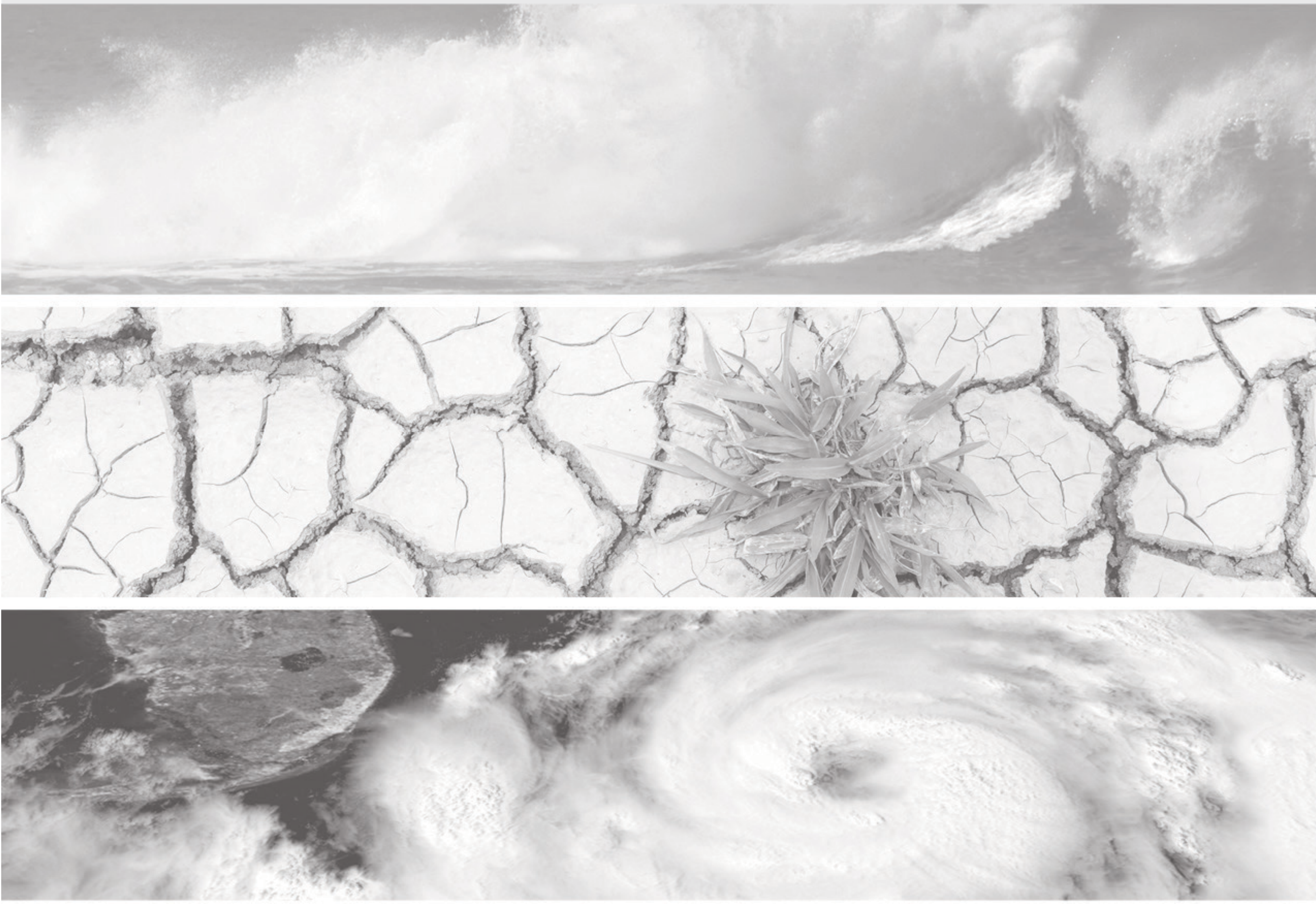
United States Environmental Protection Agency

Climate Resilience Evaluation and Awareness Tool

Version 3.1 Methodology Guide



Disclaimer

The Climate Resilience Evaluation and Awareness Tool (CREAT) was prepared by the U.S. Environmental Protection Agency (EPA) as an informational tool to assist drinking water, wastewater, and stormwater utility owners and operators in understanding and addressing climate change risks. CREAT does not purport to provide a comprehensive or exhaustive list of all impacts and potential risks from climate change or any other threats.

The information contained in CREAT was developed in accordance with best industry practices. It should not be relied on exclusively when conducting risk assessments or developing response plans. This information is also not a substitute for the professional advice of an attorney or environmental or climate change professional. This information is provided without warranty of any kind, and EPA hereby disclaims any liability for damages arising from use of this tool, including without limitation, direct, indirect, or consequential damages including personal injury, property loss, loss of revenue, loss of profit, loss of opportunity, or other loss.

Changes are periodically made to the information herein that may be incorporated in new editions of this document. EPA may make improvements or changes to CREAT at any time.

Office of Water (4608-T) EPA 817-B-21-001
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Acronyms

AWWA – American Water Works Association

CMIP5 – Coupled Model Intercomparison Project,[1] Phase 5

CREAT – Climate Resilience Evaluation and Awareness Tool

CWSS – Community Water System Survey[2]

DCR – Debt coverage ratio

EPA – U.S. Environmental Protection Agency

GCM – Global Climate Model (or general circulation model)

GEV – Generalized extreme value curve

IPCC – Intergovernmental Panel on Climate Change

MGD – Millions of gallons per day

MRR – Monetized risk reduction

NCA – National Climate Assessment[3]

NOAA – National Oceanic and Atmospheric Administration

O&M – Operations and maintenance costs

PRISM – Parameter-elevation Regressions on Independent Slopes Model[4]

SLR – Sea level rise

VLM – Vertical land movement

VSI – Value of a Statistical Injury

VSL – Value of a Statistical Life

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[1] World Climate Research Programme Coupled Model Intercomparison Project. https://www.wcrp-climate.org/wgcm-cmip

[2] U.S. Environmental Protection Agency 2006 Community Water System Survey, Volume II: Detailed Tables and Survey Methodology. EPA 815-R-09-002.

[3] National Climate Assessment. https://www.globalchange.gov/what-we-do/assessment

[4] PRISM Climate Group, Oregon State University. https://www.prism.oregonstate.edu

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Chapter 1. Background

The U.S. Environmental Protection Agency (EPA) developed the Climate Resilience Evaluation and Awareness Tool (CREAT) to assist drinking water, wastewater, and stormwater utility owners and operators in understanding potential climate change threats[5] and assessing the related risks at their individual utilities. CREAT was developed under EPA's Creating Resilient Water Utilities initiative.

CREAT was designed in consultation with a working group that helped to provide key feedback on features and functionality. The working group was composed of representatives from drinking water and wastewater utilities, water sector associations, climate science experts, risk assessment experts, and federal partners. CREAT (**Figure 1**) leverages the most current scientific information available at the time of development. Data provided within CREAT are updated and augmented, as appropriate.

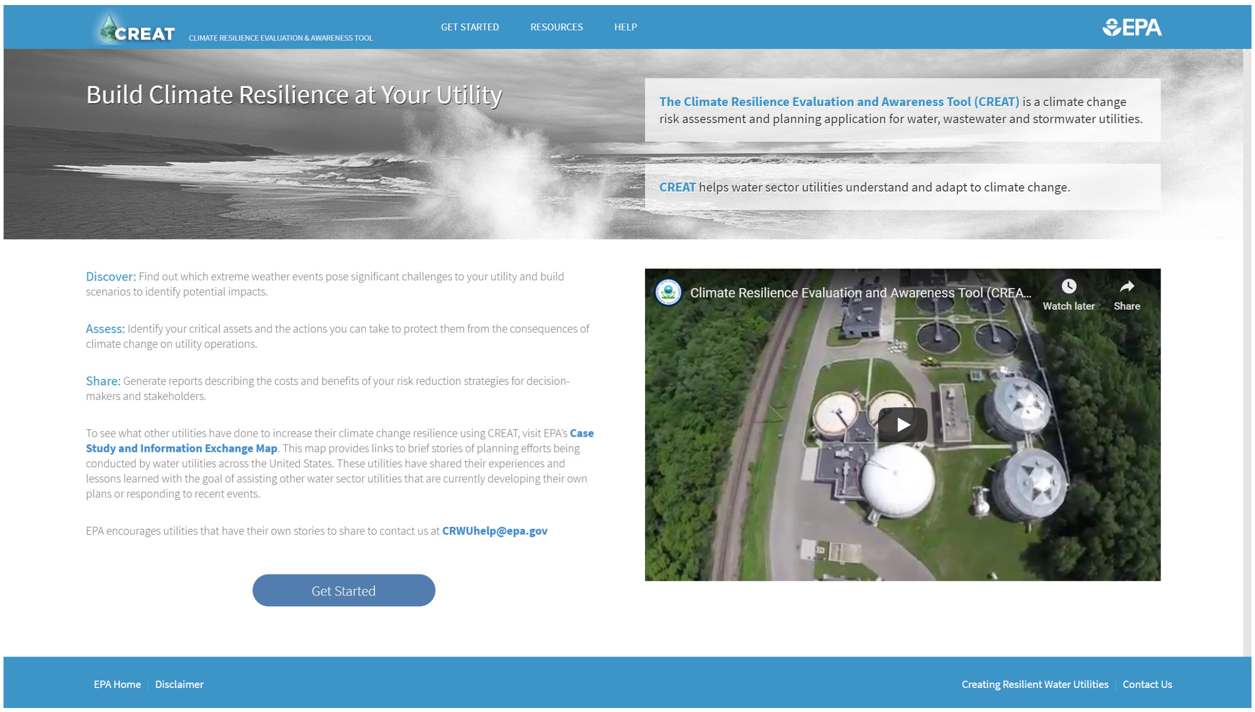

Figure 1. CREAT 3.1 Home Screen

The results generated by CREAT provide decision-support outputs to assist in the selection and justification of investments in climate change adaptation. The risk assessment process is designed to be iterative and can be revisited for future risk analyses. The fundamental goals of CREAT are to:

[5] In CREAT, climate change threats are climatic, hydrologic, geophysical, and geochemical changes in terrestrial and aquatic ecosystems that alter the operating environment of utility facilities and operations.

- Increase drinking water, wastewater, and stormwater operator awareness of potential climate change impacts on utility operations and missions;
- Assist utilities in the determination of threshold levels for asset failures and resulting consequences of an asset's inability to perform its designed function;
- Guide utilities through the risk assessment process to quantify potential consequences from climate-related or other threats;
- Inform adaptation decision-making by identifying and considering adaptation options that address identified threats and reduce associated impacts; and
- Examine the cost of these different adaptation options in comparison to the economic losses associated with the consequences of climate change threats.

Chapter 2. CREAT Overview

2.1 Framework

CREAT guides users through five modules designed to help them complete a climate change risk assessment. These modules employ a systematic process for evaluating the potential risks that may be incurred from changing climate conditions. Each module assists users to meet specific goals, such as building awareness of the latest climate science, and builds on inputs from previous modules. **Figure 2** illustrates how the CREAT modules align with the overall workflow of the application and the chapters of this guide.

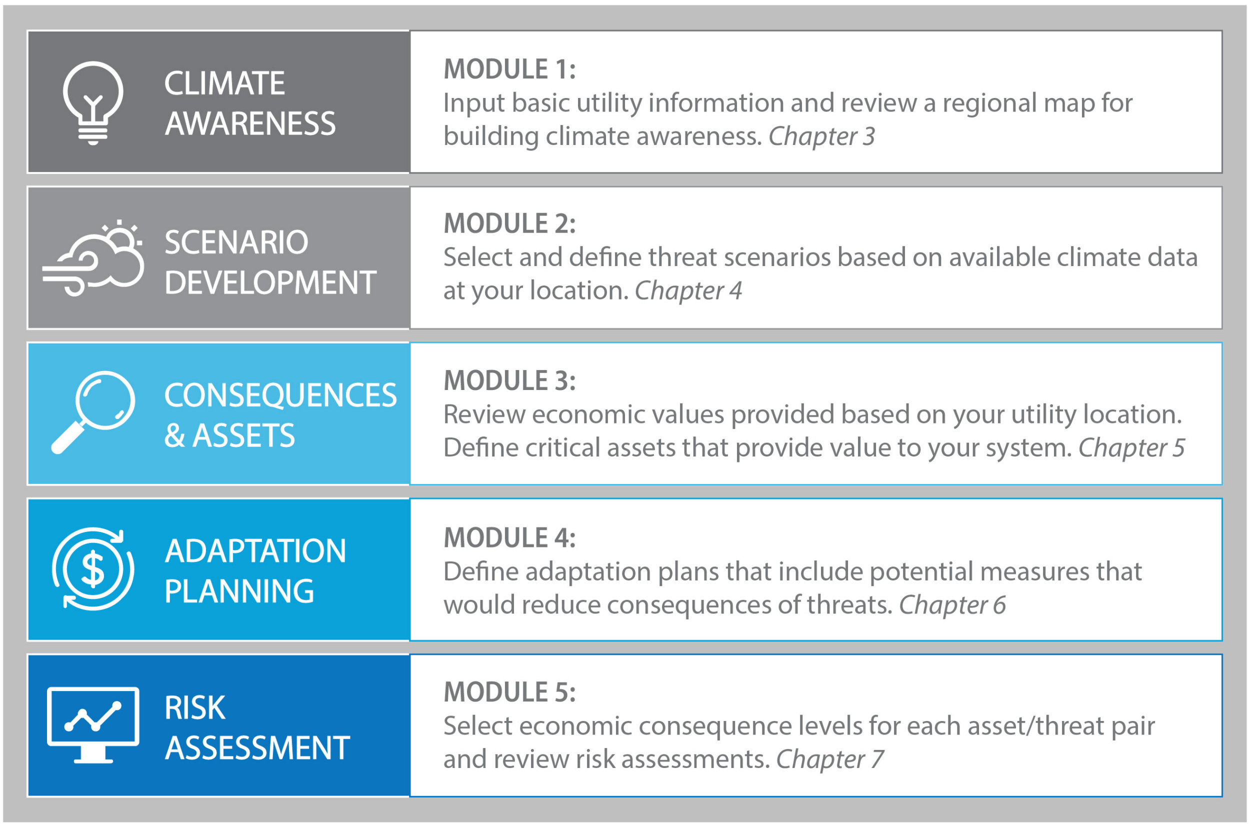

Figure 2. CREAT Module Overview

2.2 Streamlined Analysis Option

CREAT offers a streamlined analysis option that guides decisions for the analysis, provides default values, and requires only basic data entry. This workflow allows users to progress through CREAT quickly by reducing the scope of analysis and focusing on priority concerns. Selecting the streamlined option can help users to become familiar with the risk assessment process before conducting more in-depth analyses.

