Version 1.0

CLIMATE ADAPTATION TOOL FOR WATER UTILITIES

Stormwater

Visualize potential impacts | Estimate costs | Compare options

USER GUIDE & METHODOLOGY

THE Water Research FOUNDATION®

Stormwater Tool
User Guide & Methodology

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Introduction & Framework

Purpose of the Tool

Climate change presents significant challenges for stormwater utilities, from increasingly intense rainfall events to heightened flooding risks and water-quality concerns. This Climate Adaptation Decision-Support Tool, funded by the Water Research Foundation (WRF), is designed specifically to help U.S. stormwater utilities proactively address these challenges. The tool enables utility managers to identify a cost-optimized portfolio of structural climate adaptation solutions (CAS), such as rain gardens, constructed wetlands, permeable pavements, and storage vaults, that are specifically designed to meet anticipated climate-driven impacts.

This version of the tool emphasizes structural solutions, with future updates expected to include non-structural strategies, such as operational changes, rebate programs, and system optimizations.

Tool Framework Overview

The stormwater module guides users through a structured four-module process:

1. **Module 1. Inputs (SW1_Inputs):** Quantify the physical impacts of climate change by calculating additional runoff volumes and pollutant loads expected under future climate conditions.
2. **Module 2. CAS Parameters (SW2_CASParameters):** Define the feasible range of CAS by specifying options and realistic implementation limits based on local constraints.
3. **Module 3. Co-benefits (SW3_Co-benefits):** Identify community and stakeholder priorities for additional benefits, such as improved air quality, enhanced biodiversity, and reduced energy consumption.
4. **Module 4. Optimization (SW4_Optimization):** Leverage an Excel-based optimization process to determine the most cost-effective portfolio of CAS that meets climate resilience targets, optionally maximizing prioritized co-benefits within budget constraints.
5. **Module 5. Results (SW5_Results):** Summarize, interpret, and communicate the optimized portfolio's outcomes, including costs, physical benefits, co-benefits, and practical implementation considerations.

The core questions, key outputs, and data flow associated with each module is summarized in Table 1 below.

Table 1. Tool workflow

MODULE	CORE QUESTION	KEY OUTPUTS	FLOWS TO
1 – Inputs	*How big is the climate "gap" in terms of water volume and quality?*	Future runoff volume & TSS mass to remove	Module 4
2 – CAS Parameters	*What CAS will you consider and how constrained are you in using them?*	Min/max counts, unit specs, unit costs	Module 4
3 – Co-benefits	*Which co-benefits matter most?*	Priority scores (low, med, high) per co-benefit	Module 4
4 – Optimization	*What mix of CAS meets targets at least cost and—optionally—maximizes co-benefits?*	Optimized portfolio, cost, score	5 – Results
5 – Results	*What does the optimized portfolio deliver & how to communicate it?*	Cost-benefit summary tables	External reports

NOTE: You will need to enable Macros in Excel to use this tool.

Tool Boundaries and Limitations

While the tool is designed to support transparent, defensible decisions, it is a national screening tool. The points below summarize key boundaries and assumptions to keep in mind.

1. **Scope:** This is a national-level screening tool and cannot capture all local nuances. Users should refine key inputs—such as unit costs and performance—where better local data exist.
2. **Storm events:** The tool focuses on frequent rainfall events (80th–95th percentiles) commonly used for water-quality planning. Extreme return-period storms (e.g., 10-, 50-, 100-year) are not included yet and are planned for future updates.
3. **Climate data:** Projections are aggregated at the county level from CMIP6-LOCA2 (USGS, 2023). Results are indicative at county scale rather than hyper-local.
4. Benefits and Costs:
    a. Only a subset of benefits is monetized, so benefit–cost ratios may appear conservative.

b. Reported costs are capital only; operations and maintenance are excluded and can be significant, especially for BMPs.
c. Costs and benefits are expressed in 2023 dollars.

