range (or variability) is greater than one foot for an individual map, a project site survey or assessment of the most recent LiDAR elevation dataset may help users understand variations in existing site grading that may impact the projected values. If there are significant variations in existing site grading, the size of the project polygon drawn in the Tool may need to be reduced to evaluate the projected Water Surface Elevation of a specific asset location. Users may draw multiple project polygons to evaluate the variability in projected Water Surface Elevation at the site.

Identify if the asset is planned within and below the projected Water Surface Elevation for the target planning horizon. Buildings and infrastructure assets that are not intended to be exposed to coastal flooding (e.g., assets other than flood control dams, tide gates, or culverts) should consider relocation or elevation above the target maximum projected Water Surface Elevation. The area weighted average and maximum values are appropriate for planning purposes before formal design studies.

Review the existing site topography and identify areas that are above the maximum water surface elevation value. Consider the regional context of the site as well. If the project site is located along the waterfront and relocation is not feasible, identify if there are opportunities to provide local and/or regional flood protection with strategies such as berms or living shorelines that limit exposure of the asset. Identify if there are adjacent sites that would benefit or be impacted by these strategies.

If use of flood control measures is necessary where waves are interacting with the shoreline, ensure project is not reflecting waves on neighboring properties.

How Water Surface Elevation may inform Early Design:

Additional site investigations and engineering analyses are recommended to evaluate the ability to elevate the existing asset above the projected Water Surface Elevation or relocate the asset outside the extent of projected flooding. If elevation and/or relocation are not feasible, the design should consider ways that coastal flooding will not significantly impact the asset's ability to function as intended, followed by identifying measures to protect the asset from coastal flooding. Consider if the design strategy may provide additional on-and off-site benefits (regional protection benefits, community benefits, and/or ecosystem service benefits), as well as reduce the potential for negative impacts on- and off-site. The design should consider current, intermediate, and target projected Water Surface Elevations, and how the asset and site may adapt over time in conjunction with projected Wave Heights and projected Wave Action Water Elevation. Wet and dry floodproofing measures should be considered for building assets and follow existing FEMA guidance for design and materials below the target maximum Water Surface Elevation.

How Water Surface Elevation may inform Project Evaluation:

Consider how the project's design narrative and drawings or plans address current, intermediate, and/or target projected Water Surface Elevations for the asset and overall site. Projected Water Surface Elevations should be referenced in plans and designs.

Consider how the project addressed the existing site topography (including range in elevation) with the projected Water Surface Elevation for individual assets and the overall site. Were opportunities to relocate or elevate assets identified? Consider the positive benefits or negative impacts on-site or off-site because of the existing and proposed elevations planned or designed, including stormwater runoff.

Projects should provide justification if planning/designing assets below the recommended maximum projected Water Surface Elevation (both intermediate and target). For buildings, justification should be provided for design of occupiable spaces (such as first floor elevations) and critical systems (such as mechanical equipment) below the minimum projected Water Surface Elevation.

Limitations for Projected Water Surface Elevation Values, Standards, and Guidance:

The recommended Standards for Water Surface Elevation are based on the user drawn polygon and relationships as defined in the Supporting Documents. The projected Water Surface Elevation values provided through the Tool are based on the Massachusetts Coast Flood Risk Model (MC-FRM) outputs as of 9/13/2021, which included GIS-based data for three planning horizons (2030, 2050, 2070) and six annual exceedance probabilities/return periods (0.1% (1,000-yr), 0.2% (500-yr), 0.5% (200-yr), 1% (100-yr), 2% (50-yr), 5% (20-yr)). These values are projections based on assumptions as defined in the model and the LiDAR used at the time. For additional information on the MC-FRM, review the additional resources provided on the Start Here page.

The projected values, Standards, and Guidance provided within this Tool may be used to inform plans and designs, but they do not provide guarantees for future conditions or resilience. The projected values are not to be considered final or appropriate for construction documents without supporting engineering analyses. The guidance provided within this Tool is intended to be general and users are encouraged to conduct their own due diligence.

Projected Wave Heights

Definition

Wave height is measured in feet, and the value represents the vertical distance between the highest point (crest or peak) and the lowest point (trough) of the wave (per the figure shown below). The stillwater level or "calm sea" state lies between the crest and trough.

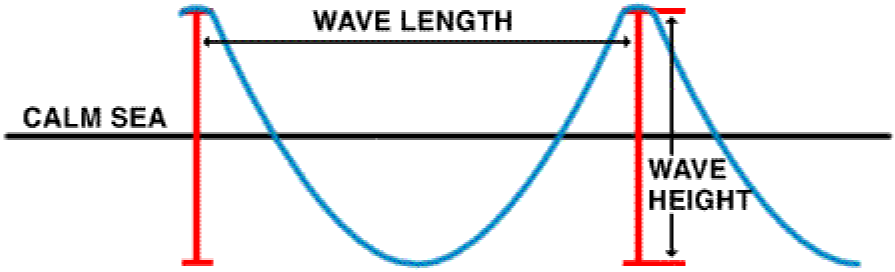


Figure of How Wave Heights are Measured
(https://www.ndbc.noaa.gov/educate/waves.shtml)

The projected Wave Height is statistically calculated using the significant wave height outputs from the Massachusetts Coast Flood Risk Model (MC-FRM). The projected Wave Height represents the wave height statistic that is slightly higher than the average of the highest 1% of wave heights and is the design maximum wave height as recommended by the Hydraulic Engineering Circular No. 25 (HEC-25) Highways in the coastal environment (USDOT, FHWA, 2020). These values are used to inform the projected Wave Action Water Elevation, in conjunction with the projected Water Surface Elevation. *Wave heights should not be directly added to the Water Surface Elevation to estimate Wave Action Water Elevations.*

Projected Wave Heights Values:

The projected Wave Heights may vary across sites, so the heights are presented as a maximum, minimum, and area weighted average values in the table below. The area weighted average represents the most typical value corresponding to the projected Wave Height of the project site.

Asset Name	Recommended Planning Horizon	Recommended Return Period	Projected Wave Height (ft.)		
			Minimum	Maximum	Area Weighted Average [I]
Test	Standards and/or Projected Values will be presented here, if available				

How Wave Heights may inform Planning:

Consider the range of the projected Wave Heights within the project area and the regional context of the site. If it is located along the waterfront, identify if there are opportunities to reduce wave heights through nature-based solutions, on-site and/or off-site. For restoration efforts, consider whether reducing wave heights is needed to meet project goals.

If the site is not along the coast and in more inland areas or outside of existing FEMA Zone AE (https://msc.fema.gov/portal/home), site-specific analysis is recommended to interpret projected Wave Heights, including identifying off-site opportunities to reduce wave heights.

The area weighted average may be appropriate for planning purposes before formal design studies, but users should consider the design intent and geographic variability of the project, including proximity to coast.

How Wave Heights may inform Early Design:

FEMA designates existing areas with expected wave heights greater than three feet as "Zone VE, a Coastal High Hazard Area, where waves and fast-moving water can cause extensive damage during the 1-percent-annual chance flood." If the area weighted average projected Wave Height is greater than three feet, design strategies appropriate in FEMA VE zones (https://www.fema.gov/sites/default/files/documents/fema_using-limit-oderate-wave-action_fact-sheet_5-24-2021.pdf), as well as nature-based strategies that mitigate wave height and impact, should be considered.

"FEMA has documented storm damage for decades. Post-storm damage shows that even 1.5-foot waves can cause significant damage to buildings that were not built to withstand them" (https://www.fema.gov/sites/default/files/documents/fema_using-limit-oderate-wave-action_fact-sheet_5-24-2021.pdf). The range of projected Wave Heights should be used to estimate wave forces for intermediate and target planning horizons. Wave forces are directly proportional to wave heights, and may be calculated using existing standards (e.g., Goda 1974).

How Wave Heights may inform Project Evaluation:

Consider how the project's design narrative and drawings address current, intermediate, and/or target projected Wave Heights for the overall site and individual assets. Projects should provide justification for not incorporating projected Wave Heights in planning/design efforts, which may include proximity to the coast (the site is not along the coast and in more inland areas or outside of existing FEMA Zone AE) and supporting analyses.