With the streamlined path, users still must proceed through the Climate Awareness Module for basic utility information entry and views additional material on climate change and current concerns for awareness purposes. One default threat and one scenario are provided in the Scenario Development module to ensure a manageable scope in the assessment. In the Consequences and Assets module, limited asset selection is encouraged. For Adaptation Planning, CREAT will define one adaptation plan including all potential adaptive measures previously entered for consideration during risk assessment.

Given that the number of assessments increases if additional assets and threats are selected, the streamlined analysis path encourages users to assess the risk for a single asset/threat pair instead of having multiple combinations to consider. The streamlined option in CREAT produces a more focused assessment requiring fewer inputs. The outputs describe a concise and focused result for users who are in the early stages of risk assessment and adaptation.

2.3 CREAT Reports

At the conclusion of each of the first four modules, users may generate interim reports to inform utility planning and decision making as described below:

- The *Climate Awareness Report* summarizes potential future climate conditions and impacts to the water sector and local communities;
- The *Scenario Development Report* lists each scenario and the associated threats as defined in the assessment;
- The *Consequences and Assets Report* includes the economic consequences matrix, a list of the assets defined, and summary information on the regional economic and public health consequences (if included); and
- The *Adaptation Planning Report* details each adaptation plan with the cost of each adaptive measure included in the plans.

The high-level summary reports document progress through the overall risk assessment process, communicate key information, and provide a basis for additional work to be conducted within the tool. The reports help to build confidence that the utility is being proactive or identifying areas where additional funding may be needed to bolster climate readiness.

The final report generated in the Risk Assessment module is the *Plan Report*, which includes the results of the risk assessment for each specific adaptation plan. The Plan Report is a summary of the risk reduction possible that can be compared with the cost of implementing the adaptation plan. This report can be used as decision support to inform adaptation planning or to determine if there is a need for further assessment.

Chapter 3. Climate Awareness: Module 1

This module begins the risk assessment process with a review of climate science and climate change impacts. Users first identify the utility location[6] for their assessment, as well as basic utility information, including population served, total flow, and financial condition. The financial condition indicates the utility's strength to endure operating revenue loss or capacity by expending funds to repair and replace equipment. Financial condition can be based on debt coverage and operating ratios. CREAT also requires users to identify a system type for the utility from the following choices:

- Water only system: a utility that provides drinking water services;
- Wastewater only system: a utility that provides wastewater or stormwater services;
- Combined Water: a combined utility with a focus on drinking water assets; and
- Combined Wastewater: a combined utility with a focus on wastewater assets.

A critical first step in the identification of potential climate-related risk for any utility is the recognition of known current concerns that are presently being addressed. In the Climate Awareness module, users identify these concerns, which help organize information to identify climate change threats, as well as assets[7] to consider during the assessment.

3.1 Climate Change Concerns in CREAT

CREAT provides climate change information to help identify the utility's current concerns and consider how these concerns may be exacerbated as a result of a changing climate. The process is designed to help organize information and identify the threats and assets to consider in the risk assessment.

Current concerns available in CREAT are related to potential threats that can be defined and assessed using CREAT, which are as follows:

- **Water Supply Management**: drought, seasonal demand, snowpack, reservoir storage, and low streamflow conditions;
- **Peak Service Challenges:** stormwater runoff, seasonal demand, and discharge under low receiving water flow conditions;
- **Water Quality Management:** runoff, treatment, violations, saltwater intrusion, source water turbidity, and algal blooms;
- **Natural Disasters:** fires, floods, tornadoes, and ice storms;

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[6] CREAT provides climate data, such as temperature, precipitation, and surface water flow data, for the analysis location selected. Coastal data including vertical land movement, sea level rise, and number of days with tidal flooding is also provided for coastal locations, which are those near tidal water bodies.

[7] In CREAT, an asset can be anything of value that contributes to a utility's ability to meet its mission, including physical infrastructure, entire facilities or natural resources that provide services or water to the utility regardless of its ownership or the parties responsible for its management.

- **Ecosystem/Landscape Management:** coastal erosion, wetland loss, and endangered species protection;
- **Population/Demographic Changes:** customer base, land use, and workforce availability;
- **Sector Water/Service Needs:** agriculture, energy sector, health services, and local industries;
- **Interdependent Sector Reliability:** power sector, transportation, and chemical suppliers; and
- **Sea Level Rise (SLR):** saltwater intrusion, and coastal storm surge.

These concerns are assessed based on an understanding of climate change and other projected trends that may impact utility operations or infrastructure. CREAT provides climate data for use in prioritizing these concerns and defining related threats in the risk assessment process.

Chapter 4. Scenario Development: Module 2

This module assists users consider CREAT-provided historical and projected climate data as scenarios[8] that represent a range of possible future climate conditions and the potential threats these conditions could generate. CREAT provides default threat selections[9] based on the current concerns identified in the Climate Awareness module.

To explore and assess their current risk, users establish a Baseline Scenario for planning decisions and other assessments, by including historical data provided within CREAT or custom data records. CREAT is flexible in its approach and users can replace CREAT provided data with custom values. Historical data provided by CREAT include:

- average annual and monthly temperature;
- average number of days exceeding 90, 95, and 100 degrees Fahrenheit in a year;
- total annual and monthly precipitation;
- storm precipitation totals over 24 hours and 72 hours for several event return intervals;
- streamflow measures for mean, minimum, and maximum flow conditions; and
- coastal data for vertical land movement and the number of days with tidal flooding for several increments of sea level rise.

If available, custom data measurements may also be added by users to track additional conditions such as population trends, alternate temperature or precipitation thresholds, or other metrics.

Once a Baseline Scenario has been established, additional Projected Scenarios for risk assessment can be based on any of the CREAT-provided projections of changes in climate conditions. These projections are based on averages of climate model outputs to provide a representative range of how temperature, precipitation, surface water, and coastal data could change. Once selected, the threats associated with these projections provide a range of possible conditions for consideration in the risk assessment.

In the Risk Assessment module (Module 5), the Baseline Scenario is compared to other scenarios and is used to help identify “no regrets” options, which are options that have benefit with or without changes in climate.

4.1 Climate Change Threats in CREAT

Threats are assessed based on an understanding of climate change and other projected trends that may impact utility operations or infrastructure. CREAT provides climate data for use in prioritizing these concerns and defining related threats in the risk assessment process.

[8] In CREAT, scenarios refer to groups of threats that are defined by users based on available historical or projected climate data, as well as any other relevant data, such as demand forecasts.

[9] The default threats in CREAT are derived from a combination of changes in climatic conditions that may result in impacts to assets, including drought, floods, ecosystem changes, service demand and use, and water quality degradation.

In the Scenario Development Module, CREAT provides five general threats related to climate conditions for use in the risk assessment, which are as follows:

- **Drought:** changing water levels in aquifers and reservoirs, loss of snowpack, and reductions in surface water flows;
- **Ecosystem Changes:** altered status, structure or functionality of an ecosystem, such as loss of coastal systems, increases in wildfires, or altered vegetation;
- **Floods:** high flows from intense precipitation events or surges associated with coastal storms in combination with SLR;
- **Service Demand and Use:** altered volume and temperature of influent or challenges meeting the needs of agricultural and energy sectors; and
- **Water Quality Degradation:** saline intrusion into aquifers and contaminated or negatively altered surface water quality.

These threats are considered starting with a Baseline Scenario consisting of climate conditions based on historical or observed data to enable comparison of current climate conditions and associated threats with how they could change in the future. This scenario helps utilities evaluate their current resilience based on threat magnitudes and timing that are already used in planning decisions and other assessments.

The climate information available in CREAT provides a snapshot of how changes in climate might exacerbate current concerns. In addition to the national and international assessments synthesized in CREAT, historical observations and model projections are organized for users to review and select as part of their scenarios.

In the Scenario Development Module, users establish Baseline and Projected Scenarios, based on p historical and projected changes in climate conditions. Scenarios are defined based on data provided in CREAT or from the utility's sources or models. Each scenario describes different changes in climate conditions that may present different threats. Considering multiple scenarios increases the range of possible future climate conditions included in the risk assessment.

4.2 Climate Change Assessments in CREAT

In the Climate Awareness Module, an interactive map (**Figure 3**) provides the ability to focus on regional impacts or impacts to specific sectors with information from the most recent National Climate Assessment[10] (NCA). CREAT provides climate information by defined geographic regions including the Northeast, Southeast, Midwest, Great Plains, Southwest, Northwest, Alaska, Islands, and Coasts, with particular emphasis on how climate may impact the water sector.

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[10] National Climate Assessment: https://www.globalchange.gov/what-we-do/assessment

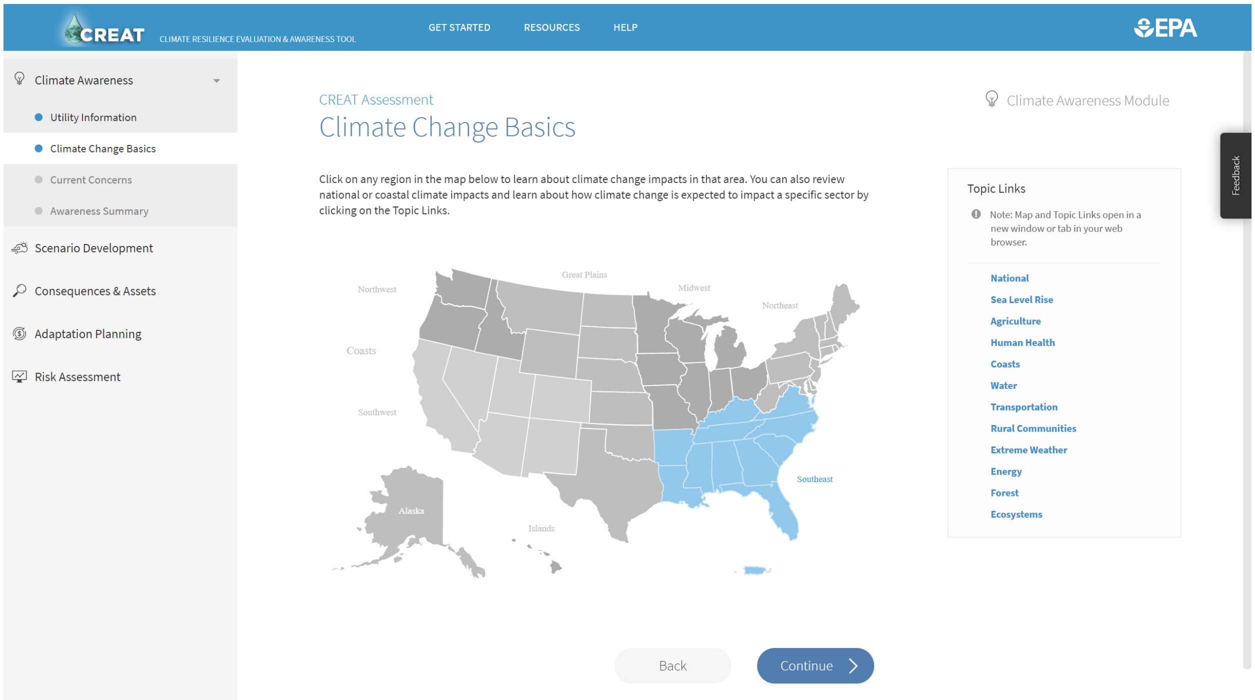

Figure 3. Climate Awareness Interactive Map

4.3 Baseline Scenario

The data used to define the Baseline Scenario should be based on event magnitudes and timing to assist in planning decisions and other assessments, such as historical data provided within CREAT or from records kept by the utility. Default data provided by CREAT for the Baseline Scenario include average temperature, total precipitation, intense precipitation, extreme temperature days (hot days), high and low streamflow, and coastal data.

In the Baseline Scenario Dashboard, users can review the default selected measurements and select or deselect additional measurements to be included in the Baseline Scenario. Users can also add custom data, such as natural resource and socioeconomic data, to provide a more robust Baseline Scenario. Once the measurements are selected, users can review and choose to accept the default data or replace default values with custom data.

4.3.1 Historical Climate Conditions

CREAT provides historical climate data for temperature and precipitation to help users assess current risk as part of their Baseline Scenario. Average annual and monthly conditions are sourced from the Parameter-elevation Regressions on Independent Slopes Model[11] (PRISM) data set based

[11] PRISM Climate Group, Oregon State University. https://www.prism.oregonstate.edu

on observations from 1981 to 2010. Data available from the Climate Research Unit[12] are used in places where PRISM data were unavailable, such as in Alaska, Hawaii, and Puerto Rico. The resultant data set covers all 50 states and Puerto Rico at a 0.5-degree resolution in latitude and longitude.

4.3.2 Historical Extreme Events

Historical data on extreme events, including both temperature and precipitation, are based on time-series analysis of the data available from the National Oceanic and Atmospheric Administration (NOAA) National Climate Data Center climate stations.[13] Data for historical extreme events are representative of each station. Users have the flexibility to select a station independent of the location used for historical average conditions.

Historical hot days, those days with daily maximum temperature exceeding 90, 95, and 100 degrees Fahrenheit, were calculated using historical daily maximum temperature data from 8,150 stations. These stations were selected based on a minimum of 95% completeness for April through October daily observations from at least one calendar year in the period of observation. For 1,825 stations (22% of data set), zero days in the record qualified as hot days.

For intense precipitation events, time series of historical daily precipitation data from 11,010 stations were reviewed and converted into annual maxima time series for 24-hour and 72-hour precipitation. Any station with data available during 1981 through 2010 was included. This time series was then used to develop the historical generalized extreme value (GEV) curve for each station that describes the maximum amount of precipitation observed over 24 hours for several event return intervals.[14] Curves were calculated using the exceedance probabilities, which are fractions of observations over a series of event magnitudes on an annual basis, from observed daily total precipitation fit to the following cumulative distribution function:

$$F(x; \mu, \sigma, \xi) = exp\{-[1 + \xi((x - \mu)/\sigma)]\hat{}((-1)\ /\ \xi)\ \}, \text{ where}$$

x is the event magnitude; ξ is the shape parameter; σ is the scale parameter; and μ is the location parameter. The three parameters (ξ, σ, and μ) were used to fit the curve. The peak magnitudes of 24-hour and 72-hour rainfall events were calculated for storms with return intervals of 5, 10, 15, 30, 50, and 100 years.