5. **Implementation timing:** Results provide a snapshot for each planning period and do not represent ramp-up schedules, sequencing, or delivery constraints.
6. **Climate gap:** The analysis assumes the agency is managing existing baseline water volume and quality. The tool is focused on helping the "climate gap," i.e., the additional precipitation volume, over and above baseline.
7. **Modeling approach:** This is a static, planning-level analysis rather than a dynamic hydrologic model (e.g., EPA SWMM or CLASIC). Routing, drawdown between storms, and multi-day sequences are not represented.
8. **Siting and capacity:** Optimization assumes perfect siting and that each CAS unit's storage is fully utilized during the design event. Real-world hydraulics, siting constraints, and maintenance may limit achievable capacity.

Module 1 – SW1_Inputs

Module Overview

Module 1 is the foundational step where you establish the baseline and future climate conditions your community or utility faces. Here, you will quantify the expected increase in stormwater volume and pollutants resulting from climate change. This creates a clear target—the "climate gap"—that your subsequent planning and investments aim to address.

How to use Module 1

Steps 1–3: Defining Your Location

Begin by clearly identifying your analysis area:

- **Location Name:** Enter a descriptive name such as your community, district, or stormwater management area.
- **State and County:** Use dropdown menus to select your state, then county. Selecting the correct county is important, as this choice determines local climate and rainfall data used throughout the tool.

Step 4: Community FIPS Code (Automatic)

(This is an automatic step hidden from view.) Based on your county selection, the tool assigns a Federal Information Processing Standard (FIPS) code to link to accurate climate data. You can verify with a Google search.

Step 5: Specify Your Management Area

Input the total geographic area you are managing (e.g., city boundary, specific drainage basin, or district). Accuracy here helps ensure all subsequent runoff and pollutant calculations reflect your precise area of responsibility.

Step 6: Impervious Surface Percentage

Enter your area's impervious surface percentage—the proportion of land covered by roofs, pavement, compacted soils, and similar surfaces. The tool defaults to 43%, but you may modify this if you have more accurate local data.

**Estimating Impervious Area

If uncertain about your community's impervious coverage, you can estimate it using tools like the MRLC NLCD Viewer which allows you to draw a boundary around any location in the U.S. and generate land cover results, including impervious cover estimates. There may also be local stormwater studies or GIS analysis that estimate impervious cover for your location. For quick reference, we've also provided a table below that summarizes Impervious Cover as a Percentage of Land Area in Selected U.S. Cities, which is based on a study published by Nowak & Greenfield (2012),[i] though actual impervious cover for your management area may differ significantly.

Table 2. Impervious Cover as a Percentage of Land Area in Selected U.S. Cities

CITY	YEAR	IMPERVIOUS COVER (%)
Albuquerque	2009	37.1%
Atlanta	2009	28.2%
Baltimore	2005	45.8%
Boston	2008	50.0%
Chicago	2009	58.5%
Denver	2009	41.4%
Detroit	2009	47.7%
Houston	2009	39.2%
Kansas City	2009	20.2%
Los Angeles	2009	54.0%
Miami	2009	61.0%
Minneapolis	2008	43.6%
Nashville	2008	18.9%
New Orleans	2009	41.7%
New York	2009	61.1%
Pittsburgh	2008	40.0%
Portland	2009	44.7%
Spokane	2007	35.8%
Syracuse	2009	49.5%
Tacoma	2005	44.3%

Step 7: Calculating Total Impervious Area

The tool automatically calculates your total impervious area based on your inputs (e.g., 3,000 acres at 55% imperviousness equals 1,650 impervious acres). This area is crucial for calculating runoff.

Steps 8–10: Selecting a Design Storm Event

Choose a design storm: Either the 80th, 85th, 90th, or 95th percentile rainfall event. These represent typical, frequently occurring storms your utility may target for runoff management, in line with MS4 permit requirements and other stormwater regulations. The tool precalculated percentile rainfall events for all counties in the US, for the period 1994–2023, and will return the design storm depth value for your selected county (Step 9), which is then used to estimate runoff volume from impervious areas (Step 10).

