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WMOST Climate Scenario Viewer and Comparison Post Processor

(Version 1: July 31, 2018)

Office of Research and Development
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ScenCompare
WMOST Climate Scenario Viewer and Comparison Post Processor

(Version 1; July 31, 2018)

Instructions

ScenCompare is a MS-Excel application designed to view and compare WMOST scenario results. ScenCompare is compatible with MS-Excel (versions 2010, 2013 and 2016). The tool is specifically intended to allow comparison of WMOST results for different climate scenarios, but ScenCompare more generally allows comparison and evaluation of any sets of WMOST results to understand the effects of varying climate, land use, and other model inputs on the set of management actions selected by WMOST to meet the specified management goal at the lowest cost. For example, ScenCompare can assist users interested in applying WMOST as part of Robust Decision Making (RDM) approaches for identifying vulnerabilities, and managing goals and risks, in the face of uncertain future conditions. Under RDM-type approaches, the outcome of a prescribed management strategy, such as a Watershed Implementation Plan (WIP) to meet Total Maximum Daily Load (TMDL) requirements, can be tested against multiple scenarios of future changes in temperature and rainfall and then analyzed within ScenCompare to determine under what conditions the strategy might be expected to fail to meet performance requirements. Further, ScenCompare provides WMOST users access to all outputs generated by a WMOST run, thereby expanding on the set of standard outputs visible in the WMOST v3 interface.

These instructions focus on the process for loading WMOST results into ScenCompare, generating summary tables comparing decision variables, and generating time series plots of user-selected variables across scenarios. ScenCompare users should already be familiar with WMOST model outputs being processed. Please refer to the WMOST documentation for details on variables and modeled components included in WMOST output files and available for processing with ScenCompare.

1 Workbook Organization

ScenCompare is an Excel workbook that uses customized Visual Basic for Applications (VBA) code to automate key tasks. The initial workbook includes:

- Introduction tab: Describes the purpose of ScenCompare and allows the user to navigate to the Controls, Variable Definitions and Loaded Scenarios tabs (the user can also navigate to the tabs by clicking on them at the bottom of the screen).
- Controls tab: Provides access to steps in compiling and analyzing WMOST data.

- Variable Definitions tab: Provides a description of the WMOST variables in the output data.
- Loaded Scenarios tab: Provides the inventory of output files imported by the user
- Model Results tab: Provides the WMOST model results output for each loaded file
- Model Input Data tab: Provides the model input data for each loaded file

Section 2 describes the steps involved in compiling and analyzing WMOST data. Note that the user can also use all standard Excel functions and capabilities from within ScenCompare to customize graphics or tables, perform calculations, etc.

2 Controls

2.1 Load WMOST Scenario Data

To load WMOST Scenario Input Data and Results into ScenCompare, click on the leftmost button on the Controls tab labeled "Load WMOST Scenario Data." When prompted, select the model *Specifications and Results* file. Note that the *Specifications and Results* file is a log file generated by WMOST during a model run and saved to the same file folder that contains the WMOST model. The log file contains the model inputs and results for the run.

ScenCompare adds the WMOST scenario outputs to the Model Results tab, the WMOST input data to the Model Input Data tab, and the name of the file and other model details to the Loaded Scenarios tab.

Repeat these steps to load the data for other WMOST model runs as many times as needed to import the desired data. Note that you may add results to ScenCompare at any time.

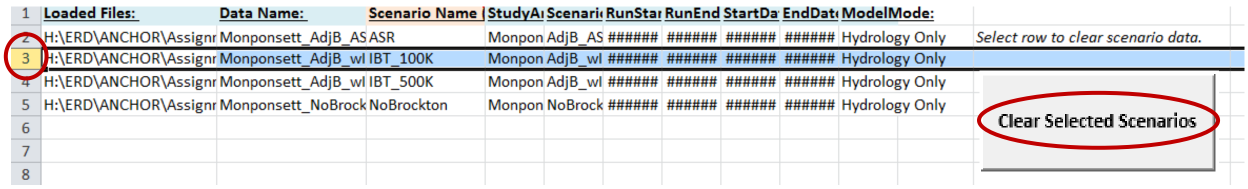
ScenCompare verifies that any data file loaded after the first data file has the same number of land uses, land use sets, water users and time steps. Differences in these variables leads to mismatches in the variable order and incorrect comparisons of data. If a difference is found, ScenCompare gives the option to keep or discard the data that was just loaded. It is recommended that you discard the data.

ScenCompare automatically fills in the average annual precipitation and temperature, if you used the hydrology module when developing the WMOST scenarios or used the Hydro-Climate Automation module (HCAM). If you developed the data manually, you can enter precipitation and temperature statistics on the Loaded Scenarios tab. ScenCompare uses this information for some of the graphs (see Section 2.3).

Note that you may also remove scenarios from the Loaded Scenarios tab by selecting the row(s) on this tab and clicking the button on the right side of the tab labeled “Clear Selected Scenarios”.[1]

See Figure 1 below for an example of how to select and delete data for a scenario. To delete Scenario 2, a user would select the row that contains Scenario 2 or the “Data Name” for the second scenario listed, and then click the “Clear Selected Scenarios” button.

Figure 1: Example of selection of scenario for deletion



TIP: Note that the Model Results and Model Input Data tabs provide the detailed WMOST outputs and inputs, respectively, for each scenario. Because many of the model variables are time series, the data set is extensive (thousands of values). You can use standard Excel filter tools (accessible through the Data menu) to hide/show a subset of variables you are interested in. You can also use standard equations in Excel to quickly identify variables that take on different values across the scenarios. For convenience, ScenCompare provides a pre-calculated column that determines whether differences exist between scenarios.

TIP: You can use the “Data Difference” column on the Model Results and Model Input Data tabs to filter for variables that assume the same or different numerical values across the scenarios, with Data Difference flags of 0 and 1, respectively.