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[12] University of East Anglia Climatic Research Unit; Jones, P.D.; I. Harris. (2013): CRU TS3.20: Climatic Research Unit (CRU) Time-Series (TS) Version 3.20 of High Resolution Gridded Data of Month-by-month Variation in Climate (Jan. 1901 - Dec. 2011). NCAS British Atmospheric Data Centre, *April 2015*. https://catalogue.ceda.ac.uk/uuid/2949a8a25b375c9e323c53f6b6cb2a3a

[13] For more information on NOAA climate stations, see: https://www.ncdc.noaa.gov/data-access/land-based-station-data

[14] A storm event with a return interval of 100 years is an event that has a 1% chance of being observed or exceeded in any year, based on the historical record. This event is sometimes called the 100-year storm. The return interval does not strictly define a frequency for the event; it is possible that historically rare events could occur more frequently in periods of the record.

4.3.3 Historical Streamflow

Historical flow data in CREAT are from approximately 8,200 U.S. Geological Survey (USGS) stream gaging sites across the United States with daily discharge information covering the period of record (USGS, 2017).[15] The time-series data were compiled to provide the following for each site:

- start and end years of the record;
- years in the record with data for at least 95% of the days ("complete" years);
- possible influence of tides in flow record (these gage sites were excluded);[16]
- average, minimum and maximum daily flows for each complete year; and
- minimum 7-day flow for each complete year.

Using the annual flow metrics above, the following data are provided in CREAT at each gage:

- average daily flow;
- average annual minimum daily flow;
- average annual maximum daily flow;
- the 10th percentile of annual 7-day low flows from complete years (7Q2); and
- the 50th percentile of annual 7-day low flows from complete years (7Q2).

Note that the period of record in CREAT may include more than 30 years, where data were available, because longer periods of record are more useful for identifying infrequent extreme conditions. Users should select the USGS gage that is most appropriate for their use. For example, an appropriate gage could be located along the same stream reach or stream network as their utility assets.

4.3.4 Coastal Data

CREAT provides projections of future flood frequency under various projected sea level rise scenarios to help users assess short-term and long-term risk of coastal flooding. Projected sea level rise and flooding scenarios are derived from models produced by the National Oceanographic and Atmospheric Administration (NOAA) and published in a series of two reports which report sea level rise scenarios and flood inundation frequency at select locations.

For assessing risk of coastal flooding for current global mean sea level (GMSL), NOAA employed methods[17] to account for regional considerations, such as earth's gravitation field and rotation, shifts in oceanographic circulation, and vertical land movement (VLM), to produce relative sea level (RSL) to compare with calculated flooding thresholds at tide gauge locations. These thresholds were developed by NOAA to provide a national definition of coastal flooding and quantification of

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[15] USGS, 2017. Surface-Water Daily Data for the Nation. U.S. Geological Survey, National Water Information System (NWIS). Available: https://waterdata.usgs.gov/nwis/dv/?referred_module=sw

[16] Gages in coastal areas that have flows influenced by tides typically have flow heading upstream as tides are rising, resulting in negative minimum annual flow values.

[17] NOAA Technical Report NOS CO-OPS 083: Global and Regional Sea Level Rise Scenarios for the United States

flood impacts. Based on these thresholds, flood frequency was estimated using empirical (kernel) probability estimates from 1998-2016 at gauge locations in all States and Territories, excluding Alaska[18].

Vertical land movement is the rate of land moving up or down due to several processes, such as tectonics, subsidence, and ground water extraction. In a place where VLM is upward, local SLR is slower than the rate of global SLR. When VLM is downward, local SLR is faster than global SLR. CREAT includes estimates from NOAA[19] using 30 to 60 years of data.

4.4 Time Period

To effectively apply risk assessment results to planning efforts, users must identify a time period for use in developing Projected Scenarios. This time period is selected for each assessment file and constitutes the range of years being considered for the analysis. The period selected, from Start Year to End Year, may be based on planning horizons for asset or water resource management, improvement schedules or climate action plans. The End Year defines the target for planning when adaptation plans would be completed and the conditions in Projected Scenarios may be experienced. CREAT provides climate data based on the End Year of the user-defined time period to support the climate change risk assessment.

4.5 Projected Scenarios

CREAT provides projected changes from Global Climate Models[20] (GCMs) as available from the Coupled Model Intercomparison Project, Phase 5 (CMIP5),[21] which are the same data used to support the IPCC Fifth Assessment Report. Data provided in CREAT were from model simulations employing Representative Concentration Pathway 8.5, a higher trajectory for projected greenhouse gas concentrations to support assessments looking at higher potential risk futures.

Because the outputs from GCMs vary, CREAT provides averages from model projections that represent a range of potential future climate conditions. Generally, all models project warming but projections for precipitation vary more widely. Users may choose to apply all, or part of the projection data provided, along with custom data projections for climate or other parameters, to enhance their scenarios. For example, users may want to incorporate data collected by the utility, in-house models, projected changes in population, demand, or energy costs.

Different approaches were used to estimate changes in different climate conditions, as described below. These differences were necessitated by the availability of data and the goal of providing CREAT users with the range of projections to select from rather than a few scenarios narrowly

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[18] NOAA Technical Report NOS CO-OPS 086

[19] NOAA, 2013. Estimating Vertical Lane Motion from Long-Term Tide Gauge Records. Technical Report NOS CO-OPS 065.

[20] Global Climate Models are mathematical models that model the physical processes of earth's atmosphere, ocean, cryosphere, and land surfaces. These models are used to simulate the response to increasing greenhouse gas concentrations. The outcomes of different GCMs vary because the feedback mechanisms of various processes that are incorporated differ from model to model.

[21] World Climate Research Programme Coupled Model Intercomparison Project, https://www.wcrp-climate.org/wgcm-cmip

defined by a few models or model runs. Due to the differences in data sources across different data types, users should not assume the conditions are linked and that a scenario represents a potential future derived by consistent model projections. Instead, scenarios represent a combination of potential conditions, artificially combined to present challenges that may necessitate changes to withstand if they were to occur.

4.5.1 Projected Changes in Temperature and Precipitation

CREAT uses an ensemble-informed approach to derive meaningful choices from the results of 38 model runs[22] for each 0.5- by 0.5-degree location. This approach involves generating a scatter plot of normalized, projected changes in annual temperature and precipitation by 2060 for all models. Statistical targets were calculated based on the distribution of these model results and the five models closest to those targets were averaged to generate each projection (**Figure 4**). The targets were designed to capture a majority of the range in model projections of changes in annual temperature and precipitation, as follows:

- Warmer and wetter future conditions: average of five individual models that are nearest to the 95th percentile of precipitation and 5th percentile of temperature projections;
- Moderate future conditions: average of five individual models that are nearest to the median (50th percentile) of both precipitation and temperature projections; and
- Hotter and drier future conditions: average of five individual models that are nearest to the 5th percentile of precipitation and 95th percentile of temperature projections.

Once the models for each projection were selected, these models were ensemble-averaged to calculate annual and monthly changes for temperature and precipitation. CREAT selects the most appropriate data to match the defined planning horizon from two available data sets: one for 2035, which is based on projection data for 2025–2045, and one for 2060, which is based on projection data for 2050–2070. The appropriate CREAT-provided time period is based on the End Year defined by users on the time period page. If the End Year is 2049 or earlier, the 2035 data are selected; otherwise, the 2060 data set is selected.

[22] List of models used in analyses provided in Appendix A-1.

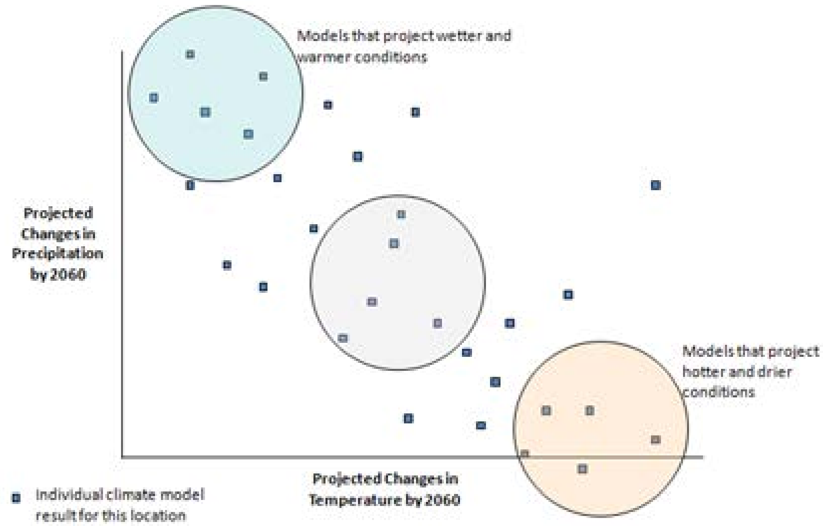

Figure 4. Illustration of Ensemble-informed Selection of Model Projections to Define Potential Future Conditions

4.5.2 Projected Extreme Events

CREAT also provides projections of extreme heat in terms of total number of days exceeding 90°F, 95°F, and 100°F following the projected increases in temperature. The projected changes in hot days were linked to the models selected for projected changes in average monthly temperature and precipitation. Changes in monthly average temperatures from each projection were used as an estimate of how the historical daily maximum temperature time series would shift for each of the model projections selected. The change in monthly average temperature for April through October for the analysis location was added to the daily time series from that station to generate a new time series for each projection. The number of days exceeding 90°F, 95°F, and 100°F were then calculated using the same method employed for historical hot days to generate projected number of days exceeding 90°F, 95°F, and 100°F.

Similar to the development of model projections of changes in average temperatures and precipitation, CREAT uses an ensemble-based approach to identify a range of possible changes in total storm precipitation. A subset of the GCMs used earlier (22 of the 38 models) provide scalars,[23] or changes in precipitation per degree of warming, for storm events of the same return intervals as the historical storms provided in CREAT. Each model provides a different scalar for each return interval based on model-projected daily precipitation patterns.

The scalars from these models were ranked based on the scalars for the storm events with a 5-year return interval. The use of 5-year storm events to rank the models was based on the assumption that water sector utilities dealing with intense storm events are often more concerned with more frequent storm events. Ensembles of five models were selected as describing a “Stormy Future,” which are the highest models, and a “Not as Stormy Future,” which are the lowest models. In each

[23] This set of spatially explicit scalars was collected in cooperation with ClimSystems: https://www.climsystems.com

case, these models were averaged to provide two model projections available to users, as shown in **Figure 5**.

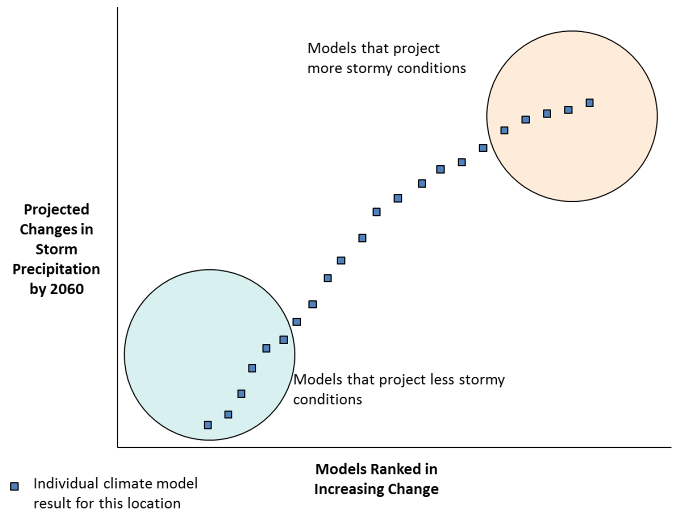

Figure 5. Illustration of Ensemble-informed Selection of Model Projections to Define Potential Future Storm Conditions

The selected models were used to provide ensemble average scalars for changes in precipitation per degree of warming for all the return intervals provided for historical data including 5-year, 10-year, 15-year, 30-year, 50-year, and 100-year. Projected changes in event magnitudes were calculated using the scalars, generating a new GEV curve for each future time period, as follows:

$$Intense\ Precip(RI, Proj) = Intense\ Precip(RI, Hist) * \left(1 + \Delta Intense\ Precip(RI, Proj)\right), \text{where}$$

$$\Delta Intense\ Precip(RI, Proj) = Scalar(RI, Proj) * \Delta Temp(Proj),$$

where ΔTemp is the change in global mean temperature from the same model.

This method provides more detailed information than simply using the values from the models identified for the average conditions. Selecting different models for storms decouples changes in storm events from changes in average events. It is recommended that the same scalars be used to estimate changes in 24- and 72-hour intense precipitation events.[24] For utilities concerned with intense precipitation, this approach will define a wider range of values for projected storm events from the available models.

4.5.3 Projected Extreme Flows

CREAT uses projections of change in extreme low and high streamflow. The flow projections are from downscaled climate and hydrologic modeling developed by a collaborative effort between the

[24] Analysis of observations and model projections of changes in 24-hour and 72-hour intense precipitation events found no significant difference in the observations or model projections. That is, the increase in intensity of 24-hour and 72-hour precipitation events does not appear to be significantly different. It was concluded that it most prudent to use the same scalars for single day and multi-day precipitation events.

U.S. Bureau of Reclamation (USBR), National Center for Atmospheric Research (NCAR), U.S. Army Corps of Engineers (USACE), U.S. Geological Survey (USGS), and a number of universities.[25] The modeling used RCP 8.5 (the same forcing scenario as used for the extreme temperature analysis) but used Bias-Corrected Spatially Disaggregated (BCSD)[26] methodology to provide higher resolution climate change projections than from the GCMs. These high resolutions climate projections were translated into runoff using the Variable Infiltration Capacity (VIC) hydrologic model,[27] and then routed through a nationwide stream network[28] of 57,000 stream reaches.

Five global climate models were used in this analysis:

- National Center for Atmospheric Research (CCSM4);
- NASA Goddard Institute for Space Studies (GISS-E2-R);
- Canadian Centre for Climate Modeling and Analysis (CanESM2);
- Met Office Hadley Centre (HadGEM2-ES); and
- Atmosphere and Ocean Research Institute, National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology (MIROC5).

These models are the same five GCMs used in the EPA's Climate Change Impacts and Risk Analysis (CIRA) project[29] and selected with the intent of capturing a wide range of climate projections for the continental United States.

Using the climate model data, CREAT estimates relative change for several metrics of interest to water utilities dependent on streamflow patterns for water supply and discharge. Projections for each metric were calculated for each stream reach, for two time periods: 2001–2030 ("Baseline") and 2046–2075 ("Mid-Century").

CREAT provides changes in flow as a ratio of Mid-Century projections versus baseline estimates from the model for the downstream location (node) of each stream reach for the following variables:

- Min Flow Ratio: change in average annual minimum flows in Mid-Century vs. Baseline periods;

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[25] Reclamation, 2014. Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections: Release of Hydrology Projections, Comparison with preceding Information, and Summary of User Needs. U.S. Department of the Interior, Bureau of Reclamation, Technical Services Center, Denver, Colorado. 110 pp.