If the area weighted average projected Wave Height exceeds three feet, what design elements are included on site to protect the asset from the wave forces? Does the design reference building standards used in FEMA Zone VE floodplain management? These may include, but are not limited to:

- Buildings elevated on pile, post, pier, or column foundations, and anchored to the foundation.
- No structural fill is proposed.
- The bottom of the lowest horizontal structural member is at or above projected Water Surface Elevation.

Limitations for Projected Wave Heights, Standards, and Guidance

The recommended Standards for Wave Heights are based on the user drawn polygon and relationships as defined in the Supporting Documents. The projected values provided through the Tool are based on the Massachusetts Coast Flood Risk Model (MC-FRM) outputs as of 9/13/2021, which included GIS-based data for three planning horizons (2030, 2050, 2070) and six annual exceedance probabilities/ return periods (0.1% (1,000-yr), 0.2% (500-yr), 0.5% (200-yr), 1% (100-yr), 2% (50-yr), 5% (20-yr)). These values are projections based on assumptions as defined in the model and the LiDAR used at the time. For additional information on the MC-FRM, review the additional resources provided on the Start Here page.

The projected values, Standards, and Guidance provided within this Tool may be used to inform plans and designs, but they do not provide guarantees for future conditions or resilience. The projected values are not to be considered final or appropriate for construction documents without supporting engineering analyses. The guidance provided within this Tool is intended to be general and users are encouraged to conduct their own due diligence.

Projected Wave Action Water Elevation

Definition

The Wave Action Water Elevation represents the flood elevation that incorporates the projected Water Surface Elevation and Wave Heights associated with the recommended return period and planning horizons. This accounts for anticipated sea level rise, tidal datums, storm surge, and storm climatology through the Massachusetts Coast Flood Risk Model (MC-FRM), which is a hydrodynamic, probabilistic model that considers hundreds of thousands of historic and simulated storms. For additional information on the MC-FRM, review the additional resources provided on the Start Here page.

Projected Wave Action Water Elevation Values:

The projected Wave Action Water Elevation may vary across any given site, so the elevations are presented as a maximum, minimum, and area weighted average values in the table below. The area weighted average represents the most typical value corresponding to the projected Wave Action Water Elevation of the project site.

Asset Name	Recommended Planning Horizon	Recommended Return Period	Projected Wave Action Water Elevation (ft-NAVD88)		
			Minimum	Maximum	Area Weighted Average [I]
Test	Standards and/or Projected Values will be presented here, if available				

How Wave Action Water Elevation may inform Planning:

Consider the range of the projected Water Surface Elevation and the range of the projected Wave Heights within the project area in conjunction with the values provided above. The projected Wave Heights directly affect wave action, so reducing wave energy through on-site or off-site design strategies may allow projects to reduce the overall projected Wave Action Water Elevation.

The area weighted average and maximum values are appropriate for planning purposes before formal design studies. Refer to additional guidance provided in projected Water Surface Elevation and Wave Heights.

How Wave Action Water Elevation may inform Early Design:

Additional site investigations should be conducted to evaluate the ability to relocate the asset above the target maximum value. If elevation and/or relocation are not feasible, the design should consider ways that coastal flooding will not significantly impact the asset's ability to maintain functionality, followed by identifying measures to protect the asset from coastal flooding and wave forces. The design should consider current, intermediate, and target elevations, and how the asset and site may adapt over time in conjunction with projected Wave Heights and projected Water Surface Elevations.

Wet and dry floodproofing measures should be considered for building assets and follow existing FEMA guidance for design and materials below the target maximum Wave Action Water Elevation.

Natural resource assets that are located below the target maximum Wave Action Water Elevation should consider design strategies that incorporate native vegetation tolerant of existing and future conditions. This includes vegetation that can tolerate periodic exposure to saltwater and can help reduce wave action, to the extent practicable.

How Wave Action Water Elevation may inform Project Evaluation:

Consider how the project's design narrative and drawings address current, intermediate, and/or target Wave Action Water Elevation for the overall site and individual assets. Projects should reference projected Wave Heights and projected Water Surface Elevations with projected Wave Action Water Elevation and how they were considered together in plans and designs.

Consider how the project addressed the existing site topography (including range in elevation) with the projected Wave Action Water Elevation for individual assets and the overall site. Were there opportunities to relocate or elevate assets above the maximum target projected Wave Action Water Elevation? If a Building/Facility asset, does the design incorporate wet and dry floodproofing measures? Consider the positive benefits or negative impacts on-site or off-site because of the existing and proposed elevations planned or designed, including stormwater runoff.

Limitations of Projected Wave Action Water Elevation, Standards, and Guidance

The recommended Standards for Wave Action Water Elevation are based on the user drawn polygon and relationships as defined in the Supporting Documents. The projected Wave Action Water Elevation values provided through the Tool are based on the Massachusetts Coast Flood Risk Model (MC-FRM) outputs as of 9/13/2021, which included GIS-based data for three planning horizons (2030, 2050, 2070) and six annual exceedance probabilities/return periods (0.1% (1,000-yr), 0.2% (500-yr), 0.5% (200-yr), 1% (100-yr), 2% (50-yr), 5% (20-yr)).These values are projections based on assumptions as defined in the model and the LiDAR used at the time. For additional information on the MC-FRM, review the additional resources provided on the Start Here page.

The projected values, Standards, and Guidance provided within this Tool may be used to inform plans and designs, but they do not provide guarantees for future conditions or resilience. The projected values are not to be considered final or appropriate for construction documents without supporting engineering analyses. The guidance provided within this Tool is intended to be general and users are encouraged to conduct their own due diligence.

Projected Duration of Flooding

Definition

Duration of Flooding is the length of time an area remains flooded during a storm event. Duration of Flooding is important because it correlates with disruption in services and the level of impact of the flood (e.g., the amount of damage done, the amount of time power is out, etc.). *

How to Estimate Projected Duration of Flooding Values:

Asset Name	Recommended Planning Horizon	Recommended Return Period
Test	Standards will be presented here, if available	

*Note: Duration of Flooding is not a standard output of the Massachusetts Coast Flood Risk Model (MC-FRM), so projected values are currently not available through this Tool. Consult a professional coastal engineer or scientist/modeler to estimate projected Duration of Flooding based on the recommended Standards and outputs provided through this Tool.

How Duration of Flooding may inform Planning:

Evaluate how projected Duration of Flooding may impact the asset, including access and operability. Flood duration impacts the length of time occupants may need to evacuate, shelter in place, or are unable to access a building. Duration of Flooding may impact infrastructure, including inaccessible transportation routes and discharges through outfalls. Identify the duration for which these impacts are tolerable, and opportunities to increase that length of time (such as considering back-up power generation). If the projected Duration of Flooding is greater than the acceptable time for the asset to be inoperable, then that is an issue that should be considered as part of the planning phase of the project.

Coastal natural resource assets are generally adapted to being flooded for periods of time, but if there are non-coastal natural resource assets exposed to coastal flooding (e.g., emergent wetlands, open recreation space, etc.), Duration of Flooding and/or salinity may impact species and asset health.

How Duration of Flooding may inform Early Design:

Establish the projected Duration of Flooding by consulting with a professional coastal engineer or modeler and using the recommended Standards and outputs provided through this Tool.

The projected Duration of Flooding may inform emergency operations and management and recovery plans; corresponding operating procedures should be considered during the design process as they are informed by the location and design of assets.

Duration of Flooding may not be a significant design consideration if assets are designed above the maximum projected Water Surface Elevation or relocated so that the asset location is not exposed to coastal flooding. Duration of Flooding may impact assets not located within the future flood extents. For example, sluice gates at flood control structures outside of the project area that may need to be closed during the duration of coastal flooding to mitigate flooding at the project site.

How Duration of Flooding may inform Project Evaluation:

Consider if the project addresses Duration of Flooding in their design narrative and/or operations plans, if any. Has a professional coastal engineer or scientist/modeler been engaged to estimate the projected Duration of Flooding based on the recommended planning horizon, return period, and projected Tidal Datums and Water Surface Elevation? If Duration of Flooding is unknown at planning or early design level, did the project identify plans and/or design measures to maintain functionality and access for the asset for at least 48 hours? This could be through design features (e.g., elevating and/or relocating assets or protecting them by barriers or dry/wet flood proofing) or operational features (e.g., deployable pumps and emergency response plans).