2.2 Compare Decision Variables Across Scenarios

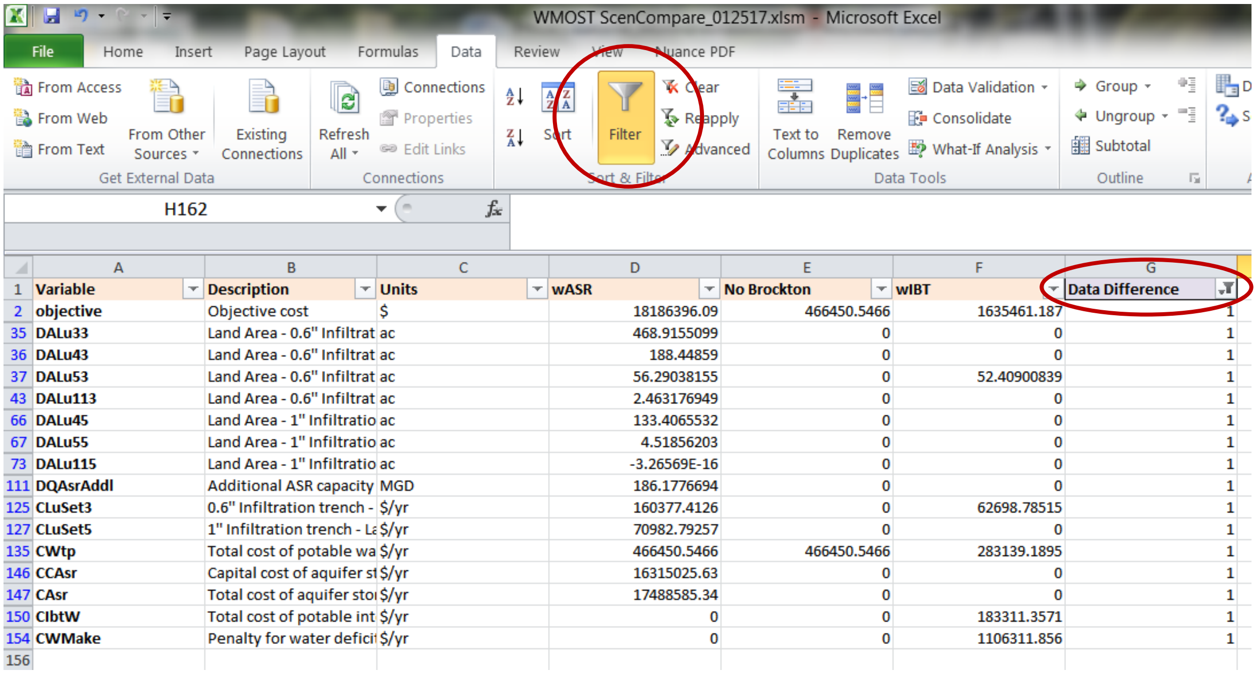
ScenCompare can be used to compare decision variables across scenarios. These are variables representing the least-cost combination of best management practices (BMPs) to meet the management objective (e.g., streamflow minimum threshold).

To compare all decision variables across scenarios, click on the button on the Controls tab labeled “Compare Scenario Decisions.” This action will create a new tab called Table_Comparison containing the values of decision variables from all model runs loaded into ScenCompare. Note that the second column (“Description”) describes each variable and the third column (“Units”) specifies the unit of measure for each variable.

The rightmost column in the sheet (“Data Difference”) contains a flag identifying whether there are differences in variable values across any of the scenarios. A Data Difference value of 1 indicates that at least one of the scenarios differs from the others for that variable.

[1] Note that if you have created comparison tables and graphs in Steps 2 and 3 on the Controls tab (see Sections 2.2 and 2.3 for details) and later delete a scenario, you will need to regenerate the data tables and time series to ensure that the tables reflect only the remaining scenarios.

Figure 2: Example of filter selecting variables that take different values among three scenarios. In this example, the scenarios show differences in total operating costs, management approaches selected (e.g., stormwater BMPs and ASR) and level of implementation, and associated costs.



	Variable	Description	Units	wASR	No Brockton	wIBT	Data Difference
2	objective	Objective cost	$	18186396.09	466450.5466	1635461.187	1
35	DALu33	Land Area - 0.6" Infiltrat	ac	468.9155099	0	0	1
36	DALu43	Land Area - 0.6" Infiltrat	ac	188.44859	0	0	1
37	DALu53	Land Area - 0.6" Infiltrat	ac	56.29038155	0	52.40900839	1
43	DALu113	Land Area - 0.6" Infiltrat	ac	2.463176949	0	0	1
66	DALu45	Land Area - 1" Infiltratio	ac	133.4065532	0	0	1
67	DALu55	Land Area - 1" Infiltratio	ac	4.51856203	0	0	1
73	DALu115	Land Area - 1" Infiltratio	ac	-3.26569E-16	0	0	1
111	DQAsrAddl	Additional ASR capacity	MGD	186.1776694	0	0	1
125	CLuSet3	0.6" Infiltration trench -	$/yr	160377.4126	0	62698.78515	1
127	CLuSet5	1" Infiltration trench - La	$/yr	70982.79257	0	0	1
135	CWtp	Total cost of potable wa	$/yr	466450.5466	466450.5466	283139.1895	1
146	CCAsr	Capital cost of aquifer st	$/yr	16315025.63	0	0	1
147	CAsr	Total cost of aquifer stoı	$/yr	17488585.34	0	0	1
150	CIbtW	Total cost of potable int	$/yr	0	0	183311.3571	1
154	CWMake	Penalty for water deficit	$/yr	0	0	1106311.856	1
156							

__TIP:__ You can use standard Excel filter tools (accessible through the Data menu) to hide/show a subset of variables you are interested in, or to show only the variables that have Data Difference of 1.