[26] Maurer, E. P., L. Brekke, T. Pruitt, and P. B. Duffy. 2007. "Fine-resolution climate projections enhance regional climate change impact studies." *Eos Transactions.* 88(47): 504.

[27] https://vic.readthedocs.io/en/master/Overview/ModelOverview/

[28] Full documentation of the raw data is available here: https://gdo-dcp.ucllnl.org/downscaled_cmip_projections/techmemo/BCSD5HydrologyMemo.pdf

[29] U.S. EPA, 2015. Climate Change in the United States: Benefits of Global Action. EPA 420-R-15-001. U.S. Environmental Protection Agency Office of Atmospheric Programs, Washington, DC.

- Max Flow Ratio: change average annual maximum flows in Mid-Century vs. Baseline periods;
- Mean Flow Ratio: change in average annual mean flows in Mid-Century vs. Baseline periods;
- 7Q10 Ratio: change in 7Q10 flow in Mid-Century vs. Baseline period; and
- 7Q2 Ratio: change in 7Q2 flow in Mid-Century vs. Baseline period.

Since only five downscaled GCM hydrologic projections were used in the Bureau of Reclamation analysis, CREAT presents the highest and lowest model changes for each flow metric by node. For example, CREAT presents the value from the model that simulates the largest decrease or smallest increase in low (minimum) flow and the model that estimates the smallest decrease or largest increase in high (maximum) flow. The high and low models for each flow metric may not be the same models, as they are selected independently. In addition, the selection of high and low models for the extreme flows varies with the geographic variance of the hydrologic projections. Thus, nodes near each other might provide values from different climate models.

CREAT users should be aware that the approach used to select models for the low and high flow analysis across the United States is a different approach from the cell-by-cell selection of models used for other climate variables in CREAT. In those other applications, models were selected from a larger suite of models for individual cells based on analysis of cell-by-cell climate projections. That means the projections of changes in extreme temperature should not be combined with projections of change in low and high flow conditions.

The projections of change in conditions can be combined with the observations to estimate how absolute flow conditions can change near locations of interest. While the stream gage locations are distinct from the locations of the future flow projections, the data are mapped along with stream reaches of future projections to enable the end user to combine data from both observed and projection data sets.

For outputs expressed as ratios, the changes in conditions should be multiplied by the appropriate metric from the observations. In other words, if minimum flow is projected to fall by 20% (a ratio of 0.8), then the value of 0.8 should be multiplied by observed low flow values to estimate projected low flows.

4.5.4 Sea Level Rise Projections

Global mean sea level (GMSL) scenarios by 2100 are based on specific scientific assumptions, including future greenhouse gas emissions, ocean-atmospheric warming, and land-ice loss. The Sea Level Rise and Coastal Flood Hazard Scenarios and Tools Interagency Task Force produced six scenarios on a decadal frequency from 2000 to 2100 (Figure x). These six GMSL scenarios included the following projections: Low (0.3 m), Intermediate-Low (0.5 m), Intermediate (1.0 m), Intermediate-High (1.5 m), High (2.0 m), and Extreme (2.5 m).

These GMSL projections are then used to produce relative sea level (RSL) projections onto a 1-degree grid for the US shoreline, as done for the Baseline Scenario with zero GMSL.

CREAT reports the results of these flood frequency estimates for approximately 100 coastal tide gauge stations across the US. For each of these coastal gauges, CREAT presents the predicted annual number of flood days for the following projections:

- 0.0m GMSL rise (baseline);
- 0.5m GMSL rise;
- 1.0m GMSL rise; and
- 2.0m GMSL rise.

CREAT provides SLR projections to facilitate climate risk assessment and climate change adaptation for coastal regions of the United States. The approach incorporates recent developments in understanding the mechanisms of SLR and the models that provide projections, as documented in peer-reviewed studies and the IPCC Fifth Assessment Report. Other federal agencies, such as the United States Army Corps of Engineers (USACE) and NOAA have developed tools that are publicly accessible and can be used calculate local sea level in the future. SLR projections in CREAT are based on current scientific understanding and approaches to avoid duplicating existing efforts from other federal agencies and eliminate possible discrepancies.

SLR projections consist of two parts: eustatic sea level change and local VLM. Eustatic sea level represents the level of the ocean independent of land movement and is often estimated based on historical tide gauge records over the globe and satellite altimeter data. The NCA considered four SLR scenarios: 0.2 meters (lowest), 0.5 meters (intermediate-low), 1.2 meters (intermediate-high), and 2.0 meters (highest) by 2100 (relative to 1992). The three highest NCA scenarios of eustatic sea level change (0.5 meters, 1.2 meters, and 2.0 meters) were incorporated in CREAT. The lowest projection of 0.2 m, which is an extrapolation of the historical trend, was excluded since it adds little benefit to the analysis of risk by coastal water utilities.

To estimate future sea level, CREAT uses the equation and constants provided by the NCA:

$$SLR(year, level) = a * Y + b(level) * Y^2, \text{ where}$$

Y is the number of years since 1992, a is an estimated global sea level trend of 1.7mm per year, and b is a curvature for each SLR curve:

- 0.156 mm per year^2 for high curve (2.0 m by 2100, relative to 1992);
- 0.0871 mm per year^2 for medium curve (1.2 m by 2100, relative to 1992); and
- 0.0271 mm per year^2 for low curve (0.5 m by 2100, relative to 1992).

Curves were calculated in 5-year increments through 2100. It should be emphasized that this straightforward quadratic approach to the time evolution is chosen in part for its simplicity; there is no scientific reason or evidence to assume that SLR will evolve in precisely this smooth manner (Parris et al., 2012). In CREAT, eustatic sea level change is adjusted relative to the reference year 2016 (**Figure 6**) by subtracting the calculated SLR, relative to 1992. Finally, if users enter a non-zero VLM, the curve is corrected for the influence of land movement on the relative projected SLR:

$$\widehat{SLR}(year, level) = a * Y + b(level) * Y^2 - SLR(2016, level) - VLM * (year - 2016)$$

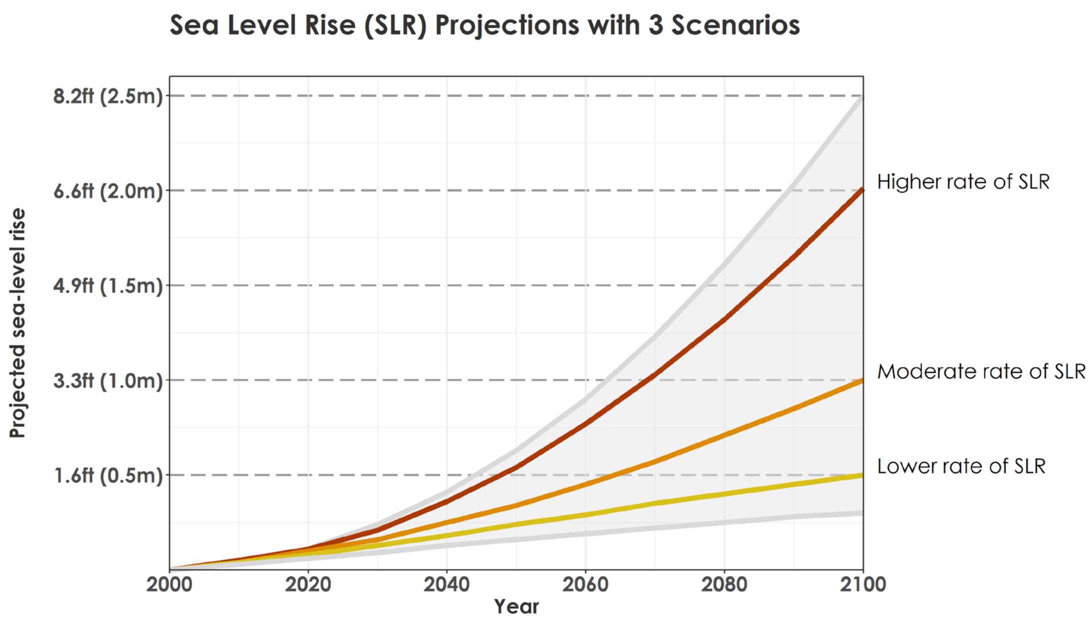

Figure 6. Three Scenarios of Eustatic Sea Level Change Relative to 1992 (solid lines) and 2016 (dashed lines)

4.6 Threat Definition

The process for scenario definition involves the review and selection of available data. Any or all of the data can be revised to meet the needs of the utility conducting a CREAT assessment. For coastal locations, users will have the ability to select a CREAT projected value for total sea level rise corresponding to potential scenarios of lower, moderate, or higher rate of SLR. Users may also choose to specify a custom value for meters of SLR. This flexibility allows users to find the amount of SLR that concerns them based on the range possible over time.

This process differs for users conducting a streamlined analysis. In that case, the single threat selected determines which of the model projections are provided as a default:

- Drought: Hotter and drier future conditions combined with the Stormy projection;
- Ecosystem Changes: Hotter and drier future conditions combined with the Stormy projection;
- Floods: Warmer and wetter future conditions combined with the Stormy projection;
- Service Demand and Use: Hotter and drier future conditions combined with the Stormy projection; and
- Water Quality Degradation: Warmer and wetter future conditions combined with the Stormy projection.

Streamlined users in coastal locations also receive a default value for SLR based on the high SLR curve for the year closest to their End Year.

Translating climate change impacts into utility-specific threats requires additional understanding of the changes that would imperil water sector assets. For their Baseline Scenario and each Projected Scenario, users are encouraged to define the selected threats in terms of their frequency, duration or magnitude based on the appropriate data for each scenario. The same threats are used in all scenarios; however, the specific threat definitions will differ based on the data used to delineate the scenario. The threat definition includes any important aspects of the threat that would affect risk assessments, including historical trends, quantitative threat metrics, links to scenario data and assumptions.

Since threat definition is often a challenging step for utilities, CREAT supports this step by providing default threat definitions as a starting point for users.[30] Assessment of risk from each threat needs to be considered with respect to a "threshold" condition for asset damage or failure. These thresholds can be based on information provided by CREAT, entered into CREAT, or already known by users. Thresholds can be defined in terms of threat magnitude, location, frequency or any other metric that represents potential damage to assets. Where possible, users should define these thresholds carefully and in detail. During assessments, these thresholds are compared with projected conditions to estimate how likely it is that the threshold will be exceeded, such as the threat occurring, and what the level of consequence will be to each asset.

[30] List of default threat definitions is provided in Appendix A-2.

Chapter 5. Consequences and Assets: Module 3

This module provides guidance for users to define the potential economic, environmental, regional economic, and public health consequences of their threats. In this module, users define the consequences that could occur if a critical asset were to be destroyed, damaged or rendered inoperable for a period. An asset/threat (A/T) pair is the unit of analysis for a climate change risk assessment. The focus is on the consequences to the critical asset if the threat were to occur across the user-defined scenarios.

CREAT provides an economic consequence matrix to help users make systemic decisions. This matrix includes consequence categories, which were developed in collaboration with federal and state partners, water associations, and utility personnel. The consequence categories in CREAT classify the types of economic consequences that would be incurred if a threat were to impact an asset. For each category, users can review the monetary range for each level of consequences based on a scale from low to very high, by either accepting the default values or providing custom monetary values. The matrix is used during risk assessment to gauge potential loss for every combination of scenario, threat, and asset.

CREAT provides methods for assessing the impacts to a region from service interruptions**; see Section 5.3.** To determine regional economic consequences, CREAT employs a method based on EPA's Water Health and Economic Analysis Tool (WHEAT), which is used in EPA's **Vulnerability Self Assessment Tool (VSAT)**. Calculations are based on the type of utility, population served, and the State in which the utility is located. These factors determine the economic loss per capita, per day, when service is not available. If a user includes regional economic consequences in the assessment, the number of days of service outage and the percent of customers affected by outages will be entered for each asset-threat combination in the Risk Assessment module (Module 5).

Public health consequences may also be assessed in CREAT. These calculations employ a value for statistical life (VSL) and statistical injury (VSI) that would result from the occurrence of a threat. These values can be adjusted and the inclusion of this method for public health consequences in the assessment is optional**; see Section 5.4.**

When assessing risk, users will need to consider consequences that could occur if an asset were to be destroyed, damaged or rendered inoperable for some period of time. In this context, consequences generally describe dollar values that would constitute low, medium, high, or very high impacts to the utility if climate change threat(s) occur. These consequences may include loss of revenue, partial or complete loss of an asset, impacts to source and receiving water, environmental damage, and public health impacts. CREAT does not assign or assess the extent of damage or consequences for each individual threat because this decision is dependent on the specific characteristics of the utility.

5.1 Economic Consequence Categories

CREAT provides categories that users can incorporate for gauging potential economic consequences to assets. Users have the opportunity to refine the categories or add custom categories for additional consequences. The most important part of this step is for users to determine if monetary values should be assigned to the levels of each consequence category. Some categories may be important to users even though monetary impacts would be too difficult to determine. These categories can be deferred for use in the comparison of plans rather than in the assessment of risk. Users can use these deferred categories to rate the performance of each plan with respect to the categories.

The default economic consequence categories are defined as follows:

- Utility Business Impact – Operating revenue loss evaluated in terms of the magnitude and recurrence of service interruptions. Consequences range from long-term loss of expected operating revenue to minimal potential for any loss;
- Utility Equipment Damage – Cost of replacing the service equivalent provided by a utility or piece of equipment evaluated in terms of the magnitude of damage and financial impacts. Consequences range from complete loss of the asset to minimal damage to the equipment;
- Source/Receiving Water Impacts – Degradation or loss of source or receiving water quality or quantity evaluated in terms of recurrence. Consequences range from long-term compromise to no more than minimal changes to water quality or quantity; and
- Environmental Impacts – Evaluated in terms of environmental damage or loss, aside from damage to water resources, and compliance with environmental regulations. Consequences range from significant environmental damage to minimal impact or damage.

5.2 Default Economic Consequences Matrix

CREAT provides an economic consequences matrix defining the monetary scales of potential loss within these consequence categories. This matrix identifies different levels of consequences that may be experienced for each consequence category as related to a given threat occurring to a specific asset. This matrix supports systematic and comparable decisions during consequence assessments across multiple assets and threats. CREAT provides default definitions for the levels of consequences in each category to use in the assessment of each asset/threat pair (**Table 1**).

For each level, there is a monetary range that is used in the risk calculation. The default values for this matrix are based on the assessment inputs in the Climate Awareness module that include: 1) system type;[31] 2) population served; 3) total flow in millions of gallons per day (MGD); 4) ownership (public or private); and 5) financial condition (adequate, good, or strong.) These inputs are used to obtain default values from available benchmark utility survey data.[32,33]

[31] The system type may be water only, wastewater only, or combined. For combined systems, users differentiate which portion of the specific system (drinking water or wastewater) is the focus of their analysis so the relevant monetary ranges can be provided. Stormwater utilities are advised to use the wastewater option in CREAT.