Limitations for Duration of Flooding Standards and Guidance

The recommended Standards for Duration of Flooding are based on the user drawn polygon and relationships as defined in the Supporting Documents. The guidance provided within this Tool may be used to inform plans and designs, but they do not provide guarantees for resilience. The guidance provided within this Tool is intended to be general and users are encouraged to do their own due diligence.

Projected Flood Velocity

Definition

Flood Velocity describes the magnitude and direction of floodwaters in terms of distance/time (e.g., feet per second or miles per hour). Flood Velocity is important for assessing the flood-induced forces on different structures (i.e., low flow/static flooding will place different stressors on a structure than high speed flows). The projected Flood Velocity is the estimated velocity associated with the recommended return period and planning horizon. *

How to Estimate Projected Flood Velocity Values

Asset Name	Recommended Planning Horizon	Recommended Return Period
Test	Standards will be presented here, if available	

*Note: Flood Velocity is currently not a standard output of the Massachusetts Coast Flood Risk Model (MC-FRM), so projected values are not available through this Tool at the time of production. Consult a professional coastal engineer or scientist/modeler to estimate projected Flood Velocity based on the recommended Standards and outputs provided through this Tool.

How Flood Velocity may inform Planning:

“The direction and velocity of floodwaters can vary significantly throughout a coastal flood event. Floodwaters can approach a site from one direction as a storm approach, then shift to another direction (or through several directions) as the storm moves through the area. Projects should consider the topography, the distance from the source of flooding, and the proximity to other buildings and obstructions; those factors can direct and confine floodwaters, with a resulting acceleration of velocities.”(https://www.fema.gov/sites/default/files/2020-08/fema543_design_guide_complete.pdf)

Materials considered as part of the project should be able to withstand the projected Flood Velocity, especially for the materials that could be mobilized by high speed flows for assets that are planned below the maximum projected Wave Action Water Elevation.

How Flood Velocity may inform Early Design:

Establish the projected Flood Velocity by consulting with a professional coastal engineer or scientist/modeler and using the recommended Standards and outputs provided through this Tool. If this is not feasible during early design, consider existing best practices to estimate coastal Flood Velocity. For critical facilities, see Section 2.1.2.3 of FEMA Design Guide 543: https://www.fema.gov/sites/default/files/2020-08/fema543_design_guide_complete.pdf.

The projected Flood Velocity may inform adaptive management of existing revetments and sizing/positioning of inlets. The projected Flood Velocity may also inform the capacity of channels, culverts, catch basins, and storm pipes for flooding events.

“In structural design, velocity is a factor in determining the hydrodynamic loads and impact loads. Even shallow, high-velocity water can threaten the lives of pedestrians and motorists” (https://www.fema.gov/sites/default/files/2020-08/fema543_design_guide_complete.pdf). For buildings and other above ground structural assets, identify if the asset is currently protected by flooding and if/how it is secured in place (i.e., foundation type). Shallow foundations are more vulnerable than deep foundations.

How Flood Velocity may inform Project Evaluation:

Consider if the project addresses Flood Velocity in their design narrative and/or operations plans, if any. Has a professional coastal engineer or scientist/modeler been engaged to estimate the projected Flood Velocity based on the recommended planning horizon, return period, and other projected values (Tidal Datums and Water Surface Elevation) provided through the Tool? If preliminary estimates for projected Flood Velocity were developed using FEMA Design Guide 543, was the projected Water Surface Elevation used in that assessment? How do plans and designs reflect Flood Velocity considerations; for example, for stream restoration projects, has the flood velocity been considered as part of the design and have appropriate measures, such as riprap or grade control, been adopted if projected Flood Velocity is greater than allowable velocity of the natural channel?

Limitations for Flood Velocity Standards and Guidance

The recommended Standards for Flood Velocity are based on the user drawn polygon and relationships as defined in the Supporting Documents. The guidance provided within this Tool may be used to inform plans and designs, but they do not provide guarantees for resilience. The guidance provided within this Tool is intended to be general and users are encouraged to conduct their own due diligence.

Projected Scour & Erosion

Definition

Coastal erosion is the loss of sediments along the coast due to sea level rise, waves, and coastal storm events. This process lowers the elevation of beaches and other landforms and shifts shorelines landward. Scour refers to a "localized lowering of the ground surface due to the interaction of currents and/or waves with structural elements, such as pilings [and seawalls]. Soil [and sediment] characteristics influence an area's susceptibility to scour. Erosion and scour may affect the stability of foundations and filled areas, and may cause extensive site damage" (https://www.fema.gov/sites/default/files/2020-08/fema543_design_guide_complete.pdf). *

How to Estimate Scour & Erosion Values

Asset Name	Recommended Planning Horizon	Recommended Return Period
Test	Standards will be presented here, if available	

*Note: Information related to Scour and Erosion is not a standard output of the Massachusetts Coast Flood Risk Model (MC-FRM), so projected values are not available through this Tool. Consult a professional coastal engineer or scientist/modeler to estimate projected extent of Scour and Erosion based on the recommended Standards and outputs provided through this Tool.

How Scour & Erosion may inform Planning:

Projects should consider the effects of scour and erosion in areas with erodible soils and sediments. Erosion affects most coastal landforms and may threaten dunes and other natural protective features, lowers ground elevations, undermines shallow foundations and below ground utilities, and reduces penetration depth of deep foundations (https://www.fema.gov/sites/default/files/2020-08/fema55_voli_combined.pdf). Therefore, understanding the extent of potential scour or erosion is valuable for assessing development setbacks, the depth to bury utilities behind dunes and seawalls, and the depth of foundations and pilings.

Erosion during storms occurs despite the presence of erosion control devices such as seawalls, revetments, and toe protection (https://www.fema.gov/sites/default/files/2020-08/fema55_voli_combined.pdf). Long-term erosion can also shift flood hazard zones landward. Refer to Limitations below. Flood depth, which is estimated by the difference between projected Water Surface Elevation and existing site topography, has direct correlations to damages. In areas susceptible to Erosion, changes in ground surface conditions during a flood event may increase the estimated flood depth. Additionally, the proposed construction materials may need to consider a plan to reduce or avoid Scour and Erosion.

How Scour & Erosion may inform Early Design:

Natural and human-caused shoreline changes (https://www.arcgis.com/apps/MapSeries/index.html?appid=80fc0c7ef5e443a8a5bc58096d2b3dc0) and Erosion and Scour potential should be considered. Shore protection structures may have unintended on-site and off-site impacts related to Erosion. Seawalls, bulkheads, and revetments may exacerbate Erosion of adjacent coastal resources and landforms. Early designs should explore opportunities to restore sediments and natural buffering capacity.

The potential effects of localized coastal Scour when planning foundation size, depth, or embedment requirements should be considered. Refer to existing FEMA guidelines (Coastal Construction Manual) for additional guidance on designs considering Scour & Erosion.

Projected Scour may be calculated using existing best practices, such as the methodologies provided in "TRB's National Cooperative Highway Research Program (NCHRP) Web-Only Document 181: Evaluation of Bridge-Scour Research: Abutment and Contraction Scour Processes and Prediction examines bridge-abutment scour and the effectiveness of the leading methods used for estimating design scour depth."

How Scour & Erosion may inform Project Evaluation:

Consider if the project's design narrative and drawings address Erosion and Scour potential for the overall site and individual assets. Is the project located in an area that has low-lying beaches, coastal dunes, coastal bluffs, coastal banks, and/or cliffs? If flood and erosion control structures are proposed (e.g., seawalls, bulkheads, revetments, etc.), does the project provide documentation for sediment modeling and reference projected Water Surface Elevations, projected Wave Heights, and estimated projected Flood Velocity? Were nature-based solutions considered instead of or in addition to 'gray' infrastructure to avoid or limit Scour and Erosion potential?

Limitations for Scour & Erosion Standards and Guidance

The recommended Standards for Scour & Erosion are based on the user drawn polygon and relationships as defined in the Supporting Documents. Scour & Erosion is recommended as design criteria for consideration based on asset type and if the site is located within the extents of the Massachusetts Coast Flood Risk Model (MC-FRM) as of 9/13/2021 for the associated planning horizon (2030, 2050, or 2070). The flood extents as defined in the current version of the MC-FRM do not reflect future extents as a result of erosion and/or scour; sites located outside of the modeled extents may be subject to Scour & Erosion as a result of long-term erosion that shifts flood hazard zones landward. For additional information on the MC-FRM, review the additional resources provided on the Start Here page.