2.3 Compare Overall Costs across Scenarios

Clicking on the "Make Climate Graphs" on the Table_Comparison tab (see Section 2.2) creates a new tab called ClimateGraph_objective. This tab contains three climate plots:

1) a scatterplot that charts the objective cost versus average annual precipitation,
2) a scatterplot that charts the objective cost versus average annual temperature, and
3) a bubble plot that charts the objective costs versus total annual precipitation and average annual temperature.

The "objective" value is the total annualized cost of all watershed management actions taken to meet the specified objective (i.e., meeting water demand subject to physical constraints and water quantity and/or quality targets).

As discussed in Section 2.1, if you did not use the hydrology module in WMOST, the model *Specifications and Results* file does not automatically include statistics for average annual precipitation and average annual temperature. This means that ScenCompare cannot automatically extract the information needed to create the climate graphs. To rectify this issue, you can enter the precipitation and temperature statistics for each scenario on the Loaded Scenarios tab before creating the tables and ScenCompare will use those values to create the climate graphs.

2.4 Compare Time Series Variables Across Scenarios

ScenCompare can also be used to compare time series variables across scenarios. These are variables representing time-dependent flows or stocks in the modeled watershed components, listed on the Controls tab.

To compare time series variables across scenarios, place the cursor in the first variable of interest in the list under Step 3 on the Controls tab, and click on the button labeled "Create Tables and Graphs for Selected Variables"[2] to the right of the data columns. This action creates a new tab called Table_*nn* where *nn* is the name of the selected variable. This new tab provides summary statistics for the selected variables for each scenario in ScenCompare (e.g., minimum, maximum, average, and number of observations greater than 0 (as the default threshold)) along with values for each time step.

This action also creates three plots on the time series variable tab:

1) a time series plot of the variable over the time period,
2) a histogram of the count of time steps (e.g., number of days if WMOST was run using a daily time step) for which the variable takes a value greater than the "Count Threshold" for each scenario, and
3) a box-and-whisker plot that shows the minimum, 1st quartile, median, 3rd quartile, and maximum for each scenario.

You can use the button on the right, "Make Climate Graphs", to create a new tab called ClimateGraph_*nn* that contains three climate graphs that compare the *average* value over the entire time series across the scenarios. Refer to Section 2.3 for more details on the climate graphs and how they are created.

TIP: You can change the "Count Threshold" from its default value of 0 to any number, and the tab adjusts the count statistics and histogram to reflect the new threshold.

TIP: You can use standard Excel tools to add or modify the formatting of the basic plot generated automatically by ScenCompare.

2.5 Compare Land Management Variables Across Scenarios

ScenCompare can also be used to compare land management decisions – such as decisions to conserve land as undeveloped or to implement stormwater BMPs – across scenarios. The comparison is done using the Table_Comparison tab.

As further described in the WMOST documentation, WMOST represents land use using hydrologic response units (HRUs) and land use management options using a series of HRU sets. Land use management option variables have units in acres.

[2] Note that you may select multiple variables to be processed at the same time by holding the control key and clicking on all desired variable names before clicking on the button.

The names of land use management variables all begin with "DALu" and are followed by two numeric identifiers. The first identifier is the HRU number and the second identifier is the HRU set number. For example, DALu12 represents the land use allocation of HRU 1 in HRU Set 2. The convention is the same for double digit HRU or HRU set numbers. For example, DALu1010 represents the land use allocation of HRU 10 in HRU set 10. The variables are described in the second column on the Table_Comparison tab and in the Variable Definitions tab based on the management option and the HRU. For example, Land Area - 0.6" Infiltration trench, "Medium to low density residential, Sand and Gravel" contains the acres of medium to low density residential land, on sand and gravel (the HRU represented by the combination of land use and soil type) on which WMOST decided to implement a 0.6" infiltration trench.

Each of the land use management options (HRU sets) has an associated cost variable that contains the cost associated with the decision. The variables are named CLuSet#, where # is the number of the HRU Set.

To compare land use allocation variables, you must look at each land use management set individually. By convention, the first land use management set represents land conservation decisions. All other sets are related to stormwater management decisions.

- Land Conservation: One of the management options available in WMOST is the decision to conserve undeveloped land. The decision essentially reallocates baseline land use to undeveloped land uses, keeping the total land area the same. The final land area allocation is reported through the first set of DALu variables (all DALu variables for HRU set 1). To determine whether land area was conserved, you can first look at the CLUSet1 variable to see if it is greater than $0 for any of the scenarios, which would indicate that WMOST incurred costs to conserve land.[3] To determine how much land area was conserved, you should then look at the DALu variables and compare values to the baseline acres you had specified in your WMOST run.[4] The resulting difference is the change due to land conservation. A positive difference means more land was conserved, and a negative difference means the land was converted to undeveloped areas or conserved.[5]
- Stormwater Management: WMOST may also implement stormwater BMPs on developed HRU areas. The areas managed using stormwater BMPs are reported in the remaining DALu variable sets. The values represent the number of acres receiving the type of stormwater BMP defined by the HRU set, e.g., acres of medium to low density residential on sand and gravel managed using a 0.6" Infiltration trench. The number of acres will be a portion of the HRU area reported in the first management set described above. WMOST may select multiple stormwater BMP types for any given scenario but the total acres managed across the HRU sets cannot exceed the total area, i.e., stormwater BMPs are mutually exclusive and WMOST applies only one type of BMP to any given parcel of land.