[32] U.S. Environmental Protection Agency (EPA), 2009. 2006 Community Water System Survey (CWSS), Volume II: Detailed Tables and Survey Methodology. EPA 815-R-09-002.

[33] American Water Works Association (AWWA), 2015. Benchmarking Performance Indicators for Water and Wastewater Utilities 2013, Survey Data and Analyses Report.

Table 1. Default Definitions for Consequence Category Levels Used for All System Types

Consequence Category	Low	Medium	High	Very High
Utility Business Impacts	Minimal potential for loss of revenue or operating income	Minor and short-term reductions in expected revenue	Seasonal or episodic compromise of revenue or operating income	Long-term or significant loss of revenue or operating income
Utility Equipment Damage	Minimal damage to equipment	Minor damage to equipment	Significant damage to equipment	Complete loss of asset
Environmental Impacts	No impact or environmental damage	Short-term environmental damage, compliance can be quickly restored	Persistent environmental damage – may incur regulatory action	Significant environmental damage – may incur regulatory action
Source/Receiving Water Impacts	No more than minimal changes to water quality	Temporary impact on source water quality or quantity	Seasonal or episodic compromise of source water quality or quantity	Long-term compromise of source water quality or quantity

Users are advised to select the most appropriate financial condition based on their understanding of their system finances, including the debt coverage ratio (DCR) and operating ratio. Utilities that can calculate their ratios may elect to use **Table 2** to select the most appropriate financial condition for their analysis. DCR is the ratio of net operating income to total debt service:

$$\boldsymbol{Debt\ Coverage\ Ratio} = \frac{(Total\ Operating\ Revenue - Total\ Operating\ Expenses)}{Total\ Debt\ Service}$$

Higher DCR values indicate more cash flow is available to meet interest, principal, and sinking fund payments. DCR ratios less than 1 indicate a negative cash flow, meaning a utility is not generating enough income to pay its debt obligations strictly through operations. The operating ratio is a utility's total operating expenses divided by its total operating revenue and takes into account expansion or debt repayment (or net sales):

$$\boldsymbol{Operating\ Ratio} = \frac{Total\ Operating\ Expenses}{Total\ Operating\ Revenue}$$

This chapter provides an explanation of how these baseline values are used for the default economic consequences matrix value calculations, by category. The ranges associated with each consequence level are indicative of how the utility might characterize the dollar value of impact associated with each consequence level. The range assigned to each consequence level is used as a proxy for the "cost" of doing nothing to protect an asset, assuming the threat occurs. Users can review and accept descriptions and values. Alternatively, users can provide the monetary values that estimate their utility-specific consequence levels, if custom values are known. All saved values will then be applied in assessment calculations of monetized risk and risk reduction.

Table 2. CREAT Financial Condition by System Type

System Type	Financial Condition	Baseline DCR	Baseline Operating Ratio
Water Only System			
Top Quartile[34]	Strong	2.62	0.50
Median	Good	1.45	0.69
Bottom Quartile	Adequate	0.47	0.86
Wastewater Only System			
Top Quartile	Strong	2.39	0.42
Median	Good	1.43	0.51
Bottom Quartile	Adequate	0.41	0.82
Combined Water			
Top Quartile	Strong	3.39	0.46
Median	Good	1.67	0.57
Bottom Quartile	Adequate	1.24	0.73
Combined Wastewater			
Top Quartile	Strong	1.93	0.47
Median	Good	1.25	0.61
Bottom Quartile	Adequate	0.67	0.73

5.2.1 Utility Business Impacts

The Utility Business Impacts category refers to revenue loss, which would manifest to the utility as an operating statement effect. Consequence levels are estimated as the loss in utility operating revenue that would cause financial changes in its baseline operating condition. The overall strength of the utility's baseline operating condition and subsequent changes due to operating revenue loss is modeled by observing changes in the baseline DCR, which is an overall indicator of operating condition. The default economic consequences matrix estimates for the Utility Business Impacts category are developed using the following five steps:

1. **Assign the utility a baseline debt coverage ratio and operating ratio value.** The utility being assessed was assigned a baseline DCR and operating ratio values from one of twelve possible model utility baseline values (**Table 2**) based on inputs for system type and financial condition;

[34] The terms top and bottom quartile refer to the distribution within the total data set. The bottom quartile is defined as the midpoint between the median and the lowest number in the data set. The top quartile is defined as the midpoint between the median and the highest number in the data set.

2. **Estimate annual operating expenses for the utility.** To calculate estimated annual operating expenses, the median total operations and maintenance costs (O&M) per million gallons for the system type (**Table 3**) was multiplied by the system total flow, in MGD over 365 days;

$$\boldsymbol{Annual\ Operating\ Expenses} = Total\ O\&M\ per\ million\ gallons * MGD * 365$$

Table 3. Total Operating Expenses by System Type based on AWWA (2015) Benchmark Data

System Type	Total O&M Cost in Dollars per Million Gallons
Water Only System	$2,176
Wastewater Only System	$1,945
Combined Water	$2,240
Combined Wastewater	$2,233

3. **Estimate annual operating revenues and annual debt service.** Annual operating revenues and debt service were estimated using the baseline ratios for the utility and annual operating expenses as follows:

$$\boldsymbol{Annual\ Operating\ Revenue} = \frac{Annual\ Operating\ Expenses}{Baseline\ Operating\ Ratio}$$

and

$$\boldsymbol{Annual\ Debt\ Service} = \frac{(Annual\ Operating\ Revenue - Annual\ Operating\ Expenses)}{Baseline\ DCR}$$

4. **Specify DCR threshold values associated with each consequence level.** For each model baseline condition, CREAT provides the loss in revenue that produces each of three possible threshold changes in DCR (**Table 4**). These threshold changes align with increases to higher consequence levels in CREAT, as outlined below:
   - Target 1, the threshold between Low and Medium impacts, is equal to a 25% decrease in the baseline DCR;
   - Target 2, the threshold between Medium and High impacts, is equal to a 50% decrease in the baseline DCR; and
   - Target 3, the threshold between High and Very High impacts, is equal to a 75% decrease in the baseline DCR.

5. **Estimate default values for each consequence level boundary.** The last step of this process was to estimate the value of operating revenue loss that would cause the baseline DCR value to move to each of the three target values specified above. These values become the new upper and lower bounds for the individual CREAT consequence levels, from Low to Very High:

$$\boldsymbol{Revenue\ Loss_i} = (\%\ decrease\ in\ DCR)_i * (Annual\ Operating\ Revenue - Annual\ Operating\ Expenses)$$

Table 4. Debt Coverage Ratio Values for CREAT Consequence Values

System Type	Baseline DCR	Target 1 Medium	Target 2 High	Target 3 Very High
Water Only System				
Strong	2.62	2.0	1.3	0.7
Good	1.45	1.1	0.7	0.4
Adequate	0.47	0.4	0.2	0.1
Wastewater Only System				
Strong	2.39	1.8	1.2	0.6
Good	1.43	1.1	0.7	0.4
Adequate	0.41	0.3	0.2	0.1
Combined Water				
Strong	3.39	2.5	1.7	0.8
Good	1.67	1.3	0.8	0.4
Adequate	1.24	0.9	0.6	0.3
Combined Wastewater				
Strong	1.93	1.4	1.0	0.5
Good	1.25	0.9	0.6	0.3
Adequate	0.67	0.5	0.3	0.2

5.2.2 Utility Equipment Damage

The Utility Equipment Damage category refers to the cost required to replace or repair damaged assets. The associated costs would occur as unplanned capital outlays for the asset repair or replacement. The approach for this category estimates consequence level thresholds based on changes in estimated cash reserves. This indicator quantifies the number of days of available cash reserves as a measure of financial liquidity. Days of cash reserves are calculated using the amount of undesignated reserves and the average daily cost of ongoing operations. The default economic consequences matrix estimates for the Utility Equipment Damage category are developed using the following four steps:

1. **Assign a baseline cash reserve days value.** A baseline cash reserve days value was assigned (**Table 5**) based on system type and financial condition.
2. **Estimate the value of undesignated cash reserves.** The value of undesignated cash reserves was estimated based on annual operating expenses, which was calculated using the methodology outlined for the Utility Business Impacts category, and the baseline cash reserve days value using the following equation:

$$\textit{Undesignated Cash Reserves} = \textit{Baseline Cash Reserve Days} * ((\textit{Annual Operating Expenses})/365)$$

3. **Specify losses in available cash reserves as threshold values associated with each consequence level.** CREAT considers different percentage thresholds of cash reserve utilization for association with the consequence levels, as outlined below:

- Target 1, the threshold between Low and Medium impacts, is equal to 10% of undesignated cash reserves;
- Target 2, the threshold between Medium and High impacts, is equal to 25% of undesignated cash reserves; and
- Target 3, the threshold between High and Very High impacts, is equal to 60% of undesignated cash reserves.

4. **Estimate default values for each consequence level boundary.** The last step was to estimate the loss of available cash reserves that would exceed the thresholds specified above. These values become the new upper and lower bounds for the individual CREAT consequence levels, from Low to Very High:

$$\boldsymbol{Cash\ Reserves\ Loss_i} = (\%\ decrease\ in\ Available\ Cash\ Reserves)_i * Undesignated\ Cash\ Reserves$$

Table 5. Baseline Cash Reserve Days by System Type from AWWA (2015)

System Type	Baseline Cash Reserve Days by Financial Condition		
	Strong	Good	Adequate
Drinking Water Only	517	258	139
Drinking Water component of Combined Utility	656	238	126
Wastewater Only	515	141	109
Wastewater component of Combined Utility	536	305	133

5.2.3 Source/Receiving Water Impacts

The Source/Receiving Water Impacts category refers to the cost associated with the degradation or loss of source water or receiving water quality or quantity, which would manifest as additional capital outlays for source and receiving water enhancement. The approach for this category relies on threshold levels of water resource spending, relative to historical levels of spending for system expansion, which align with the CREAT consequence levels.

Historical expansion outlays are used as a proxy for the cost to access or acquire new resources if current source or receiving water resources are degraded or lost. These levels are based on those reported in EPA's CWSS as per-capita historical systems expansion cost outlays differentiated by utility population size ranges.[35] The default economic consequences matrix estimates for the Source/Receiving Water Impacts category are developed using the following four steps:

[35] The corresponding data specific to wastewater systems were not available in either the CWSS or AWWA sources. Drinking water system data is used as a proxy to develop default values for all system types as reasonable estimates.

1. **Assign the utility a baseline for per capita historical system expansion cost outlays based on population served bin.** The appropriate population range bin[36] from those used to report data in the CWSS was selected to estimate per-capita historical system expansion cost outlays **(Table 6)** based on system ownership, either public or private, and population served.
2. **Calculate baseline system expansion cost outlays based on actual population served**. The estimate for baseline expansion cost outlays for the utility was estimated based on per capita historical system expansion cost derived from the population bin and the population served:

$$\boldsymbol{Baseline\ System\ Expansion\ Costs} = Per\ capita\ Historical\ Cost\ Outlays * Population\ Served$$

Table 6. Per Capita Historical System Expansion Cost Outlays by System Ownership from CWSS (2009)

Population Served (bins)	**Per capita Historical Expansion Cost Outlay**	
	Public Systems	Private Systems
100 or Less	$350.30	$132.03
101 - 500	$378.26	$28.95
501 - 3,300	$103.67	$30.16
3,301 - 10,000	$40.91	$42.41
10,001 - 50,000	$42.80	$37.87
50,001 - 100,000	$21.96	$35.08
100,001 - 500,000	$38.05	$4.69
Greater than 500,000	$32.44	$32.44*
* Value based on public system data due to missing data for this population bin		

3. **Specify levels of spending as threshold values associated with each consequence level.** CREAT considers different percentage thresholds of outlays for association with the consequence levels:
   - Target 1, the threshold between Low and Medium impacts, is equal to 10% of historical expansion costs;
   - Target 2, the threshold between Medium and High impacts, is equal to 25% of historical expansion costs; and
   - Target 3, the threshold between High and Very High impacts, is equal to 60% of historical expansion costs.

[36] Although these population bins may be more refined than the average utility operator is accustomed to, they allow CREAT to provide the best default values based on utility size. The data selection based on these categories is not visible to users.

4. **Estimate default values for each consequence level boundary.** The last step was to estimate the loss that would exceed the thresholds specified above. These values become the boundary values that separate the different CREAT consequence levels:

$$\boldsymbol{Water\ Resource\ Loss_i} = (\%\ of\ Historical\ Expansion\ Costs)_i * Baseline\ System\ Expansion\ Costs$$

5.2.4 Environmental Impacts

The Environmental Impacts category refers to the cost associated with environmental damage or loss, aside from water or other resources, and compliance with environmental regulations, which would manifest to the utility as additional costs for environmental and regulatory compliance. The approach for this category relies on threshold levels of cost for regulatory compliance, relative to historical levels of spending that align with the CREAT consequence levels. Historical levels are based on those reported in EPA's CWSS as per-capita historical regulatory compliance cost outlays differentiated by utility population size ranges.[37] The default matrix estimates for the Environmental Impacts category are developed using the following four steps:

1. **Assign a baseline for per-capita historical regulatory compliance cost outlays based on population served bin.** CREAT selects the appropriate population range bin[38] from the bin used CWSS data to select for per-capita historical regulatory compliance cost outlays **(Table 7)** based on system ownership, either public or private, and population served.
2. **Calculate baseline compliance cost outlays based on actual population served.** The estimate for baseline compliance cost outlays for the utility was estimated based on per-capita historical compliance costs derived from the population bin and the population served.

$$\boldsymbol{Baseline\ Compliance\ Costs} = Per\ capita\ Historical\ Cost\ Outlays\ * Population\ Served$$

3. **Specify levels of spending as threshold values associated with each consequence level.** CREAT considers different percentage thresholds of outlays for association with the consequence levels:
   - Target 1, the threshold between Low and Medium impacts, is equal to 10% of baseline compliance costs;
   - Target 2, the threshold between Medium and High impacts, is equal to 25% of baseline compliance costs; and
   - Target 3, the threshold between High and Very High impacts, is equal to 60% of baseline compliance costs.

[37] The corresponding data specific to wastewater systems were not available in either the CWSS or AWWA sources. Drinking water system data are used as a proxy to develop default values for all system types as reasonable estimates.

[38] Although these population bins may be more refined than the average utility operator is accustomed to, they allow CREAT to provide the best default values based on utility size. The data selection based on these categories is not visible to users.