The guidance provided within this Tool may be used to inform plans and designs, but they do not provide guarantees for resilience. The guidance provided within this Tool is intended to be general and users are encouraged to conduct their own due diligence, including but not limited to evaluating current and future erosion potential.

Conditional Text that appears with Projected Sea Level Rise / Storm Surge Values

If the design criteria is Future Tidal Datums…	If the project polygon intersects an area with "Hatch = 1" WITH underlying values, provide dynamic table output, and provide the following note below the table output: "**This project is located in an area with uncertainty for future tidal datums. These uncertain zones are either dynamic in terms of geomorphology or are restricted by manmade features (i.e., culverts, tide gates, etc.) that should be evaluated in more detail at the site-scale."** If the project polygon intersects an area with "Hatch = 1" with NO underlying value, don't provide any table output instead provide following text: "**This project is located in an area with uncertainty for future tidal datums. These uncertain zones are either dynamic in terms of geomorphology or are restricted by manmade features (i.e., culverts, tide gates, etc.) that should be evaluated in more detail at the site-scale."** For projects that receive any Exposure Score for SLR/SS (other than "Not Exposed"), but project polygon does NOT intersect with the extents of Future Tidal Datums for the corresponding planning horizon, the Tool should output the following text for Future Tidal Datums design criteria: **"Note: The site is exposed to Sea Level Rise/Storm Surge, but projected Tidal Datums are not available within the site. Additional site-specific analyses are recommended to identify projected Tidal Datums for the recommended planning horizon. Consult a professional coastal engineer or modeler to estimate projected Tidal Datums based on the recommended Standards and additional outputs provided through this Tool."**
If the project polygon intersects the "9997" hatch zone…	Display the following text for the SLR/SS climate parameter: **ATTENTION: This project intersects areas influenced by wave overtopping based flooding These areas are where flooding is caused by intermittent pulses that come from wave run-up and overtopping at a coastal structure. Additional site analyses are recommended to establish design values associated with design criteria**.
If the project polygon intersects the "9997" & "9998" hatch zones…	Display the following text for the SLR/SS climate parameter: **ATTENTION: This project intersects areas influenced by combined effect of direct flooding and wave overtopping based flooding. These areas are where flooding is caused by surge, tides, and wave setup as well as intermittent pulses that come from wave run-up and overtopping at a coastal structure. Additional site analyses are recommended to establish design values associated with design criteria.**
If the project polygon intersects the "9998" hatch zone…	Display the following text for the SLR/SS climate parameter: **ATTENTION: This project intersects dynamic landform areas. These areas are where geomorphology is extremely dynamic and expected flooding can vary drastically. Additional site analyses are recommended to establish design values associated with design criteria.**
If the project polygon intersects "9999" hatch zones…	Display the following text for the SLR/SS climate parameter: **ATTENTION: This project intersects areas that are low probability flooding zones with minimal flood risk and small depth of flooding. These areas are where flooding is expected during the most extreme storm events (>1000-yr return period) or where there is only minor water depth during the 1000-yr return period. Additional site analyses are recommended to establish design values associated with design criteria.**

GUIDANCE LANGUAGE FOR EXTREME PRECIPITATION DESIGN CRITERIA

Projected Total Precipitation Depth & Peak Intensity for 24-hour Design Storms

Definition

Total Precipitation Depth for 24-hour Design Storms is the total amount of rain in inches that falls over a period of 24-hours. It can be any 24-hour period, not just a traditional calendar day. This is given for a specific design storm (return period) such as the 100-year or 10-year storm (1% or 10%). Peak Intensity is the maximum rate of rainfall in inches per hour of a 24-hour design storm*.

Projected Total Precipitation Depth and Peak Intensity values can be used to assess potential flooding impacts and inform design of green and grey infrastructure solutions to mitigate flooding and manage stormwater.

Projected Total Precipitation Depth Values and Peak Intensity Methods

The Tool uses climate projections developed by Cornell University as part of the EEA's Massachusetts Climate and Hydrologic Risk Project (https://journals.ametsoc.org/view/journals/hydr/23/3/JHM-D-21-0183.1.xml). Assets receive a projected value for the 24-hour Total Precipitation Depth associated with a recommended return period (design storm) and planning horizon.

Asset Name	Recommended Planning Horizon	Recommended Return Period	Projected 24-hr Total Precipitation Depth (inches)	Step-by-Step Instructions for Estimating Peak Intensity
Test	Standards and Projected Values will be presented here			Downloadable Instructions PDF

*Note: The projected Peak Intensity for 24-hour Design Storms is not provided through the Tool but can be calculated using methods referenced here.

---*DYNAMIC OUTPUT ONLY FOR TIER 3 DAMS AND FLOOD CONTROL STRUCTURE ASSETS* ---

ATTENTION: This is a Tier 3, Dams & Flood Control Structures project. Due to the criticality and useful life of this project, it is recommended that NCHRP15-61 method be used to calculate projected Total Precipitation Depth for 24-hour Design Storms, and those results be compared to the projected values provided in the Tool.

---*DYNAMIC OUTPUT ONLY FOR TIER 1 ASSETS* ---

ATTENTION: This is a Tier 1 project. Due to the criticality and useful life of this project, it is recommended that the NOAA+ method be used to calculate projected Total Precipitation Depth for 24-hour Design Storms, and those results be compared to the projected values provided in the Tool.

How Total Precipitation Depth may inform Planning

It may be helpful to develop a combined hydrologic/hydraulic (H/H) model for the site, which is typically conducted as part of an engineering analysis. This may inform the placement of green and grey stormwater infrastructure to manage stormwater flooding, as well as model effectiveness of stormwater solutions.

In addition to projected Total Precipitation Depth, consider the following:

- Are there onsite, offsite, and/or upstream local or watershed scale interventions (such as tree-planting, soil/habitat restoration, forest/other ecosystem conservation and restoration, floodplain restoration, pavement removal) that may mitigate stormwater flooding and provide opportunities for collaborative stormwater management, without negatively impacting ecosystem services?
- Are there notable elevation changes on-site that may expose the assets to additional risk (such as increased water flow or erosion)? Are there potential flood pathways as a result of on-site or off-site grade changes?
- Are there existing or proposed developments upgradient from the site that may result or increase on-site flooding?
- Will stormwater design cause impacts to Environmental Justice neighborhoods or climate vulnerable populations (e.g., due to off-site flooding)?

If other rainfall projections are readily available for the project site, consider comparing these data to the projected Total Precipitation Depth values as well as historic rainfall data.

How Total Precipitation Depth may inform Early Design

The projected Total Precipitation Depth may inform design of stormwater-specific assets, such as stormwater-utility infrastructure (for example stormwater drainage pipes, force mains, underground stormwater detention storage tanks, sub-surface infiltration chambers, etc.), flood control infrastructure (for example dams, sluice gates, etc.), and green infrastructure. The associated peak intensity and distribution of the projected Total Precipitation Depth may inform design and size stormwater management systems to address stormwater quantity issues.

Non-stormwater specific assets, such as building and natural resource assets, may use the projected Total Precipitation Depth to identify how rainfall depths and associated peak intensities may impact the asset, and design the asset accordingly to reduce damage potential.

In addition to projected Total Precipitation Depth values, consider the following:

- Is it spatially/physically feasible for stormwater utility infrastructure to be sized for the projected Total Precipitation Depth?
- Can design elements be modified over time to adjust to the change in future climate projections? An adaptive management approach may be a more feasible approach.
- If on-site mitigation is not possible due to site constraints, what opportunities exist for off-site mitigation?
- Do ecosystem service benefits (stormwater or otherwise) change over time due to climate change impacts? Consider climate change impacts in the design of nature-based solutions, beyond the asset's useful life.

How Total Precipitation Depth may inform Project Evaluation

Consider how the project narrative and drawings address the projected Total Precipitation Depth with respect to the overall site and an individual asset's design or planning. Justification should be provided if using a different method than the tiered estimation method recommended by the Tool.