> ****Understanding Percentile Storms:**
>
> Percentile storms represent frequent, small to mid-sized storm events, not extreme events like 1- or 100-year floods. For example, a 95th percentile storm is larger than 95% of all daily rainfall events (excluding those ≤ 0.1") observed over the 30-year period.
>
> *(Refer to Methods Section 1 for technical details on how rainfall data were obtained and processed.)*

Step 11: Climate Projections (automatic)

In this step, the tool displays projected future temperature increases (in degrees Celsius) specific to your selected county. These projections span multiple future planning horizons (2025-2049, 2050-2074, and 2075-2099) and various climate scenarios, known as Shared Socioeconomic Pathways (SSPs). The SSPs represent different global trajectories concerning economic, social, and environmental development, which affect future greenhouse gas emissions and, consequently, future extreme weather.

Higher SSPs (such as SSP5-8.5) indicate scenarios with less climate policy intervention, leading to significantly higher warming, while lower SSPs (like SSP2-4.5) reflect scenarios in which countries take moderate to aggressive climate action, resulting in less warming.

For more detailed information about how these climate projections were developed, including the methodology for extracting and processing LOCA2 data, refer to *Methods Section 2* of this report.

Step 12-13: Selecting the Delta Change Factor

After reviewing the matrix of future temperature projections above, your next step is to select a Delta Change Factor (DCF). This choice helps you plan for how future storms might become more intense due to increased temperatures and atmospheric moisture.

The DCF is a simple multiplier used by the tool to adjust your baseline design-storm rainfall depth based on future projected changes in temperature. It reflects the scientific understanding (Clausius-Clapeyron relationship) that warmer air holds more moisture, about 7% more moisture for every 1ºC of warming. Thus, higher temperature increases typically lead to stronger, more intense rainfall events.

(For a more detailed technical background on the Clausius-Clapeyron relationship, see *Methods Section 3*)

Here's how to choose the right scenario:

- **Low:** This will select the lowest DCF available from the matrix. Select this if you prefer an optimistic approach, anticipating modest temperature increases. This might correspond to near-term planning (2025–2049) under moderate climate action scenarios (e.g., SSP2-4.5).
- **Medium:** This will select the average of all DCF values in the matrix. Choose this scenario to reflect middle-of-the-road expectations for warming—suitable for mid-century planning horizons (2050–2074) and intermediate climate change scenarios (e.g., SSP3-7.0).
- **High:** This will select the highest DCF available form the matrix. Select this if you want to be prepared for the most severe potential warming, such as late-century conditions (2075–2099) under high-emission scenarios (e.g., SSP5-8.5). This selection reflects a cautious, risk-averse approach to future storm intensification.

Step 14–18: Future Storm Calculations (automatic)

Once you select a scenario (Low, Medium, or High) in Step 13 ("Delta-Change Factor calculation method"), the tool automatically calculates the corresponding numeric factor. Specifically, it multiplies your baseline rainfall depth by:

$DCF = 1 + 0.07 \times \Delta T$

where ΔT is the projected temperature increase for your chosen scenario and planning horizon (see ID 14).

The new design-storm depth (ID 15) and additional runoff volume ("climate gap") (ID 18) will update automatically. These values provide the targets you'll aim to manage through your selected CAS.

Steps 19–24: Water Quality Target

In this final set of inputs, you convert the additional runoff volume into a pollutant mass and set a removal target. The tool uses Total Suspended Solids (TSS) as a water-quality proxy.

Selecting the Right TSS Value

TSS concentrations vary by watershed, land use, and season. Use recent local monitoring where available. When local data are not available, the default of 58 mg/L is a reasonable national planning value supported by the following sources:

- National Stormwater Quality Database (v4.02, 2018):[ii] The table "Suspended Solids" (no table number) summarizes data in the NSQD for SS. Median values range from 38-74 mg/L depending on land use. The median TSS value across all land use types is 58 mg/L.