4. **Estimate default values for each consequence level boundary.** The last step was to estimate the loss that would exceed the thresholds specified above. These values become the new upper and lower bounds for the individual CREAT consequence levels, from Low to Very High:

$$\boldsymbol{Environmental\ Loss_i} = (\%\ of\ Historical\ Compliance\ Costs)_i * Baseline\ Compliance\ Costs$$

Table 7. Per Capita Historical Regulatory Compliance Cost Outlays by System Ownership from CWSS (2009)

Population Served (bins)	Per Capita Historical Cost Outlay	
	Public Systems	Private Systems
100 or Less	$212.02	$20.31
101 - 500	$11.57	$46.58
501 - 3,300	$21.64	$5.28
3,301 - 10,000	$9.54	$36.55
10,001 - 50,000	$6.31	$0.47
50,001 - 100,000	$10.78	$10.78*
100,001 - 500,000	$6.66	$11.01
Greater than 500,000	$5.02	$5.02*
* Value based on public system data due to missing data for this population bin		

5.3 Regional Economic Consequence Assessment

Regional economic consequence estimates in CREAT include lost revenue from businesses and industries in the utility's area that cannot operate due to water or wastewater service disruptions. For each asset/threat pair, CREAT estimates state-level economic consequences for business activity in the utility's service area that are impacted by a disruption and allows for the possibility that only a portion of the utility's service may be impacted by a disruption from any give asset/threat pair. The magnitude of regional economic consequences is linked to the *duration* and *extent* of the disruption in normal services. These consequences are estimating using a multi-sector, inter-industry framework contained in CREAT.

Regional economic consequences are estimated using a combination of inputs previously specified in the assessment for the utility—location, utility type (water, wastewater), and population served—along with additional databases included in CREAT, described below:

- **Baseline regional economic activity data.** To characterize economic activity in the region served by the utility, CREAT includes a database of state-level economic activity data compiled from the U.S. 2012 Economic and Agricultural Census for 84 industries. For each economic sector, the database describes economic activity based on the annual dollar value of economic output (i.e., industry revenues).
- **Fraction of economic activity served by the utility.** Since any single utility does not service the entirety of the businesses, or population, in a given state, CREAT estimates the fraction of total state-level economic activity that is served by the utility based on the proportion of the utility's population served to the total population in the state using the calculation below.

CREAT includes a database of state-level population values from the Census' 2017 Annual Estimates of the Resident Population.[39]

$$\boldsymbol{Fraction\ of\ Business\ Activity\ Served} = \frac{Utility\ Population}{State\ Population}$$

- **Economic input-output multipliers, by economic sector.** One factor that strongly influences the magnitude of regional economic consequences is the interdependence of economic sectors. Inter-industry links in the economy are specified using final-demand multipliers from the U.S. Bureau of Economic Analysis' 2016 Regional Input-Output Modeling System (RIMS II). CREAT includes a database of state-level, final-demand input-output multipliers for 64 industries. These values are then mapped to the 84 industries in the baseline Census economic activity data.
- **Service loss economic impact factors**. All businesses are not affected to the same degree as a result of a loss in water or wastewater service. For example, businesses in some industries can more easily find ways to continuing working in whole or in part. To account for this concept, CREAT includes a database of water and wastewater service "economic loss factors" (ELF) for each economic industry. These factors are used to account for the varying resilience of industries under conditions where services are not available. Each service loss economic impact factor indicates the proportion of business activity in an industry that is lost due to a loss in water or wastewater service. These inputs are based on values in the literature from Rose and Liao (2005) and the American Technology Council (1991) for water and wastewater, respectively.
- **Service loss profile**. Lastly, the regional economic consequences also require input from users to specify the service loss profile. The service loss profile describes the extent and duration of the loss in water or wastewater services based on inputs for:
  - The duration of the service outage in days; and
  - The percentage of customers without service during this period (%).

Using the above inputs, CREAT calculates *direct* and *total* regional economic consequences. *Direct* business revenue impacts are those associated with businesses directly served by the water or wastewater system. This is estimated by industry using the calculation below:

$$\begin{aligned}&\boldsymbol{Direct\ Business\ Consequences}\\ &\quad = \text{Industry Revenue} * \text{Fraction of Industry Served} * \text{ELF}\\ &\quad * \text{Percent of Customers without Service} * (\text{Days without Service}/365.25)\end{aligned}$$

Individual industry-level estimates are then aggregated across all industries to produce an estimate of all direct economic business consequences (i.e., revenue loss) in the utility's service territory.

Total regional consequences in the state refer to the direct and indirect economic effects, a measure that captures the additional output losses among other businesses that are linked economically to businesses directly affected by the disruption. Total business revenue impacts for a service

[39] https://www.census.gov/data/tables/time-series/demo/popest/2010s-national-total.html

disruption are determined based on the direct impacts and economic input-output multipliers from the U.S. Bureau of Economic Analysis, referenced above. This is calculated as:

$$\textbf{\textit{Total Business Consequences}} = \textit{Direct Business Consequences} * \textit{IO Multiplier}$$

Again, the estimates are calculated for each individual industry, since direct consequences vary by industry and the input-output multipliers vary by industry. Total business consequences are then aggregated across all industries to produce an overall estimate of total economic business consequences (i.e., revenue loss) in the utility's service territory.

5.4 Public Health Consequence Assessment

In CREAT, public health impacts are evaluated in terms of the number of fatalities and injuries expected or used in ranking the effectiveness of different adaptation plans. This quantitative approach to public health impacts is based on the estimate of human fatalities or injuries for each asset/threat pair. CREAT assists users by providing default values for the Value of a Statistical Life (VSL),[40] which is the value attributed to each fatality assessed due to the occurrence of a threat to a particular asset, and the Value of a Statistical Injury (VSI),[41] or the value attributed to each injury assessed due to the occurrence of a threat to a particular asset. The tool uses the following calculation to monetize public health consequences:

Public Health Impact *= (# fatalities * VSL) + (# injuries * VSI)*

While CREAT provides default values for VSL and VSI that can be used in these calculations, users may edit these values if desired. When monetized, the public health impacts are added to the economic impacts calculated based on the selected levels of consequence across all the categories used in the risk assessment. For users who do not wish to monetize public health consequences, public health impacts can be considered by ranking their adaptation plans on a qualitative impact scale.

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[40] VSL is the value attributed to each fatality assessed due to the occurrence of a threat to a particular asset. A VSL value of $7,400,000 is in 2006 dollars is recommended to be used in all benefits analyses that seek to quantify mortality risk reduction benefits regardless of the age, income or other characteristics of the affected population (https://www.epa.gov/environmental-economics/mortality-risk-valuation). This approach was vetted and endorsed by the Agency when the *Guidelines for Preparing Economic Analyses* and remains EPA's default guidance for valuing mortality risk changes. EPA is currently reviewing this guidance through a Science Advisory Board Environmental Economics Advisory Committee (SAB-EEAC) expert panel and commissioned reports on the various approaches used in the literature to estimate the value of mortality risk reductions (Alberini 2004, Black *et al*. 2003, and Blomquist 2004). EPA has prepared a white paper on *Valuing Mortality Risk Reductions in Environmental Policy* (https://www.epa.gov/environmental-economics/valuing-mortality-risk-reductions-environmental-policy-white-paper-2010) featuring EPA's latest review of important issues surrounding how to value the reductions in risk to human health from environmental regulations and other Agency decisions. EPA has submitted the whitepaper to its Science Advisory Board for feedback and recommendations. Among the potential forthcoming revisions is a change to the often misunderstood term "value of statistical life" with the more accurate term "value of mortality risk reduction." .

[41] VSI is the value attributed to each injury assessed due to the occurrence of a threat to a particular asset. VSI of $74,000 based on 1% of the default VSL. This fraction of the VSL was selected based on the range of possible values and injuries characterized in the "Department of Transportation. Revised Departmental Guidance 2013: Treatment of the Value of Preventing Fatalities and Injuries in Preparing Economic Analyses" and literature cited therein for the severity of injuries that would characterize those for water sector asset loss and damage.

Chapter 6. Adaptation Planning: Module 4

This module prompts users to define adaptive measures and adaptation plans. Adaptive measures are physical infrastructure or actions and strategies that a utility can use to protect their assets and mitigate the impacts of threats. These measures include currently implemented measures that provide resilience now (Existing Measures), as well as potential measures that could increase resilience when implemented as part of adaptation plans. Each measure is defined based on the cost of implementation and whether the measure is expected to be effective in reducing consequences from each defined threat.

Adaptation plans can be based on several goals, such as protecting critical assets, addressing specific threats or exploring options as part of broader utility planning decisions. Each assessment considers the implementation of a specific adaptation plan and compares those results with the Current Measures plan, which contains results if no additional adaptation was implemented.

After considering consequence criteria, CREAT guides users to identify assets at risk from each previously defined threat. Users are encouraged to focus on these critical assets rather than attempting to define all of their assets. CREAT also provides an opportunity to review adaptation options that may protect vulnerable assets, as well as the ability to consider the potential cost of implementing these adaptation options.

6.1 Asset Identification and Assignment

Users can choose from assets provided in a CREAT library or add custom assets. After assets are defined, users select those that are critical for the risk assessment. In CREAT, critical assets are those assets that have the potential for loss from damage or destruction due to the occurrence of threats. In some cases, critical status could be influenced by asset location, elevation, age or may simply be based on historical knowledge and experience.

Asset definition includes a description and assignment of relevant threats. This selection is the basis for asset/threat pairs in CREAT. An asset/threat pair is the unit of analysis for a climate change risk assessment; the focus is on the consequences to the asset if the threat were to occur across a number of scenarios.

Users are prompted to consider whether all consequence categories apply to each asset included in their assessment. For example, a pump station is selected as a critical asset; for this assessment, the utility may be concerned about only potential utility business impacts and utility equipment damage. Only those categories selected for an asset will be available during the risk assessment.

6.2 Adaptation Plan Selection and Use in Assessments

Adaptation plans may be designed to protect specific assets, meet utility goals for resilience and sustainability or address specific threats or vulnerabilities. Typically, these plans are composed of various strategies capable of reducing risk associated with climate-related or other threats.

Users begin their adaptation planning by identifying existing adaptive measures, either from the CREAT Adaptation Library or by defining custom adaptive measures. Existing adaptive measures are actions or strategies a utility has already implemented to protect critical assets.

A Current Measures plan is generated within the tool for users and includes all of the existing adaptive measures that were identified and defined. This plan represents the current capacity of a utility to address threat-related impacts today without any further action being taken or strategies being implemented. The Current Measures plan is used as part of risk assessment for comparison with the same results following the implementation of adaptation plans.

The process of selecting and defining adaptive measures is repeated for potential adaptive measures, which are those measures being considered for future implementation as part of adaptation plans. Some potential adaptive measures can be defined by improving existing adaptive measures already entered into CREAT. The ability to improve current capabilities reflects the practice of identifying opportunities to incrementally improve protection rather than develop new projects to adapt to climate change.

For each measure, cost data and threat relevance must be entered to support calculations following the risk assessment. Cost of a measure is defined either as a monetary range or as a single value depending on available adaptive measure cost information, and the preferred approach of the assessment. To assist users in gauging the potential cost of implementation, CREAT provides default unit costs for several adaptive measures within the CREAT library (**Table 8**). Unit-cost values refer to the cost associated with implementing a specific adaptive measure, such as the amount it would cost for each kilowatt of capacity of back-up power, or the cost of a gallon of storage. Default unit-cost values for each measure were developed using data from publicly available sources, such as EPA, the Federal Emergency Management Agency and RSMeans,[42] including available case-study reports for projects implemented at utilities.[43] Users can choose to adopt the default ranges or provide their own estimated cost.

Table 8. Default Costs for Selected Adaptive Measures in CREAT Adaptation Library

Adaptive Measure	Default Unit-Cost Range
Construct	
Back-up power	$250 to $800 per kilowatt of capacity
Levee	$80 to $220 per linear foot
Low-head dam	$3,411 to $29,333 per linear foot
Sea wall	$350 to $760 per linear foot
Temporary flood barrier	$63 to $750 per linear foot
Ecosystem / Land Use	
Erosion and sediment control	$12 to $1750 per linear foot
Fire management	$660 to $1,500 per acre treated
Wetlands for flood protection	$4,700 to $154,300 per acre-foot of stormwater captured
Green infrastructure	
Bioretention facilities	$7 to $26 per square foot of bioretention infrastructure
Green roofs	$8 to $40 per square foot of green roof
Permeable pavement	$10 to $22 per square foot of permeable pavement
New Supplies and Demand Management	
Demand management	$465 to $980 per acre-foot
Desalination - inland	$375 to $1,290 per acre-foot
Desalination - seawater	$1,600 to $3,250 per acre-foot

[42] For more information, visit: https://www.rsmeans.com/

[43] See subsection (adaptive measure cost sources) in Chapter 7, References, for the sources of cost estimates.

Adaptive Measure	Default Unit-Cost Range
Groundwater / aquifer recharge with possible conjunctive use	$90 to $1,100 per acre-foot
Increased storage	$0.005 to $4 per gallon of storage
Interconnections	$95 to $1,250 per linear foot
Municipal water reuse system - non-potable	$300 to $2,000 per acre-foot
Municipal water reuse system – potable	$800 to $2,000 per acre-foot
Rainwater collection / use - rain barrels	$70 to $300 per residential rain barrel system (or household)
Repair/Retrofit	
Altered treatment – total dissolved solids	$2.7M to $3.8M per MGD
Distributed treatment	$600,000 to $10.4M per MGD
Infiltration reduction	$1,000 to $5,000 per number of laterals
Leakage reduction	$100 to $200 per acre-foot
Retrofit intakes	$450,000 to $3.1M per MGD
Retrofit intakes – Invasive species	$18,000 to $76,000 per MGD
Silt removal	$5 to $20 per cubic yard
Sewage separation	$240 to $300 per linear feet of pipe being separated

The default range presented for an adaptive measure generally reflects a range of approaches for implementing the measure. When default unit costs are available for a selected adaptive measure, users are prompted to define the number of units needed to implement the adaptive measure. This approach enables CREAT to scale the default cost values according to specific conditions or criteria, rather than using a one-size-fits-all costing approach.

In addition to defining costs, users also select threat relevance for each measure. For example, some adaptive measures, such as a sea wall, have a high capacity to deal with a threat like coastal flooding but may not be relevant to other threats like drought. By default, adaptive measures are "Relevant" to all threats, and users can either accept this default setting or switch any of them to "Not Relevant."

Users develop adaptation plans by grouping their potential measures together. CREAT calculates a total cost based on the cost of all included measures and indicates the relevance to threats for each plan based on the relevance entered for the included adaptive measures. If a selected measure for a plan is relevant to a threat, then the plan is also relevant to the same threat. Users are encouraged to review these relevance results to ensure that plans apply to all identified threats of concern and that no gaps remain when all plans are defined. For streamlined users, CREAT assembles an "All Potential Measures" plan that contains all potential measures defined in this module for consideration in risk assessment.