In addition, consider the following:

- If the runoff generated for the projected Total Precipitation Depth cannot be accommodated on-site, how does the project propose to manage the additional stormwater? What are the ramifications of not managing stormwater on-site? Will resource areas be adversely affected if runoff is directed offsite?
- Does the proposed stormwater management system incorporate an adaptive approach such that modifications in the future can improve climate resilience?
- Does the project propose use of green infrastructure or nature-based solutions in conceptual design of the overall project site or assets within?
- What actions or plans are proposed to mitigate potential on-site and off-site impacts as a result of projected Total Precipitation Depth and Peak Intensity, including potential impacts to Environmental Justice neighborhoods or climate vulnerable populations?

Limitations for Projected Total Precipitation Depth & Peak Intensity, Standards, and Guidance

The recommended Standards for Total Precipitation Depth & Peak Intensity are determined by the user drawn polygon and relationships as defined in the Supporting Documents. The projected Total Precipitation Depth values provided through the Tool are based on the climate projections developed by Cornell University as part of EEA's Massachusetts Climate and Hydrologic Risk Project, GIS-based data as of 10/15/21. For additional information on the methods for producing of these precipitation outputs, see Steinschneider & Najibi 2022[1], Najibi et al. 2022[2], and the dataset technical documentation[3].

While Total Precipitation Depth & Peak Intensity for 24-hour Design Storms are useful to inform planning and design, it is recommended to also consider additional longer- and shorter-duration precipitation events and intensities in accordance with best practices. Longer-duration, lower-intensity storms allow time for infiltration and reduce the load on infrastructure over the duration of the storm. Shorter-duration, higher-intensity storms often have higher runoff volumes because the water does not have enough time to infiltrate infrastructure systems (e.g., catch basins) and may overflow or back up during such storms, resulting in flooding. In the Northeast, short-duration high intensity rain events are becoming more frequent, and there is often little early warning for these events, making it difficult to plan operationally. While the Tool does not provide recommended design standards for these scenarios, users should still consider both short- and long-duration precipitation events and how they may impact the asset.

The projected values, standards, and guidance provided within this Tool may be used to inform plans and designs, but they do not provide guarantees for future conditions or resilience. The projected values are not to be considered final or appropriate for construction documents without

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[1] Steinschneider and Najibi (2022). Observed and Projected Scaling of Daily Extreme Precipitation with Dew Point Temperature at Annual and Seasonal Scales across Northeastern United States." *Journal of Hydrometeorology* Vol. 23(3), pp. 403-419. Doi: https://doi.org/10.1175/JHM-D-21-0183.1

[2] Najibi, Mukhopadhyay, and Steinschneider (2022). "Precipitation Scaling with Temperature in the Northeast US: Variations by Weather Regime, Season, and Precipitation Intensity." *Geophysical Research letters* Vol. 49(8), e2021GL097100. Doi: https://doi.org/10.1029/2021GL097100

[3] Steinschneider and Najibi (2022). "Future Projections of Extreme Precipitation across Massachusetts: A Theory-Based Approach Technical Documentation." *MA EOEEA Data Services* <https://eea-nescaum-dataservices-assets-prd.s3.amazonaws.com/cms/GUIDELINES/FinalTechnicalDocumentation_IDF_Curves_Dec2021.pdf>

supporting engineering analyses. The guidance provided within this Tool is intended to be general and users are encouraged to do their own due diligence.

Projected Riverine Peak Discharge & Peak Flood Elevation

Definition

Riverine Peak Flood Elevation is defined as the elevation of surface water resulting from, or anticipated to result from, the flooding of a river. Riverine Peak Discharge is defined as the highest discharge rate usually displayed as cubic feet per second (CFS). Riverine flooding examples include inundation of roads, infrastructure, or structures due to extreme precipitation resulting in overbank flooding or flash flooding. If the site is potentially exposed to riverine flooding based on preliminary exposure score, assets will receive riverine design standards recommendations.*

How to estimate Projected Riverine Peak Discharge & Peak Flood Elevation Values

Asset Name	Recommended Planning Horizon	Recommended Return Period	Tiered Estimation Method	Step-by-Step Instructions
Test	Standards will be presented here			Downloadable Instructions PDF

*Note: Projected Riverine Peak Discharge and Peak Flood Elevation are not currently available through this Tool. Users should follow the step-by-step instructions outlined in the downloadable instructions PDF to estimate the projected Riverine Peak Discharge and Peak Flood Elevation based on the recommended planning horizon, percentile, and tiered estimation method. The three tiers represent various anticipated levels of effort for calculating design criteria values, dependent upon the consequences of failure of an asset as a function of scope, time, and severity and useful life of the asset.

Ecological restoration projects may consider use of alternative hydrology design methods for riverine environments (per NOAA and USGS guidance) instead of methods provided through the Tool. Coordination with the appropriate State Agencies on design process and how future climate conditions are considered is recommended.

How Riverine Peak Discharge & Peak Flood Elevation may inform Planning

Consider riverine flood exposure and risk when planning for design and consider how risk may increase over time due to increases in rainfall. It can be helpful to develop a combined hydrologic/hydraulic (H/H) model for the site using the projected Total Precipitation Depth, which is typically conducted as part of an engineering analysis. This can inform a broader context to understand where flooding is projected to assess both upstream and downstream impacts at a regional/watershed scale. This may include considering the following:

- If possible, consider locations where the asset could be relocated away from riverine flooding exposure, particularly high exposure areas. Consider other on-site locations where critical assets can be relocated away from riverine flooding exposure and impact.
- Are there notable elevation changes on-site that may expose the assets to additional risk (such as increased water flow or erosion)? Are there flood pathways on-site or from off-site grade changes?
- Can the site provide the opportunity for flood protection beyond the site through increasing the floodplain or flood barriers? (i.e., local, neighborhood, or regional scale?)
- Are there other local or regional interventions that would reduce riverine flooding at the site?

How Riverine Peak Discharge & Peak Flood Elevation may inform Early Design

Evaluate how the projected Riverine Peak Discharge and Peak Flood Elevation may impact the asset and design the asset accordingly to reduce damage potential. It may be useful to consider adaptive management approaches, including improvements beyond the project area. Consider identifying how peak discharge flows, elevations, and flood pathways may change over time. If the climate risk changes through the asset's useful life, evaluate if the asset and/or site can be designed/constructed incrementally to mitigate riverine flood risk.

How Riverine Peak Discharge & Peak Flood Elevation may inform Project Evaluation

Consider how the project narrative and drawings address the projected Riverine Peak Discharge and Peak Flood Elevation with respect to the overall site and an individual asset's design or planning. Justification should be provided if using a different method than the tiered estimation method recommended by the Tool.

In addition, consider the following:

- Are green infrastructure or nature-based solutions being proposed for planning and conceptual design of the site and assets?
- Did the project consider relocation away from riverine flood exposure?
- Does the project incorporate an adaptive approach to riverine flood exposure and risk, such that modifications in the future can improve climate resilience?
- Does the project coordinate with, or plan to coordinate with, related regional or watershed efforts?

Limitations for Riverine Peak Discharge & Peak Flood Elevation Standards and Guidance

The recommended Standards for Riverine Peak Discharge and Peak Flood Elevation are determined by the user drawn polygon and relationships as defined in the Supporting Documents. The guidance provided within this Tool may be used to inform plans and designs, but they do not provide guarantees for resilience. The guidance provided within this Tool is intended to be general and users are encouraged to do their own due diligence.

GUIDANCE LANGUAGE FOR EXTREME HEAT DESIGN CRITERIA

Projected Annual/Summer/Winter Average Temperatures

Definition

Average Temperatures represent the daily average temperature over a period of time: Annual represents January through December, Summer represents June through August, and Winter represents December through February. Annual Temperatures are anticipated to increase with climate change, but the rate of change varies depending upon the season.