- EPA Preliminary Data Summary of Urban Storm Water BMPs (1999):[iii] Table 4-1 summarizes typical urban TSS concentrations and ranges by land cover, which range from 67-101 mg/L. The value for "mixed" use is 67 mg/L.

Module 2: SW2_CASParameters

Module Overview

After determining your climate adaptation needs in Module 1, the next step involves identifying and describing the range of possible CAS that can meet those needs. CAS can include both structural and non-structural approaches. The structural approaches are commonly known as Best Management Practices (BMPs) and typically include various forms of green infrastructure like rain gardens, green roofs, and constructed wetlands, as well as traditional engineered options such as storage vaults or detention basins.

This module guides you through selecting appropriate CAS for your community, setting realistic constraints based on your local context, and ensuring the assumptions used for optimization match your real-world capabilities and limitations. Properly setting these parameters is critical, as it directly affects the feasibility and effectiveness of the optimized solution portfolio you'll create later in Module 4.

How to Use Module 2

Step 1: Activating and Selecting CAS

On this page, you'll see a list of potential CAS organized in rows. The first task is to decide which CAS you want to consider in your analysis. Next to each CAS name, you'll find checkboxes in **Column A:**

- **Check (✓)** a CAS to activate it, making it eligible for inclusion in your final optimized portfolio.
- **Uncheck** a CAS if it is not suitable, feasible, or desirable in your community. This will exclude it entirely from the optimization process.

> **Tip**
>
> Carefully consider factors like site conditions, public acceptance, maintenance capability, and regulatory support when selecting or deselecting CAS. You don't have to select every option—focus on solutions that realistically fit your community's context.

Step 2: Reviewing CAS Definitions and Selecting Typical Sizes

Each CAS has an associated definition and typical size used by similar agencies. Definitions can be viewed by clicking the **"View/hide definitions"** button in **Column C**. Definitions will help you understand what each CAS entails and why you might choose it.

In **Column D (Size)**, select the typical size that best matches your agency's usual practice or local standards. You'll typically see small, medium, or large sizing options (for instance, rain gardens might range from small residential lots to large municipal installations). Currently the tool only allows selection of a single size, so select the size that is most typical or "average" for your agency.

> **Tip**
>
> If you're uncertain about the typical sizes, consult your engineering or planning departments to identify what's commonly used in your region. You can also click on cell D3 to view a tab with a "size guide" that helps you visualize the different sizes provided.

Step 3: Confirming Unit Specifications

Once you select a size, several columns will automatically populate with detailed information about each CAS:

- **Cost per Unit (Column G):** The estimated average capital cost to install one unit of that CAS.
- **Storage Volume per Unit (Column H):** The amount of stormwater runoff each CAS can handle per event.
- **Water Quality Improvement per Unit (Column I):** The amount of Total Suspended Solids (TSS) each unit removes, expressed in pounds per event.

These figures are primarily based on standard specifications from a trusted reference (the WRF-funded CLASIC tool), which you can review separately on the reference tab **REF_BMPSpecs** or by clicking on cell G3. You should verify these values, and you can override them if you have detailed local data from previous projects or cost estimates.

> **Tip**
>
> It's generally recommended to use default values unless you have reliable, local cost estimates and performance data. If you do have local data, consult your local cost engineering or stormwater specialists to review and adjust these numbers.

Step 4: Setting Minimum and Maximum Bounds (Very Important)

The final, and perhaps most important, step in this module is to set realistic physical constraints, minimum and maximum numbers, for how many units of each CAS your community can feasibly implement. This is entered in **Column O (Minimum)** and **Column P (Maximum)**.

These constraints are crucial because:

- **Minimum:** Represents the least number of units you're committed to implementing, regardless of cost.
- **Maximum:** Reflects your community's upper limit based purely on physical or practical considerations, such as available space, anticipated community adoption rates, or known feasibility limits.