Chapter 7. Risk Assessment: Module 5

This module is the last module in the climate change risk assessment process and provides monetized risk results from assessments to support adaptation planning decisions and characterize current and potential risks to utility assets and resources. Monetized risk refers to the anticipated financial impact of a threat if it occurs, which is based on those consequences assessed for each critical asset. Users assess risk for each asset/threat pair across scenarios and plans to generate results that can be compared in terms of their cost and potential risk reduction to identify those that would be most effective.

The monetized risk results overview also provides an opportunity to view the regional economic consequences and public health consequences if selected for assessment and specified during asset selection and asset definition.

CREAT guides users through an assessment of risk for each asset/threat pair across all defined scenarios. Each assessment considers the implementation of a specific adaptation plan; these results can be compared with the results from the Current Measures plan, or a "no-action" alternative, where no potential adaptive measures are implemented. **Figure 7** depicts the risk reduction that can be achieved through the implementation of adaptation strategies.

Monetized risk reduction (MRR) is the change in assessed risk based on the increased capabilities of assets to withstand impacts of threats, following the implementation of an adaptation plan. Results from the implementation of each adaptation plan, compared to Current Measures, can help to inform adaptation planning and decision making.

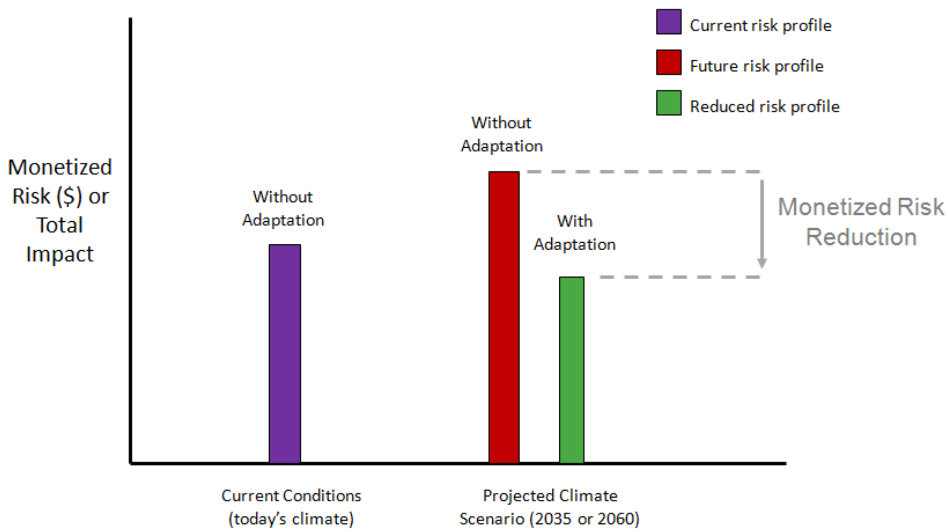

Figure 7. CREAT Results Showing Monetized Risk Reduction

CREAT provides MRR from assessments to support adaptation planning decisions and characterization of current and potential risk to utility assets and resources. Ideally, a risk assessment would consider three components:

1. **Consequences:** CREAT focuses on the assessment of monetary consequences for each scenario with Current Measures and the adjustment of these consequences when considering the implementation of potential adaptation plans;

2. **Vulnerability:** Vulnerability refers to the degree to which assets are susceptible to, and unable to cope with, adverse impacts. CREAT does not directly support the ability to consider how adaptation may reduce asset vulnerability; and
3. **Likelihood:** In CREAT, users consider threats assuming the threats have a 100% chance of occurring in the given time period. The tool provides an option to explore the effect of differing percentages of scenario likelihood on risk reduction to potentially further inform adaptation planning and decision making.

7.1 Consequence Assessment Process

To assess risk, CREAT guides users through an assessment of the consequences following implementation of each adaptation plan for all scenarios as described below:

- Each assessment begins with the Current Measures plan to establish current risk in the Baseline Scenario and the potential risk if no additional adaptation actions are implemented;
- Users select a level of consequence in each category relevant to the asset and for each scenario where the threat is defined. CREAT retrieves the monetary value ranges for each assessed level from the consequence matrix; and
- This assessment is repeated for each plan, where each consequence level assessed for the plan is either the same or reduced when compared to the same assessment with only Current Measures in place.

The final outputs from CREAT are based on a standard risk assessment process where consequences are assessed as monetary impacts. The sum of these impacts for a specific asset/threat pair, including regional economic consequences and public health impacts, provides a measure of risk, expressed as a range from minimum to maximum overall impact:

$$\boldsymbol{Minimum\ Overall\ Impact} = \sum\left(Min\ Impact_{Economic\ Consequence\ Categories}\right) + Impact_{Regional\ Economic} + Impact_{Public\ Health}$$

$$\boldsymbol{Maximum\ Overall\ Impact} = \sum\left(Max\ Impact_{Economic\ Consequence\ Categories}\right) + Impact_{Regional\ Economic} + Impact_{Public\ Health}$$

7.2 Risk Assessment Results

The difference between the consequences following implementation of an adaptation plan and the consequences without adaptation is reported as MRR in CREAT. This reduction could be considered as a benefit from adapting that can be directly compared to the cost of implementing the plan. CREAT calculates the MRR by summing the difference in consequence level in each category, rather than the difference in the overall consequence.[44] Therefore, the MRR for each category is calculated as follows:

[44] See example calculations in Appendix A-4.

$$\boldsymbol{Monetized\ Risk\ Reduction} = \left(Max\ Impact_{PL,Category} - Min\ Impact_{CM,Category}\right) \text{ to } \left(Max\ Impact_{CM,Category} - Min\ Impact_{PL,Category}\right),$$

where the risk based on Current Measures in place for this consequence category is the range:

(Min Impact $_{CM,Category}$ to Max Impact $_{CM,Category}$) and,

the risk following implementation of an Adaptation Plan for the same category is the range:

(Min Impact $_{PL,Category}$ to Max Impact $_{PL,Category}$).

The sum of these reductions provides the final result for the risk reduction attributable to the adaptation plan for a single asset/threat pair:

$$\boldsymbol{Min\ Risk\ Reduction} = \sum\left(Min\ Monetized\ Risk\ Reduction_{Consequence\ Categories}\right)$$

$$\boldsymbol{Max\ Risk\ Reduction} = \sum\left(Max\ Monetized\ Risk\ Reduction_{Consequence\ Categories}\right)$$

Finally, all of these ranges are summed for all asset/threat pairs to provide the total risk reduction that can be achieved; these results can be filtered within CREAT to focus on a specific scenario, asset, or adaptation plan.

As the assessments are completed, the results dashboard is updated to provide users with tabular and graphical comparisons of overall results:

- Monetized risk with Current Measures;
- Monetized risk with the Adaptation Plan implemented;
- Monetized risk reduction;
- Adaptation Plan cost;
- Regional economic consequences for both Current Measures and the selected Adaptation Plan; and
- Public health impacts for both Current Measures and the selected Adaptation Plan.

7.3 Scenario Likelihood Sensitivity Analysis

Up to this point, users have considered threats as if the threats are 100% likely to occur in the given time period. This assumption allows the risk assessment to be more straightforward and helps prevent difficulties among users that are unfamiliar with the process of assessing likelihood or are unable to determine likelihood for any or all scenarios. Once the risk assessment has been completed, users are provided with an opportunity to review the data and consider how different likelihood values may influence their decisions.

Each adaptation plan has a cost for implementation and a range of MRR for each scenario. When the risk reduction for a conditional threat is less than the implementation cost of a plan, users can clearly see that the plan does not provide a return on investment that supports an implementation decision. Alternatively, MRR in excess of the implementation cost would indicate that the benefit of taking action would exceed the cost for some range of scenario likelihood.

CREAT calculates three ranges of scenario likelihood where the comparison of cost with risk reduction would support different decisions:

- **Wait and See:** The range of implementation cost of the selected plan exceeds the entire range of possible risk reduction for the threats in the selected scenario. Based on the current assessment, there would be a negative return on investment. It is possible that based on additional experience and improved data, a later assessment may reduce this range of likelihood and support implementation;
- **Consider Implementing Plan:** The range of implementation cost of the selected plan overlap with the range of possible risk reduction for the threats in the selected scenario. Based on the current assessment, there would be an uncertain return on investment. Consider additional benefits from implementing this plan or return to conduct another assessment to support the decision regarding implementation of this plan; and
- **Implement Plan:** The entire range of implementation costs of this selected plan is below the entire range of possible risk reduction for the threats in the selected scenario. Based on the current assessment, there would be a positive return on investment. The MRR alone provides adequate benefit to support the decision regarding implementation of this plan.

7.4 Plan Comparison

In the final step of the tool, CREAT provides a table of adaptation plans that were considered during the risk assessment. Users are asked to consider additional impacts for the adaptation plans that were not considered as part of the consequence assessment earlier in this module. These impacts may relate to or influence utility planning priorities, such as energy and socioeconomic impacts. Each impact is rated as a change relative to the Current Measures plan where no new actions are taken. Energy impacts reflect the net change in energy use due to adaptation, and plans may be rated as Energy Saving, Neutral, or increasing energy use to a Low, Medium, or High degree. Socioeconomic impacts are rated on a similar scale, with the potential to recognize plans that are beneficial versus those that may impact public or ecosystem services. At this point, users also revisit consequence categories that were previously deferred for consideration.

Plan reports detailing the results of the assessment are available for download as well. These reports are the final output from CREAT and are designed to support adaptation planning based on assessment results.

Chapter 8. References

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Appendices

A-1: Models Used in Developing Climate Data

Table 9. Models Used in Developing Climate Data

Model Name (Year)	Storm Scalars	Source / Institution
ACCESS1_0		Australia, Commonwealth Scientific and Industrial Research Organization (CSIRO) and Bureau of Meteorology (BOM)
ACCESS1-3	X	
BCC-CSM1_1		China, Beijing Climate Center, China Meteorological Administration
BCC_CSM1_1_M		
BNU_ESM		China, College of Global Change and Earth System Science, Beijing Normal University
CANESM2	X	Canada, Canadian Centre for Climate Modelling and Analysis
CCSM4	X	USA, National Center for Atmospheric Research (NCAR)
CESM1_BGC	X	USA, Community Earth System Model Contributors
CESM1_CAM5		
CMCC_CM	X	Italy, Centro Euro-Mediterraneo per i Cambiamenti Climatici
CMCC_CMS	X	
CNRM_CM5	X	France, Centre National de Recherches Météorologiques / Centre Européen de Recherche et Formation Avancée en Calcul Scientifique
CSIRO_Mk_3_6	X	Australia, Commonwealth Scientific and Industrial Research Organization in collaboration with Queensland Climate Change Centre of Excellence
EC_EARTH		EC-EARTH consortium
FGOALS_G2		China, LASC, Institute of Atmospheric Physics, Chinese Academy of Sciences and CESS, Tsinghua University
FGOALS_S2		China, LASC, Institute of Atmospheric Physics, Chinese Academy of Sciences
GFDL_CM3		USA, NOAA General Fluid Dynamics Lab
GFDL_ESM2G	X	
GFDL_ESM2M	X	
GISS_E2_H		USA, NASA Goddard Institute for Space Studies
GISS_E2_H_CC		
GISS_E2_R		
GISS_E2_R_CC		
HADGEM2_AO		Korea, National Institute of Meteorological research/Korea Meteorological Administration
HADGEM2_CC		UK, Met Office Hadley Centre (additional HadGEM2-ES realizations contributed by Instituto Nacional de Pesquisas Espaciais)
HadGEM2_ES	X	
INMCM4	X	Russia, Institute for Numerical Mathematics
IPSL_CM5A_LR	X	France, Institute Pierre Simon Laplace
IPSL_CM5A_MR	X	
IPSL_CM5B_LR	X	
MIROC_ESM	X	Japan, Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies
MIROC_ESM_CHEM	X	
MIROC5	X	
MPI_ESM_LR	X	Germany, Max-Planck-Institut für Meteorologie (Max Planck Institute for Meteorology)
MPI_ESM_MR	X	
MRI_CGCM3	X	Japan, Meteorological Research Institute
NorESM1_M	X	Norway, Norwegian Climate Center
NORESM1_ME		

A-2: Default Threat Definitions

Drought: Increasing temperature and changing precipitation patterns could result in lower lake and reservoir levels, as well as reduced groundwater recharge and reduced snowpack. Through evaporation and insufficient inflows following precipitation events, declines in reservoir levels would jeopardize supply and other resources dependent on sufficient inflows. Lower soil moisture, total precipitation and a greater fraction of precipitation during intense events all act to restrict percolation into aquifers to maintain the water table and well production. Changes in precipitation timing, rain rather than snow, and earlier snowmelt will change the amount and timing of water supply, as well as impact receiving water quality in downstream waterways.

Default definitions for drought threats provided in CREAT are as follows:

- Lower lake and reservoir levels: Decreases in annual precipitation will lead to lower lake and reservoir levels that utilities rely on for surface water supplies. In addition, evaporation rates and water loss from vegetation will be higher due to increasing temperatures. These lower levels may make it difficult to meet water demands, especially in summer months and may drop water levels below intake infrastructure;
- Reduced groundwater recharge: Decreases in annual precipitation will decrease surface water supplies and groundwater recharge, especially impacting utilities that rely on groundwater supplies. In addition, evaporation rates and water loss from vegetation will be higher due to increasing temperatures; and
- Reduced snowpack: Increasing temperature and changing precipitation patterns combine to decrease the depth and extent of snowpack; often considered a reservoir of source water. Changes in precipitation timing, rain rather than snow, and earlier snowmelt will change the amount and timing of water supply, as well as impact receiving water quality in downstream waterways.

Ecosystem Changes: Increasing temperature and changing precipitation patterns may shift environmental conditions in a way that alters the dominant species of vegetation or persistence of pests or disease that impact current vegetation. Shifts in biodiversity and potentially drier conditions may also increase the risks of wildfire. Water resources and facilities can be damaged by these shifts, depending on the rate of change, extent of impacted ecosystems and frequency of fire events. In addition, intense storms, coupled with rising sea level, are capable of eroding coastal landforms and compromising the flood protection and ecological value provided by them. These climate drivers may impact the inflow and retention of water in current wetlands and damage wetland vegetation through salinity changes. Storm damage and shifts in the sediment balance through erosion or accretion could change wetland coverage along a shoreline.