How to Estimate Projected Annual/Summer/Winter Average Temperatures Values

Asset Name	Recommended Planning Horizon	Recommended Percentile**	Projected Annual Average Temperature [˚F]	Projected Summer Average Temperature [˚F]	Projected Winter Average Temperature [˚F]
seawall	Standards and/or Projected Values will be presented here, if available				

How Annual/Summer/Winter Average Temperatures may inform Planning

Evaluate how the change in projected Average Temperatures may impact the initial planning and pre-design considerations associated with the asset and overall project. Average Temperatures represent a generalized trend, so it may be useful to identify locations along the East Coast with current conditions similar to the projected conditions. If there are other locations or zones that currently experience these climate patterns, they may inform adaptive plans and design strategies. Based on the region, will the asset use, function, or maintenance change as a result of increased projected Average Temperatures? For example: building assets may see changes in heating, cooling, and ventilation needs; infrastructure assets may see increased maintenance frequency; natural resources assets may see changes in flora and fauna with changes in Average Temperatures.

How Annual/Summer/Winter Average Temperatures may inform Early Design

Early design studies may include evaluating strategies from other locations along the East Coast that currently experience similar Average Temperatures to projected values. Are there design strategies that are applicable for today's climate conditions (or the climate conditions at the time of construction) and the projected Average Temperatures? Refer to additional applicable design criteria for more guidance related to Maximum Temperature, Heat Index, Cooling and Heating Degree Days, and Growing Degree Days that may support and inform early design and conceptual strategies.

How Annual/Summer/Winter Average Temperatures may inform Project Evaluation

Consider if the project and subsequent assets address changes in Average Temperatures as part of the design narrative and/or operations plans, if any. Have the projected changes in Average Temperatures been estimated following the recommended standards (planning horizon, percentile, and tiered estimation method) of this Tool? If not, justification should be provided for using a different method than the tiered estimation method recommended by the Tool. Some of the examples of strategies may include lighter color pavement materials with high SRI for roadways, flexible design of HVAC systems based on building usage to handle both present and future cooling loads, increasing tree canopy and shade structures for parks and open spaces.

Limitations for Average Annual/Summer/Winter Temperature Standards and Guidance

The recommended Standards for Projected Average Annual/Summer/Winter Temperature are determined by the user drawn polygon and relationships as defined in the Supporting Documents. The guidance provided within this Tool may be used to inform plans and designs, but they are not comprehensive and do not provide guarantees for resilience. The guidance provided within this Tool is intended to be general and users are encouraged to do their own due diligence.

Projected Number of Days Per Year with Maximum Temperature > 95°F, >90°F, <32°F

Definition

Temperatures above 90°F and above 95°F are considered heat and extreme heat events in New England, respectively. Temperatures below 32°F are considered freezing events. An increase in Number of Days Per Year with Maximum Temperature above 90°F and 95°F may lead to an extended summer season. A decrease in Number of Days per Year with Minimum Temperatures below 32°F may lead to less snowfall and a shorter "traditional" New England winter season*

How to Estimate Projected Days Per Year with Maximum Temperature > 95°F, >90°F, <32°F Values

Asset Name	Recommended Planning Horizon	Recommended Percentile**	Projected Days with Max Temp > 95˚F (days)	Projected Days with Max Temp > 90˚F (days)	Projected Days with Max Temp < 32˚F (days)
Test	Standards and/or Projected Values will be presented here, if available				

How Days Per Year with Maximum Temperature > 95°F, >90°F, <32°F may inform Planning

Evaluate how the increase in projected Days Per Year with Maximum Temperature > 95°F and >90°F may impact the initial planning and pre-design considerations associated with the asset and overall project. It may be useful to compare the percent increase between current and estimated projected days per year values or create visuals that help communicate the increase in temperature expected, as well as the reduction in cold days. For example, with a 100% increase in days per year over >90°F between present and future, we can expect twice as many days per year as we experience now. With a 25% decrease in days per year <32°F, we can expect 1 out of 4 of our current days per year below 32°F to be above 32°F.

Identify how the asset's typical use and maintenance may be impacted by these changes in extreme temperatures. For example, planting selection (forests, parks, gardens, crops) may be affected by the extreme hot and reduced cold temperatures. Some plant species require a defined period of below freezing weather to thrive. Consider if there are other zones/locations that currently experience these climate patterns that may inform adaptive plans and design strategies.

Identify how these changes in extreme temperatures will impact public health and safety, especially populations that reside within Environmental Justice neighborhoods or climate vulnerable populations. Plans should consider how that impact may be mitigated through design.

How Days Per Year with Maximum Temperature > 95°F, >90°F, <32°F F may inform Early Design

Consider the asset's useful life and possible operational and maintenance protocols that may need to change throughout the asset's useful life based on changes in extreme temperatures. The useful life of the asset may be less than expected due to changes in extreme temperatures. It may be helpful to examine an adaptive framework that considers increased maintenance needs and reduced useful life; identify tipping points or triggers as part of routine maintenance and inspection that would inform action for retrofits and/or replacement of assets to adapt to extreme temperatures over time.

Material selection may be impacted by changes in extreme temperatures, from pavement design to façade color choice. Integrating light colors with a high solar reflectance index (SRI), high density vegetation, increased tree canopy, and elements that provide shading can reduce the impacts of extreme heat by decreasing observed surface temperatures.

Extreme heat may also impact construction, including workplace safety considerations, and material selection, including potential deformation of heat sensitive materials (for example, steel or asphalt). Refer to additional applicable design criteria for more guidance related to Heat Index, Cooling and Heating Degree Days, and Growing Degree Days that may support and inform early design strategies.

<u>How Days Per Year with Maximum Temperature > 95°F, >90°F, <32°F may inform Project Evaluation</u>

Consider if the project and subsequent assets address changes in extreme temperatures (increased extreme heat and reduced extreme cold) as part of the design narrative and/or operations plans, if any. Have the projected Days Per Year with Maximum Temperature > 95°F, >90°F, <32°F been estimated following the recommended standards (planning horizon, percentile, and tiered estimation method) of this Tool. If not, justification should be provided for using a different method than the tiered estimation method recommended by the Tool. Have the impacts to public health and safety, in particular impacts to populations that reside within Environmental Justice neighborhoods or climate vulnerable populations been identified with plans for mitigating those impacts as part of planning and design efforts? For examples of strategies, refer to Project Evaluation guidance under Projected Annual/Summer/Winter Average Temperatures above. Do they provide additional co-benefits for public space and/or the environment?

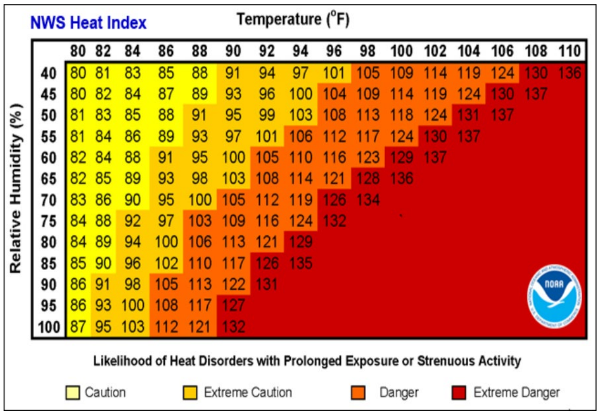
<u>Limitations for Days Per Year with Maximum Temperature > 95°F, >90°F, <32°F Standards and Guidance</u>

The recommended Standards for Days Per Year with Maximum Temperature > 95°F, >90°F, <32°F are determined by the user drawn polygon and relationships as defined in the Supporting Documents. The guidance provided within this Tool may be used to inform plans and designs, but they do not provide guarantees for resilience. The guidance provided within this Tool is intended to be general and users are encouraged to do their own due diligence.

Projected Heat Index

Definition

The National Weather Service (NWS) Heat Index or the "real feel" is based on temperature and relative humidity. The Heat Index is what the temperature feels like to the human body when relative humidity is combined with the air temperature and is measured in °F following the chart published by NWS.*



	80	82	84	86	88	90	92	94	96	98	100	102	104	106	108	110
40	80	81	83	85	88	91	94	97	101	105	109	114	119	124	130	136
45	80	82	84	87	89	93	96	100	104	109	114	119	124	130	137	
50	81	83	85	88	91	95	99	103	108	113	118	124	131	137		
55	81	84	86	89	93	97	101	106	112	117	124	130	137			
60	82	84	88	91	95	100	105	110	116	123	129	137				
65	82	85	89	93	98	103	108	114	121	128	136					
70	83	86	90	95	100	105	112	119	126	134						
75	84	88	92	97	103	109	116	124	132							
80	84	89	94	100	106	113	121	129								
85	85	90	96	102	110	117	126	135								
90	86	91	98	105	113	122	131									
95	86	93	100	108	117	127										
100	87	95	103	112	121	132										

Figure of Heat Index Chart from NWS (https://www.weather.gov/ama/heatindex)

The NWS Heat Index considers shady and light wind conditions but does not account for strong winds or full sun exposure. Exposure to full sunshine can increase Heat Index values by up to 15°F and strong wind of very hot dry air can be detrimental to public health and safety. The NWS uses the Heat Index to issue warnings and advisories relevant to public health considerations when daytime heat indices is more than 100°F for two or more hours.