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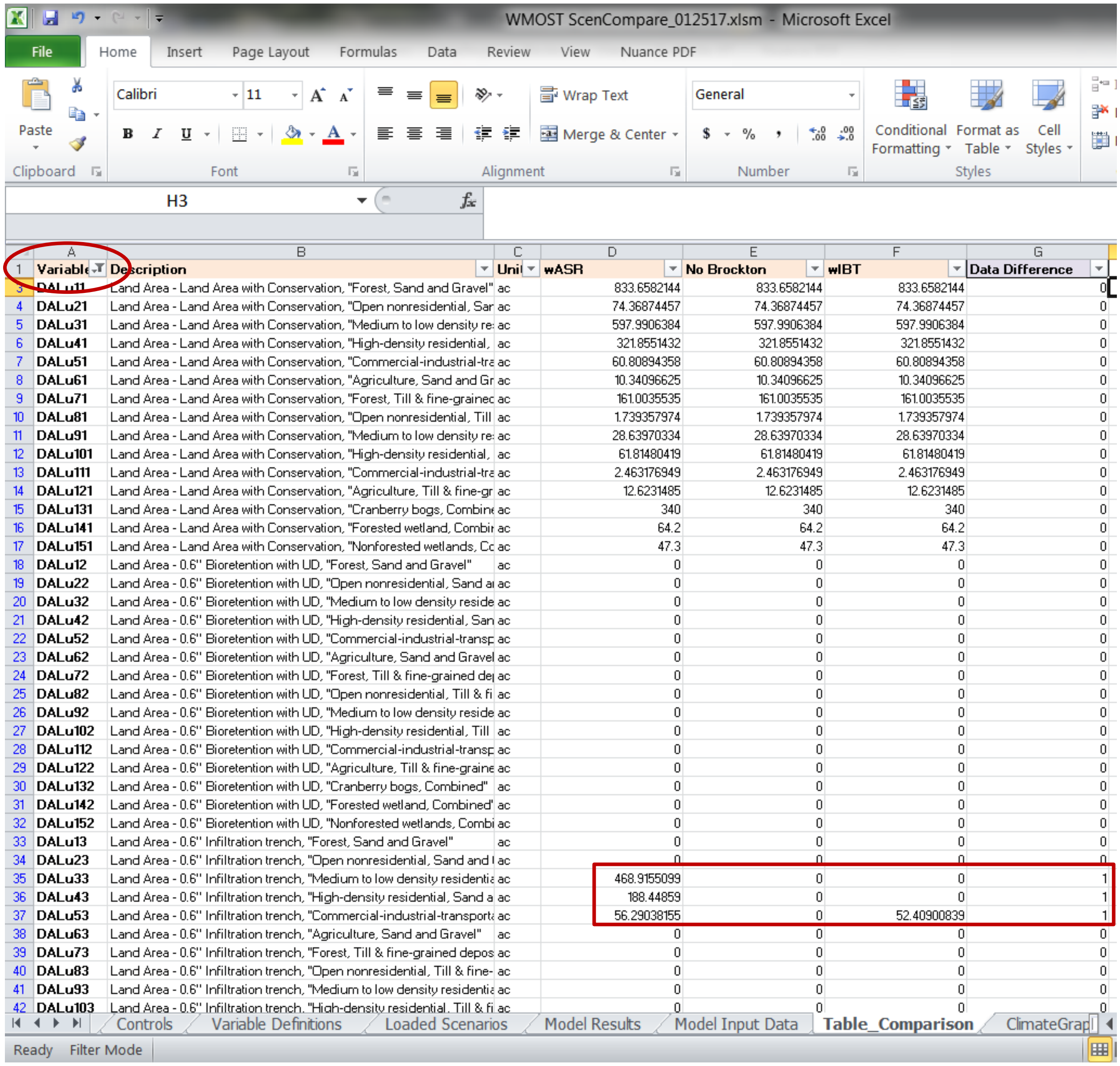
[3] This presumes that you specified non-zero costs to acquire land for conservation in your WMOST inputs.

[4] Note that the baseline HRU acres are reported in the Model Input Data tab, using the variable ALuBase and HRU number.

[5] Note that decisions to conserve land will not be flagged as a change in the Data Difference column in Table_Comparison tab unless the allocations differed across scenarios.

TIP: To only view results that relate to land use management, you can use MS-Excel filter tool to select the relevant variables: DALu## and CLuSet#.

Figure 3: Example of selected variables related to land use management decisions. The screen shows differences in the number of acres managed using 0.6" infiltration trenches for several HRUs.