Default definitions for ecosystem change threats provided in CREAT are as follows:

- Altered vegetation / wildfire risk: Increasing temperature and changing precipitation patterns can contribute to vegetation changes or persistence of pests or disease. Shifts in biodiversity and potentially drier conditions also increase the risks of wildfire. Water resources and facilities can be damaged by these shifts, depending on the rate of change, extent of impacted ecosystems and frequency of fire events;
- Loss of coastal landforms: Sea level rise and increasing frequency of damaging tropical storms can lead to losses of coastal and stream ecosystems. Loss of these landforms can reduce the buffer against coastal storms, which may damage coastal treatment plants and infrastructure, leading to service disruptions; and

- Loss of wetlands: Increasing temperature, changing precipitation patterns and rising sea level will impact wetland habitats. These climate drivers have the potential to alter the inflow and retention of water in current wetlands and damage wetland vegetation through salinity changes. Storm damage and shifts in the sediment balance through erosion or accretion could change wetland coverage along a shoreline.

Floods: Changes in precipitation patterns, particularly greater storm intensities, may generate additional floods associated with high flow events. Intense storms, coupled with rising sea level in coastal locations, are capable of generating floods associated with coastal storm surges. Several factors can influence extent and depth of flooding, requiring some knowledge of how storms generate floods under current and future sea levels. Increasing floods and high flow events are most problematic when the events occur in areas with little previous experience with flooding and knowledge of connecting precipitation to potential extent and depth of flooding is limited.

Default definitions for flood threats provided in CREAT are as follows:

- Coastal storm surges: Increases in storm frequency or intensity may increase the frequency and extent of coastal storm surges, especially when combined with sea level rise. This combination results in inundation of coastal areas, disruption of service and damage to infrastructure such as treatment plants, intake facilities, water conveyance and distribution systems, pump stations and sewer infrastructure; and
- High flow events: Changes in precipitation patterns, particularly greater storm intensities, may generate additional floods associated with high flow events. These flooding events may challenge current infrastructure for water management and flood control. When these protections fail, inundation may damage infrastructure such as water treatment plants, intake facilities and water conveyance and distribution systems. More extreme events can lead to combined sewer overflows and reduce the capacity of sewer systems already impacted by inflow and infiltration.

Service Demand and Use: Increasing temperature and changing precipitation patterns combine to change the demand for water used in agriculture and irrigation, as well as impact the generation of and demand for energy. Increased demand for water related to agriculture and irrigation results from decreased precipitation and increased evaporative losses from soil and crops. The consumption of energy is strongly linked to seasonal temperatures, such as indoor climate control and the energy needs of water utilities. Residential demand for water, such as bathing and drinking water, is also strongly linked to seasonal temperatures. Additionally, changes in temperature and flow may have important ramifications on influent conditions, altering the effectiveness of treatment and capacity of the system, as well as challenge the ability of utilities to provide adequate wastewater and stormwater services. Each municipality should critically evaluate historical demand for their systems and any link to climate conditions to project changes in demand.

Default definitions for service demand and use threats provided in CREAT are as follows:

- Changes in agricultural practice and outdoor use: Increasing temperature and changing precipitation patterns combine to increase evaporative losses from soil and crops. A change in agricultural demand could impact the ability of drinking water utilities to provide sufficient supply for their ratepayers;
- Changes in energy sector water needs: Increasing temperature and changing precipitation patterns combine to change the demand for water used in the generation of energy. The consumption of energy is strongly linked to seasonal temperatures and the energy needs of water utilities;

- Changes in influent flow and temperature: Increasing temperature and changing precipitation patterns both alter influent conditions. Changes in temperature and flow may have important ramifications on the effectiveness of treatment and capacity of the system; and
- Changes in residential use: Residential demand for water is strongly linked to seasonal temperatures. Changes in future temperatures will challenge the ability of utilities to provide adequate levels of wastewater and stormwater services.

Water Quality Degradation: For surface waters, water quality will be affected by increasing temperature, changing precipitation patterns, and rising sea level. All drivers have the potential to degrade water quality in ways that limit or prohibit the use of the water resource as either a source or receiving water. Examples of water quality degradation include harmful algal blooms, nutrient or sediment runoff from storm events, and saline intrusion into historically freshwater bodies. For coastal aquifers, both changing precipitation patterns and rising sea level have the potential to generate favorable groundwater conditions for the intrusion of saline waters into freshwater aquifers. Through time, without additional treatment or relocation of supply, the relative depths of saline and freshwater tables will drive the interface past wells and limit production.

Default definitions for water quality degradation threats provided in CREAT are as follows:

- Altered surface water quality: Surface water quality is affected by changes in temperature, precipitation patterns and the number of extreme hot days. Examples of water quality degradation include harmful algal blooms, nutrient or sediment runoff from storm events and saline intrusion into historically freshwater bodies; and
- Saline intrusion into aquifers: Projected sea level rise, combined with higher water demand from coastal communities, can lead to saltwater intrusion in both coastal groundwater aquifers and estuaries. This combination may reduce water quality and increase treatment costs for water treatment facilities.

A-3: Examples of Economic Consequences Matrices

The default economic consequences matrix includes definitions and impacts for each level within each consequence category (**Table 10**). The standardized definitions define the basis for the monetary impact values provided by CREAT and serve as a starting point for users to revise the levels based on their own assessment priorities.

Table 10. Default Definitions for CREAT-provided Economic Consequences Matrix (all users)

Category	Low	Medium	High	Very High
Utility Business Impacts	Minimal potential for loss of revenue or operating income	Minor and short-term reductions in expected revenue	Seasonal or episodic compromise of revenue or operating income	Long-term or significant loss of revenue or operating income
Utility Equipment Damage	Minimal damage to equipment	Minor damage to equipment	Significant damage to equipment	Complete loss of asset
Environmental Impacts	No impact or environmental damage	Short-term environmental damage, compliance can be quickly restored	Persistent environmental damage – may incur regulatory action	Significant environmental damage – may incur regulatory action
Source/Receiving Water Impacts	No more than minimal changes to water quality	Temporary impact on source water quality or quantity	Seasonal or episodic compromise of source water quality or quantity	Long-term compromise of source water quality or quantity

The default values in the consequences matrix vary based on utility system type, population served, service volume, financial condition and ownership. This method is described in **Chapter 5, Consequences and Assets: Module 3**. These default values provided by CREAT serve as a starting point for users to revise based on their experience and known thresholds for significant impacts from asset loss or damage. **Tables 11 through 14** provide examples of default consequence matrices based on hypothetical utilities.

Table 11. Default Economic Consequence Matrix for Drinking Water Assets of a Public Combined Water System Serving 25,000 Customers with 5 MGD Service in Good Financial Condition

Category	Low	Medium	High	Very High
Utility Business Impacts	Up to $800,000	$800,000 - $1.6M	$1.6M - $2.4M	Greater than $2.4M
Utility Equipment Damage	Up to $275,000	$275,000 - $690,000	$690,000 - $1.66M	Greater than $1.66M
Environmental Impacts	Up to $15,750	$15,750 - $39,500	$39,500 - $94,500	Greater than $94,500
Source/Receiving Water Impacts	Up to $107,000	$107,000 - $267,500	$267,500 - $642,000	Greater than $642,000

Table 12. Default Economic Consequence Matrix for Drinking Water Assets of a Public Combined Water System Serving 1,000,000 Customers with 150 MGD Service in Strong Financial Condition

Category	Low	Medium	High	Very High
Utility Business Impacts	Up to $37.35M	$37.35M - $74.55M	$74.55M - $111.9M	Greater than $111.9M
Utility Equipment Damage	Up to $22.8M	$22.8M - $57.15M	$57.15M - $137.1M	Greater than $137.1M
Environmental Impacts	Up to $500,000	$500,000 - $1.26M	$1.26M - $3.01M	Greater than $3.01M
Source/Receiving Water Impacts	Up to $3.24M	$3.24M - $8.11M	$8.11M - $19.47M	Greater than $19.47M

Table 13. Default Economic Consequence Matrix for Wastewater Assets of a Public Combined System Serving 25,000 Customers with 5 MGD Service in Good Financial Condition

Category	Low	Medium	High	Very High
Utility Business Impacts	Up to $675,000	$675,000 - $1.35M	$1.35M - $2.03M	Greater than $2.03M
Utility Equipment Damage	Up to $355,000	$355,000 - $885,000	$885,000 - $2.12M	Greater than $2.12M
Environmental Impacts	Up to $15,750	$15,750 - $39,500	$39,500 - $94,500	Greater than $94,500
Source/Receiving Water Impacts	Up to $107,000	$107,000 - $267,500	$267,500 - $642,000	Greater than $642,000

Table 14. Default Economic Consequence Matrix for Wastewater Assets of a Public Combined System Serving 1,000,000 Customers with 150 MGD Service in Strong Financial Condition

Category	Low	Medium	High	Very High
Utility Business Impacts	Up to $35.7M	$35.7M - $71.4M	$71.4M - $107.25M	Greater than $107.25M
Utility Equipment Damage	Up to $18.6M	$18.6M - $46.5M	$46.5M - $111.6M	Greater than $111.6M
Environmental Impacts	Up to $500,000	$500,000 - $1.26M	$1.26M - $3.01M	Greater than $3.01M
Source/Receiving Water Impacts	Up to $3.24M	$3.24M - $8.11M	$8.11M - $19.47M	Greater than $19.47M

A-4: Examples of Monetized Risk Reduction Calculation

The assessment process utilizes the decisions made by users related to levels of consequences and their matrix of monetary impacts for each level within the consequence categories; this method is described in **Chapter 7, Risk Assessment: Module 5**. The following sections provide examples from two hypothetical utilities and the results based on their entries.

A.4.1 Combined Water Example

This analysis is based on the default matrix of economic consequences, provided by CREAT, for the drinking water assets of a public combined water system serving 25,000 customers with 5 MGD service, and good financial condition. See **Table 11** to review their Economic Consequences matrix. This example assessment pursues a single asset/threat pair: loss of water in their only aquifer source, a well. For this asset, only Utility Business and Source/Receiving Water Impacts are expected. Two scenarios of the threat were assessed: Baseline and Projected. Upon considering current resilience, which is based on a consideration of existing measures, the following assessment was selected:

Table 15. Current Measures Assessment for Drinking Water Assets of a Public Combined System Serving 25,000 Customers with 5 MGD Service in Good Financial Condition

Current Measures	Scenarios	
	Baseline	**Projected**
Utility Business Impacts	Medium $800,000 - $1.6M	High $1.6M - $2.4M
Utility Equipment Damage	n/a	n/a
Environmental Impacts	n/a	n/a
Source/Receiving Water Impacts	Low Up to $107,000	High $267,500 - $642,000
Overall Consequence	$800,000 - $1.71M	$1.87M - $3.04M

Previously, the utility identified a set of potential adaptive measures that would cost $300,000 to $550,000 to implement. These measures were selected for inclusion in their adaptation plan, which they named "DW Adaptation Plan." Next, the levels of consequence were considered following the implementation of the DW Adaptation Plan:

Table 16. DW Adaptation Plan Assessment for Drinking Water Assets of a Public Combined System Serving 25,000 Customers with 5 MGD Service in Good Financial Condition

DW Adaptation Plan	Scenarios	
	Baseline	**Projected**
Utility Business Impacts	Medium $800,000 - $1.6M	Medium $800,000 - $1.6M
Utility Equipment Damage	n/a	n/a
Environmental Impacts	n/a	n/a
Source/Receiving Water Impacts	Low Up to $107,000	Low Up to $107,000
Overall Consequence	$800,000 - $1.71M	$800,000 - $1.71M

The overall consequence from the second assessment is the same for the Baseline Scenario and is lower than the overall impact without adaptation for the Projected Scenario.

The difference in the two assessments was calculated by CREAT using the movement of consequence level in each category, rather than the difference in the overall consequence:

Table 17. Monetized Risk Reduction for Combined Water System DW Adaptation Plan

DW Adaptation Plan	Scenarios	
	Baseline	**Projected**
Utility Business Impacts	$0	$0 - $1.6M
Utility Equipment Damage	n/a	n/a
Environmental Impacts	n/a	n/a
Source/Receiving Water Impacts	$0	$160,500 - $642,000
Monetized Risk Reduction	$0	$160,500 - $2.24M

This final range, the MRR, for the Baseline Scenario is negligible. For the Projected Scenario, the risk reduction overlaps the range of implementation cost of the DW Adaptation Plan ($300,000 to $550,000).

A.4.2 Combined Wastewater Example

This analysis is based on the default matrix of economic consequences, provided by CREAT, for the wastewater assets of a public combined system serving 1,000,000 customers with 150 MGD service and strong financial condition. See **Table 12** to review the consequences matrix. This assessment example pursues a single asset/threat pair: flooding at their wastewater treatment plant. For this asset, only Utility Equipment and Environmental Impacts are expected. Two scenarios of the threat are being assessed: Baseline and Projected. Upon considering their current resilience, based on existing measures, the following assessment was selected:

Table 18. Current Measures Assessment for Wastewater Assets of a Public Combined System Serving 1,000,000 Customers with 150 MGD Service in Strong Financial Condition

Current Measures	Scenarios	
	Baseline	**Projected**
Utility Business Impacts	n/a	n/a
Utility Equipment Damage	Medium $18.6M - $46.5M	Very High Greater than $111.6M
Environmental Impacts	Low Up to $500,000	Medium $500,000 - $1.3M
Source/Receiving Water Impacts	n/a	n/a
Overall Consequence	$18.6M - $47M	Greater than $112.9M

The utility identified a set of potential adaptive measures that would cost $10,000,000 to $20,000,000 to implement. These measures were selected for inclusion in their adaptation plan, which was named "WW Adaptation Plan."

Next, the levels of consequence were considered following the implementation of the WW Adaptation Plan:

Table 19. WW Adaptation Plan Assessment for Wastewater Assets of a Public Combined System Serving 1,000,000 Customers with 150 MGD Service in Strong Financial Condition

WW Adaptation Plan	Scenarios	
	Baseline	**Projected**
Utility Business Impacts	n/a	n/a
Utility Equipment Damage	Low Up to $18.6M	Low Up to $18.6M
Environmental Impacts	Low Up to $500,000	Low Up to $500,000
Source/Receiving Water Impacts	n/a	n/a
Overall Consequence	Up to $19.1M	Up to $19.1M

The overall consequence from the second assessment is lower than the overall impact without adaptation. The difference in the two assessments is calculated by CREAT using the movement of consequence level in each category, rather than the difference in the overall consequence:

Table 20. Monetized Risk Reduction for Combined Water System WW Adaptation Plan

WW Adaptation Plan	Scenarios	
	Baseline	**Projected**
Utility Business Impacts	n/a	n/a
Utility Equipment Damage	\$0 - \$46.5M	Greater than \$93.1M
Environmental Impacts	\$0	\$0 - \$1.3M
Source/Receiving Water Impacts	n/a	n/a
Monetized Risk Reduction	\$0 - \$46.5M	Greater than \$93.1M

This final range, the MRR, for both scenarios either overlaps or exceeds the implementation cost of the WW Adaptation Plan (\$10,000,000 to \$20,000,000).

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