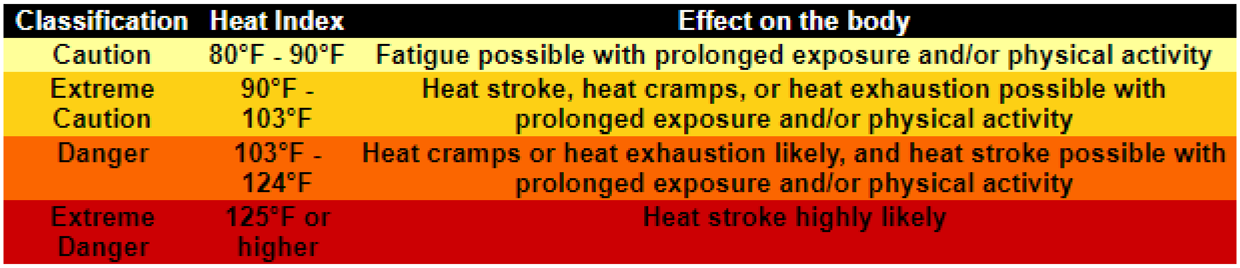
How to Estimate Projected Heat Index Values

Asset Name	Recommended Planning Horizon	Recommended Percentile**	Tiered Estimation Method	Step-by-Step Instructions
Test	Standards will be presented here			Downloadable Instructions PDF

***Note**: Projected Heat Index are not currently available through this Tool. Users should follow the step-by-step instructions outlined in the downloadable instructions PDF to estimate the projected Heat Index based on the recommended planning horizon, percentile, and tiered estimation methods. The three tiers represent various anticipated levels of effort for calculating design criteria values, dependent upon the consequences of failure of an asset as a function of scope, time, and severity and useful life of the asset.

How Heat Index may inform Planning

Evaluate how the increase in projected Heat Index may impact public health and safety, especially populations that reside within Environmental Justice neighborhoods or climate vulnerable populations, since Heat Index is a direct measure of feel-like temperatures. See the figure below for Heat Index effects on the human body.



Classification	Heat Index	Effect on the body
Caution	80°F - 90°F	Fatigue possible with prolonged exposure and/or physical activity
Extreme Caution	90°F - 103°F	Heat stroke, heat cramps, or heat exhaustion possible with prolonged exposure and/or physical activity
Danger	103°F - 124°F	Heat cramps or heat exhaustion likely, and heat stroke possible with prolonged exposure and/or physical activity
Extreme Danger	125°F or higher	Heat stroke highly likely

Figure of Heat Index Classification from NWS (https://www.weather.gov/ama/heatindex)

How Heat Index may inform Early Design

Consider the asset's useful life and possible design and/or operational and maintenance protocols that may need to change throughout the asset's useful life based on changes in Heat Index.

- For building assets, consider if the building materials can accommodate increased humidity and vapor impacts. Consider the potential increased need to reduce indoor air temperature and remove moisture. Will back-up power supply be needed for occupancy safety in the event of power shortages?
- For infrastructure assets, early design may need to consider seasonal implications and location considerations for regular maintenance activities. For example, will the asset need regularly scheduled maintenance during summer months in areas when the Heat Index is typically high? Consider if there will be an increased demand as a result of Heat Index? What are the implications on health and safety for people using or maintaining infrastructure assets?
- For open space assets, are there opportunities for increased vegetation and tree/constructed canopies that may reduce the temperature and relative humidity on site? Are there opportunities to add programming with water fountains, shaded structures, and/or cooling centers, especially for populations that reside within Environmental Justice neighborhoods or climate vulnerable populations?

How Heat Index may inform Project Evaluation

Consider if the project and subsequent assets address changes in Heat Index as part of the design narrative and/or operations plans, if any. Have the projected changes in Heat Index been estimated following the recommended standards (planning horizon, percentile, and tiered estimation methods) in this Tool? If not, justification should be provided for using a different method than the tiered estimation method recommended by the Tool. Have the impacts to public health and safety, in particular populations that reside within Environmental Justice neighborhoods or climate vulnerable populations, been identified with plans for mitigating those impacts as part of planning and design efforts? For examples of strategies, refer to Project Evaluation guidance under Projected Annual/Summer/Winter Average Temperatures above.

Limitations for Heat Index Standards and Guidance

The recommended Standards for Heat Index are determined by the user drawn polygon and relationships as defined in the Supporting Documents. The guidance provided within this Tool may be used to inform plans and designs, but they do not provide guarantees for resilience. The guidance provided within this Tool is intended to be general and users are encouraged to do their own due diligence.

Projected Number of Heat Waves Per Year & Average Heat Wave Duration

Definition

A Heat Wave is defined as three or more consecutive days with maximum temperatures of 90°F or above. Number of Heat Waves represents number of events (with one event representing at least three consecutive days with maximum temperatures of 90°F), and Average Heat Wave Duration represents the number of days for the average duration of each event over the year.*

Heat Waves are a public health and safety threat that may result in heat-related deaths. According to World Health Organization (WHO), Heat Waves, "can burden health and emergency services and also increase strain on water, energy and transportation resulting in power shortages or even blackouts. Food and livelihood security may also be strained if people lose their crops or livestock due to extreme heat."

How to Estimate Projected Number of Heat Waves Per Year & Average Heat Wave Duration Values

Asset Name	Recommended Planning Horizon	Recommended Percentile**	Projected Number of Heat Waves per Year (events)	Projected Average Heat Wave Duration (days)
building	Standards and/or Projected Values will be presented here, if available			

How Number of Heat Waves Per Year & Average Heat Wave Duration may inform Planning

Evaluate how the increase in projected Heat Waves (number of events and duration) may impact public health and safety, especially populations that reside within Environmental Justice neighborhoods or climate vulnerable populations. Refer to Heat Index for additional considerations related to human health impacts.

Planning may consider early decisions related to asset orientation and location. For example, assets located in urban areas typically experience more Heat Waves than rural areas as a result of Urban Heat Island (UHI) effect (https://www.mapc.org/resource-library/extreme-heat/). Are there opportunities to relocate the asset to an area with less frequent Heat Waves per year? Are there opportunities to mitigate or adapt to the threats of Heat Waves in preliminary planning, through passive design or programming?

How Number of Heat Waves Per Year & Average Heat Wave Duration may inform Early Design

Consider the asset's useful life in conjunction with projected Number of Heat Waves Per Year & Average Heat Wave Duration. Evaluate if consecutive high heat days may shorten the useful life and/or operational ability of the asset. Identify if there are design and/or operational and maintenance protocols that may need to change throughout the asset's useful life.

Heat Waves may increase demand for emergency services and/or water and power supply that may result in strained resources, including water shortages and blackouts. Food and livelihood security may also be impacted as a result of frequent or prolonged Heat Waves due to loss of crops or livestock. Consider if the asset and/or site are impacted by these related threats, and if populations that reside within Environmental Justice neighborhoods or climate vulnerable populations are impacted as a result. Identify what may be needed to adapt or mitigate these impacts, including redundancies for critical systems and/or regional coordination efforts. Refer to additional applicable design criteria for more guidance related to Heat Index, Maximum Temperatures, Heating and Cooling Degree Days, and Growing Degree Days that may support and inform early design and early strategies.

How Number of Heat Waves Per Year & Average Heat Wave Duration may inform Project Evaluation

Consider if the project and subsequent assets address increased events of sustained extreme heat (number and duration of Heat Waves) as part of the design narrative and/or operations plans, if any. Have the projected changes in Number of Heat Waves Per Year & Average Heat Wave Duration been estimated following the recommended standards (planning horizon, percentile, and tiered estimation methods) of this Tool? If not, justification should be provided for using a different method than the tiered estimation method recommended by the Tool. Have the impacts to public health and safety, in particular populations that reside within Environmental Justice neighborhoods or climate vulnerable populations, been identified with plans for mitigating those impacts as part of planning and design efforts? For examples of strategies, refer to Project Evaluation guidance under Projected Annual/Summer/Winter Average Temperatures above.