	Variable	Description	Unit	wASR	No Brockton	wIBT	Data Difference
3	DALu11	Land Area - Land Area with Conservation, "Forest, Sand and Gravel"	ac	833.6582144	833.6582144	833.6582144	0
4	DALu21	Land Area - Land Area with Conservation, "Open nonresidential, Sar	ac	74.36874457	74.36874457	74.36874457	0
5	DALu31	Land Area - Land Area with Conservation, "Medium to low density re:	ac	597.9906384	597.9906384	597.9906384	0
6	DALu41	Land Area - Land Area with Conservation, "High-density residential,	ac	321.8551432	321.8551432	321.8551432	0
7	DALu51	Land Area - Land Area with Conservation, "Commercial-industrial-tra	ac	60.80894358	60.80894358	60.80894358	0
8	DALu61	Land Area - Land Area with Conservation, "Agriculture, Sand and Gr	ac	10.34096625	10.34096625	10.34096625	0
9	DALu71	Land Area - Land Area with Conservation, "Forest, Till & fine-grainec	ac	161.0035535	161.0035535	161.0035535	0
10	DALu81	Land Area - Land Area with Conservation, "Open nonresidential, Till	ac	1.739357974	1.739357974	1.739357974	0
11	DALu91	Land Area - Land Area with Conservation, "Medium to low density re:	ac	28.63970334	28.63970334	28.63970334	0
12	DALu101	Land Area - Land Area with Conservation, "High-density residential,	ac	61.81480419	61.81480419	61.81480419	0
13	DALu111	Land Area - Land Area with Conservation, "Commercial-industrial-tra	ac	2.463176949	2.463176949	2.463176949	0
14	DALu121	Land Area - Land Area with Conservation, "Agriculture, Till & fine-gr	ac	12.6231485	12.6231485	12.6231485	0
15	DALu131	Land Area - Land Area with Conservation, "Cranberry bogs, Combine	ac	340	340	340	0
16	DALu141	Land Area - Land Area with Conservation, "Forested wetland, Combir	ac	64.2	64.2	64.2	0
17	DALu151	Land Area - Land Area with Conservation, "Nonforested wetlands, Cc	ac	47.3	47.3	47.3	0
18	DALu12	Land Area - 0.6" Bioretention with UD, "Forest, Sand and Gravel"	ac	0	0	0	0
19	DALu22	Land Area - 0.6" Bioretention with UD, "Open nonresidential, Sand ai	ac	0	0	0	0
20	DALu32	Land Area - 0.6" Bioretention with UD, "Medium to low density reside	ac	0	0	0	0
21	DALu42	Land Area - 0.6" Bioretention with UD, "High-density residential, San	ac	0	0	0	0
22	DALu52	Land Area - 0.6" Bioretention with UD, "Commercial-industrial-transp	ac	0	0	0	0
23	DALu62	Land Area - 0.6" Bioretention with UD, "Agriculture, Sand and Gravel	ac	0	0	0	0
24	DALu72	Land Area - 0.6" Bioretention with UD, "Forest, Till & fine-grained de|	ac	0	0	0	0
25	DALu82	Land Area - 0.6" Bioretention with UD, "Open nonresidential, Till & fi	ac	0	0	0	0
26	DALu92	Land Area - 0.6" Bioretention with UD, "Medium to low density reside	ac	0	0	0	0
27	DALu102	Land Area - 0.6" Bioretention with UD, "High-density residential, Till	ac	0	0	0	0
28	DALu112	Land Area - 0.6" Bioretention with UD, "Commercial-industrial-transp	ac	0	0	0	0
29	DALu122	Land Area - 0.6" Bioretention with UD, "Agriculture, Till & fine-graine	ac	0	0	0	0
30	DALu132	Land Area - 0.6" Bioretention with UD, "Cranberry bogs, Combined"	ac	0	0	0	0
31	DALu142	Land Area - 0.6" Bioretention with UD, "Forested wetland, Combined"	ac	0	0	0	0
32	DALu152	Land Area - 0.6" Bioretention with UD, "Nonforested wetlands, Combi	ac	0	0	0	0
33	DALu13	Land Area - 0.6" Infiltration trench, "Forest, Sand and Gravel"	ac	0	0	0	0
34	DALu23	Land Area - 0.6" Infiltration trench, "Open nonresidential, Sand and I	ac	0	0	0	0
35	DALu33	Land Area - 0.6" Infiltration trench, "Medium to low density residenti	ac	468.9155099	0	0	1
36	DALu43	Land Area - 0.6" Infiltration trench, "High-density residential, Sand a	ac	188.44859	0	0	1
37	DALu53	Land Area - 0.6" Infiltration trench, "Commercial-industrial-transport	ac	56.29038155	0	52.40900839	1
38	DALu63	Land Area - 0.6" Infiltration trench, "Agriculture, Sand and Gravel"	ac	0	0	0	0
39	DALu73	Land Area - 0.6" Infiltration trench, "Forest, Till & fine-grained depos	ac	0	0	0	0
40	DALu83	Land Area - 0.6" Infiltration trench, "Open nonresidential, Till & fine-	ac	0	0	0	0
41	DALu93	Land Area - 0.6" Infiltration trench, "Medium to low density residenti	ac	0	0	0	0
42	DALu103	Land Area - 0.6" Infiltration trench, "High-density residential, Till & fi	ac	0	0	0	0

3 Example Application for Wading-Threemile Watershed

Below is an example of an application of ScenCompare using a WMOST case study on the Wading-Threemile River Watershed in the Taunton Basin in Massachusetts. The example provides a guide for setting up and loading scenario runs in ScenCompare (Section 3.1), using the tool's functions and evaluating the scenario data (Section 3.2), and analyzing the various land use management decisions in WMOST (Section 3.3).

3.1 Getting Started

The specific purpose of ScenCompare is to provide users with an interface and tool for comparing WMOST results for different future climate scenarios. Therefore, this example details the differences in WMOST management decisions between the baseline and future climate scenarios.

However, in general, the functions of this tool can be used to evaluate any set of WMOST results and help you to understand the effects of model inputs on the management actions selected by the WMOST optimization model, which meets specified management goals at the lowest cost. The following section discusses the development of the WMOST scenarios for the Wading-Threemile River Watershed, and how those scenarios are loaded into ScenCompare to prepare the tool for analysis.

3.1.1 Run WMOST Scenarios

Data for this example come from the Wading-Threemile subwatershed in the upper Taunton River basin in Massachusetts (https://www.mass.gov/service-details/taunton-river-watershed). The Taunton River watershed is the second largest watershed in Massachusetts and the largest freshwater contributor to Narragansett Bay. The Taunton River is the longest undammed tidal river in New England, supporting the largest herring run in the state. In 2009 it was designated as a Partnership Wild and Scenic River by the National Park Service. In these Partnership Wild and Scenic Rivers communities protect their own outstanding rivers and river-related resources through a collaborative approach. Challenges faced by communities in the Taunton include protection of outstanding natural resource areas, flooding, sea level rise and storm surges, water body impairments related to eutrophication, water supply constraints, and the need to protect the downstream Hope Bay (RTI 2014). This case study was developed in cooperation with a consortium of regional development agencies (Southeast Regional Planning and Development District, SERPDD and the Metropolitan Area Planning Council, MAPC) and nongovernmental organizations (Manomet, the Nature Conservancy, and Mass Audubon) which had received funding from EPA Region 1 from the Healthy Communities Grant Program to assess the benefits of green infrastructure within the watershed and to educate the public about those benefits.