Examples of setting these constraints include:

- **Green Roofs:**
  - Minimum: Could be zero if there's no regulatory requirement or current commitment.
  - Maximum: You might estimate an adoption rate of 10% of single family homes (i.e. 10% of homes that do not currently have green roofs will adopt green roofs) based on incentives or regulations.
- **Rain Gardens (Bioretention):**
  - Minimum: Set by any existing stormwater program targets or community commitments.
  - Maximum: Determined by assessing residential lot sizes, available green space, and anticipated homeowner participation rates.
- **Storage Vaults or Tunnels:**
  - Minimum: Based on existing project plans or municipal requirements.
  - Maximum: Limited by known engineering constraints, subsurface conditions, and funding availability.

Setting Realistic Min/Max Constraints

To establish realistic bounds, consider the following steps:

- **GIS analysis:** Quickly estimate available spaces using GIS data for rooftops (green roofs), vacant lots (wet ponds), roadways (permeable pavement), or public parks (constructed wetlands).
- **Adoption rates:** Reference adoption rates from similar municipalities or regions to estimate practical uptake (e.g., rain barrels might only achieve a 5–10% adoption in residential neighborhoods without strong incentives).
- **Regulatory and Policy Drivers:** Your minimum values might reflect local regulatory mandates (such as stormwater retention requirements in new development areas).

Confirming Your Settings

Once you've carefully set these minimum and maximum constraints, give your selections a final review. Ask yourself:

- Do these ranges feel realistic given our community context and past experience?
- Are the minimum constraints achievable, and do they reflect commitments or regulatory requirements?
- Are the maximum constraints physically feasible or overly optimistic?

If your constraints are too restrictive, you may struggle to meet your adaptation targets in Module 4. If they're too generous, your optimized portfolio may recommend unrealistic numbers of a single CAS, which may be challenging or undesirable in practice.

After completing Module 2, your CAS parameters will feed directly into Module 4, where the Excel Solver will generate a cost-optimized portfolio of solutions.

Module 3: SW3_Co-benefits

Module Overview

While Modules 1 and 2 focus primarily on addressing stormwater volumes and improving water quality, this module broadens the view to include additional positive outcomes known as co-benefits. Co-benefits are the extra environmental, social, and economic benefits that certain CAS provide beyond stormwater management. Examples include energy savings, enhanced air quality, biodiversity support, and improved urban aesthetics.

Identifying and prioritizing co-benefits helps ensure your final optimized portfolio of CAS aligns closely with broader community values and stakeholder interests.

> **Tip**
>
> This step provides an excellent opportunity to integrate perspectives from various stakeholders, including municipal departments, elected officials, community groups, and the public.

How to Use Module 3

Step 1: Reviewing Co-benefits

On this module's worksheet, you'll see a list of potential co-benefit categories along with brief descriptions. Examples include:

- **Energy Savings:** Reduced energy consumption and cost savings from practices like green roofs and increased shading from trees.
- **Water Supply:** Enhanced groundwater recharge and improved water conservation from infiltration-based CAS.
- **Air Quality:** Improved local air quality due to vegetation that filters pollutants and reduces particulate matter.
- **Property Values:** Increased desirability and property value uplift due to aesthetically pleasing green infrastructure.
- **Urban Heat Reduction:** Cooling urban areas through increased vegetation coverage, reducing heat island effects.
- **Habitat/Biodiversity:** Support for local wildlife and ecological connectivity through habitat enhancement.
- **Carbon Reduction:** Decreased atmospheric carbon through vegetation growth, energy use reductions, and carbon sequestration.

Step 2: Assigning Priority Levels

For each co-benefit listed, you'll select a priority level:

- **High Priority:** Very important; should significantly influence which CAS are selected. CAS providing this benefit will strongly be favored in the optimization.
- **Medium Priority:** Moderately important; will have a moderate influence on CAS selection.
- **Low Priority:** Nice to have, but not critical. These will not influence CAS selection, though CAS in your final portfolio may still generate these co-benefits.