Limitations for Number of Heat Waves Per Year & Average Heat Wave Duration Standards and Guidance

The recommended Standards for Number of Heat Waves Per Year & Average Heat Wave Duration are determined by the user drawn polygon and relationships as defined in the Supporting Documents. The guidance provided within this Tool may be used to inform plans and designs, but they do not provide guarantees for resilience. The guidance provided within this Tool is intended to be general and users are encouraged to do their own due diligence.

Projected Cooling Degree Days & Heating Degree Days (base = 65°F)

Definition

Cooling Degree Days (CDD) is a metric used to inform the energy consumption needed to cool indoor spaces for occupancy comfort when outside temperatures exceed 65°F. CDD measures the difference between the average daily temperature and 65°F. For example, if the average temperature for the day is 95°F, the difference between 65°F results in 30 CDD for that day.

Heating Degree Days (HDD) is a metric used to inform the energy consumption needed to heat indoor spaces for occupancy comfort when outside temperatures are below 65°F. HDD measures the difference between the average daily temperature and 65°F. For example, if the average temperature for the day is 35°F, the difference between 65°F results in 30 HDD for that day.*

How to Estimate Projected Cooling Degree Days & Heating Degree Days Values

Asset Name	Recommended Planning Horizon	Recommended Percentile**	Projected Cooling Degree Days (base = 65˚F) (degree days)	Projected Heating Degree Days (base = 65˚F) (degree days)
building	Standards and/or Projected Values will be presented here, if available			

How Cooling Degree Days & Heating Degree Days may inform Planning

Massachusetts has historically had more HDD than CDD. Evaluate how the change in projected HDD and CDD may impact the initial planning and pre-design considerations associated with the asset and overall project. It may be useful to compare the percent increase between current and estimated projected HDD and CDD values. For example, there may be a 100% increase in CDD between present and future (twice as many CDD as we experience now), but only a 25% decrease in HDD. Planning and pre-design efforts should consider how the asset and overall project respond to current and future conditions through an asset's useful life.

It may be useful to compare the projected CDD and HDD with climate zones that have similar CDD and HDD under current conditions as a basis-for-discussion and reference. Evaluate how energy demands may need to change over time (annually or seasonally) and opportunities for sustainable and passive design strategies.

Identify potential impacts to public health and safety as a result of changes in projected CDD and HDD and identify what steps may be taken in planning and design to mitigate those impacts. Identify if are there additional impacts if the building serves populations that reside within Environmental Justice neighborhoods or climate vulnerable populations.

How Cooling Degree Days & Heating Degree Days may inform Early Design

Consider the asset's useful life and possible operational and maintenance protocols that may need to change throughout the asset's useful life based on changes in projected CDD and HDD. The supporting mechanical, electrical, and plumbing components of the building may have a shorter useful life than the overall building due to changes in CDD and HDD. It may be helpful to examine an adaptive framework that considers increased maintenance needs and reduced component useful life; identify tipping points or triggers as part of routine maintenance and inspection that would inform action for retrofits and/or replacement of assets to adapt to changes in CDD and HDD over time. For example, are there opportunities for heating, ventilation, and air conditioning (HVAC) systems to be designed to efficiently perform under current and future conditions? Energy efficiency and sustainable design strategies are recommended to reduce overall energy consumption needs associated with CDD and HDD.

How Cooling Degree Days & Heating Degree Days may inform Project Evaluation

Consider if the design narrative (especially related to the mechanical, electrical, and plumbing components) and/or operations plans address changes in CDD and HDD. Have the projected changes in CDD and HDD been estimated following the recommended standards (planning horizon, percentile, and tiered estimation methods) of this Tool? If not, justification should be provided for using a different method than the tiered estimation method recommended by the Tool. Have the impacts been identified with plans for mitigating those impacts as part of planning and design efforts? Could this impact existing capital planning and/or regular maintenance schedules? Are there additional risks to populations that reside within Environmental Justice neighborhoods or climate vulnerable populations that are addressed in plans and designs? For examples of strategies, refer to Project Evaluation guidance under Projected Annual/Summer/Winter Average Temperatures above.

Limitations for Cooling Degree Days & Heating Degree Days Standards and Guidance

The recommended Standards for Cooling Degree Days & Heating Degree Days are determined by the user drawn polygon and relationships as defined in the Supporting Documents. The guidance provided within this Tool may be used to inform plans and designs, but they do not provide guarantees for resilience. The guidance provided within this Tool is intended to be general and users are encouraged to do their own due diligence.

Projected Growing Degree Days (base = 50°F)

Definition

According to the Climate Smart Farming program at Cornell University, Growing Degree Days (GDD) "measures heat accumulation to help agricultural producers predict when a crop will reach important developmental stages. It can also be used to help predict potential pest and disease threats."

Growing Degree Days (GDD) are a measure of heat accumulation that can be correlated to express crop maturity (plant development). GDD is calculated by subtracting a base temperature of 50°F from the average of the maximum and minimum temperatures for the day. Minimum temperatures less than 50°F are set to 50, and maximum temperatures greater than 86°F are set to 86. These substitutions indicate that no appreciable growth is detected with temperatures lower than 50° or greater than 86°. Increases in daily average temperatures over 50°F will result in an increase in GDD.*

GDD may inform planning and early design considerations for forested ecosystems, agricultural resources, and open spaces.

How to Estimate Projected Growing Degree Days Values

Asset Name	Recommended Planning Horizon	Recommended Percentile**	Projected Growing Degree Days (base = 50 ˚F, max = 86 ˚F) (degree days)
Test	Standards and/or Projected Values will be presented here, if available		

How Growing Degree Days may inform Planning

For planning purposes, GDD is often used to predict plant development and manage crop harvest. The projected GDD can help users assess how a particular season (current or historical) may compare to future seasons. For example, if an agricultural resource asset, consider if the asset or site is important for food security and how changes in GDD may impact food security. Evaluate if current species of plants/vegetation may be able to adapt to the increase in GDD. Identify if pollination may be affected as a result of changes to GDD. For example, if a forested ecosystem asset, evaluate if there may be impacts to forestry management or maple syrup production. Identify if there are populations that reside within Environmental Justice neighborhoods or climate vulnerable populations that rely on this asset and how changes in growing season length and timing affect them.

How Growing Degree Days may inform Early Design

Identify if the projected GDD may inform selection of crop varieties and planting and harvesting schedules. Analysis of GDD in relation to plant hardiness zones may be helpful in assessing species selection is for a site. https://www.fs.fed.us/nrs/pubs/rmap/rmap_nrs9.pdf. Identify if certain species may be appropriate for selection that are suitable to the changing climate and increased GDD; species selection may need to evolve over time to adapt to the changing climate. What alternatives should be considered that would increase resiliency of the ecosystem in growing season? Consider how increasing precipitation events (frequency and duration) as well as prolonged periods of drought may also inform planning and design.

How Growing Degree Days may inform Project Evaluation

Consider if the project and natural resource assets address increased GDD as part of the design narrative and/or planting plans for the growing season. Have the projected changes in GDD been estimated following the recommended standards (planning horizon, percentile, and tiered estimation method) of this Tool? If not, justification should be provided for using a different method than the tiered estimation method recommended by the Tool. Have the impacts to populations that reside within Environmental Justice neighborhoods or climate vulnerable populations that may rely on this asset been identified with plans for mitigating those impacts as part of planning and design efforts? For examples of strategies, refer to Project Evaluation guidance under Projected Annual/Summer/Winter Average Temperatures above. Consider if the strategies response to other climate impacts (for example heavy rainfall or drought conditions).

Limitations for Growing Degree Days Standards and Guidance

The recommended Standards for Growing Degree Days are determined by the user drawn polygon and relationships as defined in the Supporting Documents. The guidance provided within this Tool may be used to inform plans and designs, but they do not provide guarantees for resilience. The guidance provided within this Tool is intended to be general and users are encouraged to do their own due diligence.