The EPA ORD team has applied WMOST v3 to the two subwatersheds within the upper Taunton. A two-stage objective was established: first, to minimize costs (capitol plus operations and maintenance) for near term planning, and second, to minimize future costs under projected growth and climate scenarios. Goals and constraints considered in Stage 1 included ecoregional targets for total phosphorus in lakes and flowing waters, a reduction in total nitrogen loads to the Mt Hope Bay, and maintenance of minimum low flows for a stable water supply and to support fish populations. Management options under consideration include land conservation, stormwater best management practices (BMPs, including green infrastructure), forested riparian buffer restoration, repair of water infrastructure leaks, upgrades in wastewater treatment, water conservation, and aquifer storage and recharge. A comparison of different traditional (“gray”) and nature-based (“green) stormwater BMPs showed that infiltration basins were the most cost-effect option to meet water quality goals. Initial results were shared with the Resilient Taunton Watershed Network (RTOWN).

WMOST v3 is now being applied to future growth and climate scenarios to identify the most cost-effective management actions. Future projections of mean annual temperature and mean annual precipitation were obtained from the general circulation models (GCMs) included in the 5th Coupled Model Intercomparison Project (CMIP5) for two of the representative concentration pathways (rcp-4.5 and rcp-8.5) adopted by the Intergovernmental Panel on Climate Change (IPCC) in its 5th Assessment Report (IPCC 2014). The pathways in this report correspond to changes in radiative forcing relative to pre-industrial values (i.e. +2.6, +4.5, +6.0, +8.5 W/m^2) that are possible in year 2100 based on projections of greenhouse gas emissions (IPCC 2014). These data were corrected for bias and statistically downscaled to a regional scale (Brekke et al. 2013). Four combinations of changes in temperature and precipitation (ΔT, ΔP) were selected for this study to roughly bound the extremes of ΔT and ΔP reflected by the collection of GCMs, thereby representing a range of possible future climate scenarios, and an average of these scenarios was also calculated. A new set of input hourly temperature and precipitation data was generated for each scenario by uniformly adjusting the baseline temperature and precipitation records by the corresponding ΔT (absolute) and ΔP (percentage) values, respectively. Using the adjusted temperature and precipitation data, hourly runoff rates were generated for each scenario using SWMM. Similarly, the temperature, precipitation, and runoff data were used in SWMM to generate four new sets of hourly nitrogen and phosphorus loading rates. In the following, climate change scenarios are labeled as General Circulation Model (GCM) ΔT (°F)/ ΔP (%).

One of the objectives of the WMOST Wading-Threemile case study is to analyze the robustness of WMOST management decisions over these future climate scenarios. To do this, we created a series of WMOST runs based on a historical dry year (2002) and five climate scenarios (one median projection and four bounding scenarios). Bounding scenarios were identified using the US EPA LASSO tool (Morefield 2016), focusing on 21 of the models that had been shown to perform well for New England in hindcasting exercises (Sheffield et al. 2015). The average projection was ΔT = +4.4°F/ΔP = +10.1%. The bounding scenarios were based on the FGOALS-s2, realization 3 (GCM ΔT = +6.2°F/ΔP = +19.4%), IPSL-CM5A_LR, realization 1 (GCM ΔT = +5.0°F/ΔP = -1.7%), MPI-ESM-LR realization 2 (GCM ΔT = 3.7°F/ ΔP = -2.2%), and CSIRO-Mk3-6-0 realization 1 (GCM ΔT = +3.3°F/ΔP = +19.5%) model runs[6].

[6] CSIRO-Mk3-6-0 is from the Commonwealth Scientific and Industrial Research Organisation in collaboration with the Queensland Climate Change Centre of Excellence; FGOALS-s2 is from the LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences; IPSL-CM5A-LR is from Institut Pierre-Simon Laplace; MPI-ESM-LR is from Max Planck Institute for Meteorology (MPI-M).

We ran the historical climate and five future climate scenarios (four bounding and one median) for three types of comparisons:

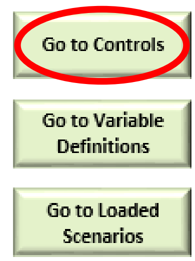
1. Baseline (baseline land use with no land management options);
2. Optimal stormwater BMP implementation for 2002 (fixed set of optimal stormwater land use BMPs for climate scenario runs); and
3. Optimal riparian zone implementation for 2002 (selection of 10 potential riparian buffer land conversions from developed land to forest).

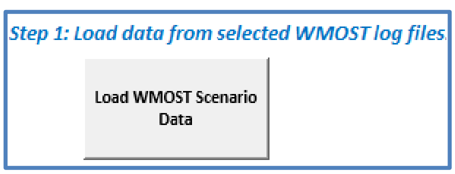
The TN loading target (1,156 lbs N) was turned off for the baseline run (for the historical scenarios and the climate scenarios), as well as in the climate scenarios for the stormwater BMP and riparian zone runs to see if the future scenarios would meet the target given optimal BMPs selected for 2002. This set of runs was designed to test how robust the original solution was.

In addition to the three comparisons listed above, we also compared the differences in decisions between the historical baseline and two climate scenarios (the median and extreme) with the TN loading target turned on and a stormwater BMP set available (Section 3.3.2). This set of comparisons evaluated whether optimal management practices would change given climate change scenarios.