This simple ranking system helps clarify which additional benefits matter most to your community. Behind the scenes, your priority selections translate directly into a scoring system. The second step of the optimization process in Module 4 uses these scores to prioritize CAS that deliver higher-ranked co-benefits, ensuring your resulting portfolio isn't only cost-effective but also aligns with community preferences and broader sustainability goals.

Module 4: SW4_Optimization

Module Overview

Module 4 turns your inputs and constraints into an implementable portfolio of CAS. Using Excel's Solver, it first finds the lowest-cost mix of CAS that meets your water-volume and TSS targets. You can then optionally allow a small budget increase to re-optimize for higher co-benefit scores while still meeting the same physical targets.

This module enables you to:

1. Find the minimum-cost portfolio that satisfies all targets and bounds.
2. Optionally boost co-benefits within a user-defined budget ceiling.

How to Use Module 4

Step 1: Finding the Minimum-Cost Portfolio

Running the optimization

Click the blue "Optimize Portfolio" button in cell B7. Excel's Solver will find a portfolio of CAS that minimizes Total Cost while enforcing:

1. Your physical targets for water volume and water quality (TSS) from Module 1.
2. The per-CAS min/max bounds you set in Module 2.

Reviewing the results

1. **Value (C7):** Minimum total capital cost for the feasible portfolio. This value is also saved as the Baseline Cost for Step 2.

2. **Constraint status (C8):** Indicates whether both physical targets (water volume and quality) are met. If not feasible, try one or more of the following:
    a. Increase the maximum bounds or activate additional CAS in Module 2
    b. Select a less aggressive climate scenario or a lower design-storm percentile in Module 1

Interpreting the “Results” section

There are two tables under the Results heading:

1. **Actions:** For each CAS shows unit cost, your min/max bounds, and RESULTS: Optimal Portfolio (solver-selected units). The score column summarizes each action’s relative co-benefit weighting.
2. **Physical Targets:** Lists required targets and the amount provided by your recommended portfolio. You can see here whether water volume of quality is your main limiting factor. The final column reports whether each constraint is satisfied.

Step 2: Maximizing Co-benefits (Optional)

Adjusting for Co-benefits

Module 4 allows you to further enhance your portfolio by prioritizing co-benefits identified in Module 3. To do this:

- Enter a percentage budget increase you're willing to allow (e.g., 10%, 15%, 20%) in **Cell C12**. Cells C14 and C14 will then show your budget increase and new budget respectively.
- **Click the blue "Maximize Co-benefits" button in cell B15.** Solver will re-optimize the CAS portfolio within this adjusted budget, prioritizing CAS that deliver higher co-benefit scores.

This secondary optimization provides flexibility to align financial investments with community values and additional sustainability goals.

Interpreting Optimization Results

After running the optimization(s), critically assess the resulting CAS portfolio:

- **Balance and Feasibility:** Does the distribution of CAS appear balanced and realistic?
- **Cost vs. Benefit:** Evaluate whether the incremental cost increase from enhancing co-benefits aligns well with community priorities and stakeholder expectations.

If results seem impractical or heavily skewed toward a single CAS type, revisit Module 2 to adjust minimum and maximum constraints to better reflect actual physical and social feasibility.

Once satisfied with the optimized results, proceed to Module 5, which summarizes and visually represents your portfolio outcomes, helping you effectively communicate these results to stakeholders and decision-makers.

Methods

Section 1. Percentile Storm Analysis Using Daymet Climate Data

Stormwater utilities across the United States often rely on percentile-based rainfall metrics, such as the 85th or 95th percentile daily rainfall depth—to determine the volume of runoff that must be managed or treated on-site. These metrics are commonly used to meet Municipal Separate Storm Sewer System (MS4) permit requirements and water quality goals. This tool provides standardized, county-level rainfall statistics to support consistent and defensible design decisions across jurisdictions.

The methodology follows U.S. Environmental Protection Agency (EPA) guidance outlined in *Technical Guidance on Implementing the Stormwater Runoff Requirements for Federal Projects under Section 438 of the Energy Independence and Security Act*.[iv]

Data Source

Daily precipitation data were obtained from the Daymet gridded climate dataset, produced by the Oak Ridge National Laboratory (ORNL) and supported by NASA's Earth Science Data and Information System (ESDIS).[v] Daymet provides daily weather estimates, including precipitation, on a 1 km x 1 km grid for North America, spanning from 1980 through the most recent complete calendar year.

For this tool, daily precipitation values from 1994 through 2023 (30 full calendar years) were extracted from Daymet at the geographic centroid of each U.S. county or county equivalent.[1] All values were converted from millimeters to inches to support U.S.-based design criteria.

Rainfall Event Screening

Daily precipitation values were filtered to exclude very small rainfall events that are unlikely to produce runoff. Specifically, only days with **≥ 0.1 inches** of precipitation were retained for analysis. This threshold is consistent with EPA recommendations, which suggest that small rainfall events generally do not exceed depression storage and initial abstraction and therefore do not contribute significantly to stormwater runoff.

Percentile Storm Depth Calculation

For each county, data were extracted from Daymet and the following daily rainfall percentiles were calculated 80th, 85th, 90th, and 95th percentiles. These values represent the daily rainfall depths that are greater than X% of all qualifying precipitation events over the 30-year period.

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[1] The county centroid file used for this analysis contained 3,135 counties, omitting eight recent county-equivalents—such as Alaska's Chugach and Copper River Census Areas, South Dakota's Oglala Lakota County, and Virginia's independent city of Covington. These gaps stem from post-2015 name changes or newly created census areas that were not yet included in the source dataset.

For example, the 90th percentile value is the depth that exceeds 90% of all recorded daily rainfall events above the 0.1-inch threshold.

Percentile storm depths are commonly used to design stormwater treatment practices intended to retain frequent, small-to-moderate storm events. Local and federal design standards often reference specific thresholds. For example, the 95th percentile event is identified in EPA guidance as an appropriate design target for water quality treatment under Section 438 of the Energy Independence and Security Act.

All county rainfall data is saved in the tool in the **REF_RainfallByCounty** tab.

Annual Rainfall and Volume Contribution

To provide data for valuation of certain co-benefits, the following information was also extracted from Daymet:

- **Average annual rainfall** (in inches per year), based on the total precipitation from qualifying events (≥ 0.1") averaged over the 30-year dataset.
- **Annual rainfall volume below each percentile** — the cumulative rainfall contributed by all events equal to or smaller than the 80th, 85th, 90th, 95th, and 99th percentiles.

Section 2. Developing Climate Projections Data by County

To accurately estimate future climate impacts and support stormwater management planning, this tool provides defensible, county-specific projections of average air temperature increases using data from the CMIP6-LOCA2 dataset. This dataset, spatially aggregated at the county level, was obtained from the U.S. Geological Survey (USGS) and covers the period from 1950 to 2100, allowing consistent comparison across historical and future climate conditions.[vi]

The primary data source for this analysis is the CMIP6-LOCA2 monthly dataset, specifically the "CMIP6-LOCA2 1950–2100 County2023" NetCDF file, publicly accessible via USGS (DOI: 10.5066/P1N9IRWC). The dataset includes projections under three representative emissions scenarios (SSP245, SSP370, SSP585) from the Climate Model Intercomparison Project Phase 6 (CMIP6). Each scenario represents different assumptions about future greenhouse gas emissions, global policies, and socio-economic development trajectories. The USGS pre-processed these data, spatially averaging the original high-resolution (6 km) LOCA2 grid cells to U.S. county boundaries (as defined by the TIGER 2023 dataset) using the GDPtools software package.