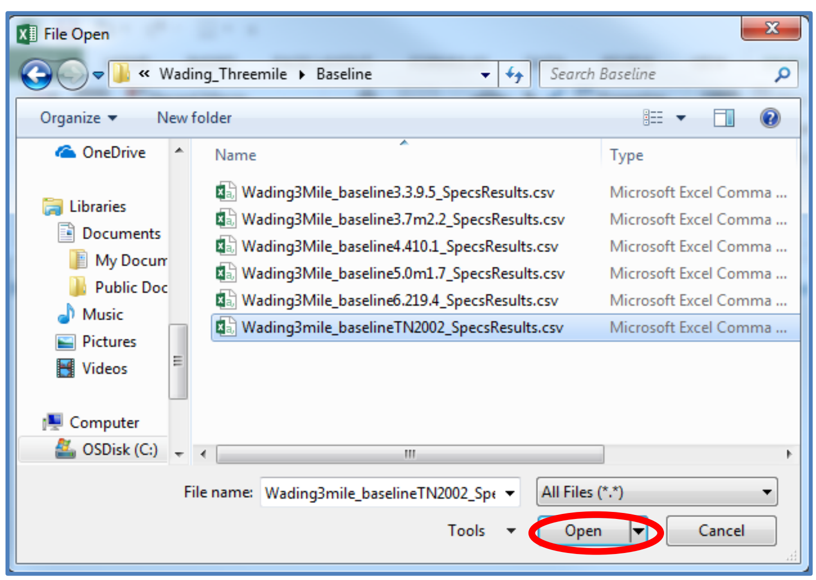
3.1.2 Load WMOST Data

Once you have completed your scenario runs and prepared the Scenario Log Files in WMOST (see WMOST V3 User Guide[7] for more details), open the ScenCompare application. From the Introduction tab, navigate to the Controls tab. You can also use the Introduction tab to navigate to the Variable Definitions tab and the Loaded Scenarios tab.



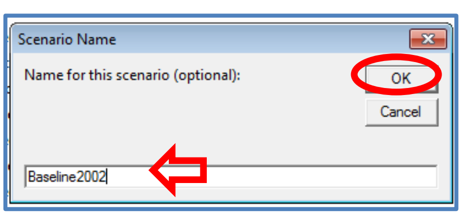


On the Controls tab, click the "Load WMOST Scenario Data" button to open a file selection dialog box. In the dialog box,



select the Scenario Log File you created for your baseline run and click "Open".

After opening your file, another dialog box will pop up, prompting you to name this scenario. Enter a



[7] Available from https://www.epa.gov/ceam/wmost-30-download-page

name in the text box that will help you quickly identify the scenario, if you would like one (this step is optional). Then, click “OK” to load the scenario.

Once the data is loaded, you can view the summary information for the scenario on the Loaded Scenarios tab, which includes the average annual precipitation and average temperature statistics for the model run. If these columns have “NA” for the statistics, enter the average annual precipitation and average temperature statistics for the scenario in their given columns. This tab also includes information, including the file path of the data file, study area name, scenario name, and start and end dates.

Loaded Scenarios tab

	A	B	C	D	E	F	G	H	I	J	K
1	Loaded Files:	Data Name:	Scenario Name (edit here):	StudyAreaName:	ScenarioName:	RunStartTime:	StartDate:	EndDate:	ModelMode:	Avg Annual Precip	Avg Temperature
2	\\camfile01.corp.abtas	Wading3mile_TN	Baseline2002	Wading3mile	TN2002baselin	7/1/2018 12:35	1/1/2002	12/31/2002	Hydrology & Loa	42.05	52.697
3											

You can view the input data and results in the Model Input Data and Model Results tabs, respectively, for the scenario you just loaded.

Repeat the steps above to load as many scenarios as you would like. You can use the “Return to Controls” button on the Loaded Scenarios tab to easily return to the Controls tab to load additional scenario data files. If you want to remove a scenario, select the row of that scenario and click the “Clear Selected Scenarios” button. A message box will pop up asking you if you are sure you want to delete the data for that scenario.

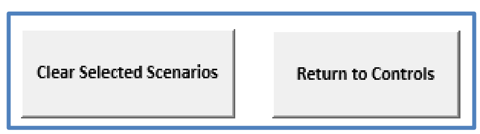
Model Input Data tab

	A	B	C	D	E	F
1	Wadir	Wadir	Wadir	Wadir	mile_TN2002baseline	
2	Variable	Identifie	Value	Units		
3	AvgAnnu	None	42.05	total inches per year		
4	AvgTemp	None	52.697	deg F		
5	NDateHy	None	365	time steps in model		
6	Dt	None	1	days in time step		
7	NLu	None	16	# HRUs		
8	NLuName	1	forest sa	-		
9	NLuName	2	open nor	-		
10	NLuName	3	MLD res s	-		
11	NLuName	4	MHHD re	-		
12	NLuName	5	comindtr	-		
13	NLuName	6	ag sand	-		
14	NLuName	7	forest til	-		
15	NLuName	8	open nor	-		
16	NLuName	9	MLD res t	-		
17	NLuName	10	MHHD re	-		
18	NLuName	11	comindtr	-		
19	NLuName	12	ag till	-		
20	NLuName	13	cranberry	-		
21	NLuName	14	forested	-		
22	NLuName	15	nonfores	-		
23	NLuName	16	water	-		
24	ALuBase	1	13647	acre		
25	ALuBase	2	2296.36	acre		
26	ALuBase	3	5948.68	acre		
27	ALuBase	4	973.221	acre		
28	ALuBase	5	2536.94	acre		
29	ALuBase	6	634.234	acre		
30	ALuBase	7	12553.5	acre		
31	ALuBase	8	1082.57	acre		
32	ALuBase	9	2821.25	acre		

Model Results tab

	A	B	C	D	E	F
1	Wadir	Wadir	Wadir	Wadir	mile_T	002baseline
2	Variable	Identifie	Value	Units		
3	objective	None	2261.31	$/yr		
4	DALu11	None	13647	ac		
5	DALu21	None	2296.36	ac		
6	DALu31	None	5948.68	ac		
7	DALu41	None	973.221	ac		
8	DALu51	None	2536.94	ac		
9	DALu61	None	634.234	ac		
10	DALu71	None	12553.5	ac		
11	DALu81	None	1082.57	ac		
12	DALu91	None	2821.25	ac		
13	DALu101	None	448.338	ac		
14	DALu111	None	1104.44	ac		
15	DALu121	None	240.572	ac		
16	DALu131	None	98.4156	ac		
17	DALu141	None	6473.56	ac		
18	DALu151	None	2132.34	ac		
19	DALu161	None	1330.48	ac		
20	DQSwExt	1	131.162	MGD		
21	DQSwExt	2	99.0065	MGD		
22	DQSwExt	3	105.615	MGD		
23	DQSwExt	4	99.6948	MGD		
24	DQSwExt	5	93.6522	MGD		
25	DQSwExt	6	93.4212	MGD		
26	DQSwExt	7	128.981	MGD		
27	DQSwExt	8	96.3411	MGD		
28	DQSwExt	9	97.379	MGD		
29	DQSwExt	10	99.5948	MGD		
30	DQSwExt	11	119.877	MGD		
31	DQSwExt	12	100.46	MGD		