Our processing approach began by reading the temperature data (“tas”, representing mean near-surface air temperature) into Python using the xarray library for efficient handling of large multidimensional datasets. The analysis focused on one baseline period (1981–2010) and three future periods: near-term (2025–2049), mid-century (2050–2074), and late-century (2075–2099). The baseline period and future periods match those used by USGS in its interactive National Climate Change Viewer, which makes a summary of these data available online using an interactive map.

For each climate scenario and future period, we computed an unweighted multi-model mean temperature across all available model ensemble members (72 realizations). This approach assumes equal skill among models, providing a transparent and straightforward estimate, though this approach could be refined in future.

Temperature projections were calculated as the average monthly temperature over each 25-year future window, smoothed into multi-annual means to reduce seasonal variability. Differences (delta changes) from the baseline period were then derived by subtracting the baseline temperature average from each future period average. Results were exported and stored in CSV format, providing county-level baseline and future period average temperatures, scenario details, and calculated delta changes. These data are incorporated directly into the stormwater decision-support tool under the reference tab REF_ClimateByCounty.

Quality assurance checks included random validation of temperature projections against the official USGS National Climate Change Viewer (NCCV). Results were very close to the NCCV with small differences, likely because NCCV includes a bias correction step, while our analysis did not.

While we believe county-level climate data is appropriate for a national screening tool like the one being developed, the county-level spatial aggregation does smooth out smaller-scale climatic variations, particularly in regions with significant topographic diversity. Users requiring finer-scale data should consult the original high-resolution LOCA2 dataset. Future iterations of the tool could incorporate bias correction and model weighting to further refine temperature projections.

Section 3. Delta Change Factors & the Clausius-Clapeyron Relationship

The Delta Change Factor (DCF) approach used in this tool is a straightforward and scientifically grounded method for adjusting historical design-storm rainfall depths to future climate conditions. The DCF builds on the fundamental thermodynamic principle known as the Clausius-Clapeyron relationship, which describes how the water-holding capacity of air increases as temperature rises. Specifically, this relationship shows that air can hold roughly 6–7% more moisture per each 1°C increase in temperature. Since atmospheric moisture is a key driver of rainfall intensity, warming typically leads to more intense precipitation events, all else being equal.

In practice, the DCF is applied using the simplified linear formula:

$$DCF = 1 + 0.07 \times \Delta T$$

where ΔT is the future projected temperature increase derived from county-level CMIP6 LOCA-2 climate data (see Methods Section 2 above) in degrees Celsius. Users select a "Low," "Medium," or "High" scenario based on their risk tolerance and planning horizon, which corresponds directly to these projected temperature increases. For instance, selecting a "Medium" DCF for mid-century conditions under an intermediate climate scenario (SSP3-7.0) might use a ΔT of around 2.7°C, resulting in about a 19% increase in rainfall depth for your selected design storm (1 + 0.07 × 2.7 = 1.19).

This temperature-based scaling provides a transparent, robust, and simple alternative to the precipitation estimates in climate models. The DCF method has been widely adopted for climate-informed water resource planning due to its clarity, ease of use, and strong scientific foundation, as recommended in recent water-sector literature such as Maimone et al. (2023).[vii]

It's important to note that the Clausius-Clapeyron scaling represents a thermodynamic guideline, not an exact predictor. Real-world observations indicate that local storm responses can vary significantly, sometimes exceeding the standard 7% per degree ("super-CC" scaling) or falling below it, depending on factors such as storm type (convective vs. frontal), local atmospheric dynamics, and landscape features. Consequently, while the DCF values generated by this tool serve as useful planning-level estimates, utilities addressing critical infrastructure vulnerabilities may wish to complement this screening approach with more detailed, localized hydrologic modeling to refine their understanding of future storm intensities and flood risks.

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[i] Nowak, D. J., & Greenfield, E. J. (2012). Tree and impervious cover change in US cities. Urban Forestry & Urban Greening, 11(1), 21-30.

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