In the example below, there are five climate scenarios loaded in addition to the baseline run. The precipitation change and temperature change columns calculate the difference between the average annual precipitation and average temperature of the climate scenario and the baseline run. For example, if the average temperature change is positive, then the climate scenario has a greater average temperature than the baseline run for the time period.



Loaded Files:	Data Name:	Scenario Name (edit here):	StudyAreaName:	ScenarioName:	RunStartTime:	StartDate:	EndDate:	ModelMode:	Avg Annual Precip	Avg Temperature	Precipitation Change	Temperature Change
H:\ERD\ANCHOR\Assi	Wading3mile_TN	Baseline2002	Wading3mile	TN2002baselin	7/1/2018 12:35	1/1/2002	12/31/2002	Hydrology & Loa	42.05	52.697		
H:\ERD\ANCHOR\Assi	Wading3M	Baseline3.3	Wading3Mile	baseline3.3.9.5	6/29/2018 13:25	1/1/2002	12/31/2002	Hydrology & Loa	50.32	55.997	8.27	3.3
H:\ERD\ANCHOR\Assi	Wading3M_2	Baseline3.7	Wading3Mile	baseline3.7m2	6/29/2018 13:35	1/1/2002	12/31/2002	Hydrology & Loa	41.182	56.397	-0.868	3.7
H:\ERD\ANCHOR\Assi	Wading3M_3	Baseline4.4	Wading3Mile	baseline4.410.	6/29/2018 13:42	1/1/2002	12/31/2002	Hydrology & Loa	46.258	57.097	4.208	4.4
H:\ERD\ANCHOR\Assi	Wading3M_4	Baseline5.0	Wading3Mile	baseline5.0m1	6/30/2018 15:32	1/1/2002	12/31/2002	Hydrology & Loa	41.348	57.697	-0.702	5
H:\ERD\ANCHOR\Assi	Wading3M_5	Baseline6.2	Wading3Mile	baseline6.219.	6/29/2018 14:05	1/1/2002	12/31/2002	Hydrology & Loa	50.287	58.897	8.237	6.2

In this example, the precipitation difference between the climate scenarios and the baseline run varies, with less annual precipitation in the GCM ΔT = +3.7°F/ΔP = -2.2% and ΔT = +5.0°F/ΔP = -1.7% climate scenarios (-0.868 and -0.702 in/year, respectively) and more precipitation in all the other climate scenarios compared to 2002 (up to from +4.208 and +8.237 in/year). The average temperature in the future climate scenarios is always greater than the baseline year of 2002, varying from +3.3°F to +6.2°F.

3.2 Baseline and Climate Scenarios

In this section, we detail how to use the functions in ScenCompare to compare model input data and model results across scenarios. Function buttons can be found under Step 2 and Step 3 on the Controls tab to facilitate the creation of tables and graphs, and all Excel functionality can be used with the Model Input Data and Model Results tabs to facilitate data value comparisons.

3.2.1 Compare Model Input Data

First, we look at the model input data. As an example, we will consider the first comparison type in our list: the baseline historical run versus the future climate scenarios with no management targets or land use decisions. In this run, the only varying model input data is the hydrology data inputs (runoff, recharge, runoff loadings, and recharge loadings). To see this, we navigate to the Model Results tab and filter the "Data Difference" column to show only values of "1". Values of "1" indicate that the input data values are different in at least one scenario. Values of "0" indicate that the input data values are all the same.

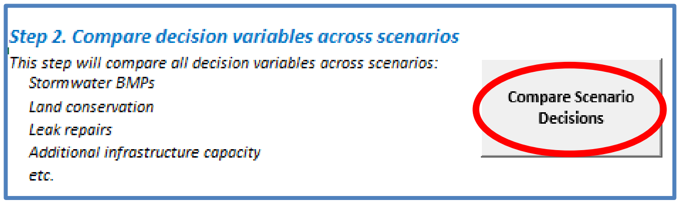
Wading3M_5	Wadir	Wadir	Wading3M_5	Data Difference
AvgAnnualPrecip	None	50.287	total inches per year	1
AvgTemp	None	58.897	deg F	1
QRuT	1;1	8.9818	in/acre/month	1
QRuT	2;1	5.95246	in/acre/month	1
QRuT	3;1	15.0658	in/acre/month	1
QRuT	4;1	10.6832	in/acre/month	1
QRuT	5;1	17.6976	in/acre/month	1
QRuT	6;1	11.9563	in/acre/month	1
QRuT	7;1	0.95592	in/acre/month	1
QRuT	8;1	6.34416	in/acre/month	1
QRuT	9;1	19.1135	in/acre/month	1
QRuT	10;1	12.068	in/acre/month	1
QRuT	11;1	18.4752	in/acre/month	1
QRuT	12;1	16.9107	in/acre/month	1
QReT	1;1	37.0396	in/acre/month	1
QReT	2;1	21.9068	in/acre/month	1
QReT	3;1	58.6548	in/acre/month	1
QReT	4;1	28.8215	in/acre/month	1
QReT	5;1	47.4223	in/acre/month	1
QReT	6;1	19.4081	in/acre/month	1
QReT	9;1	26.7919	in/acre/month	1
QReT	10;1	34.0932	in/acre/month	1
QReT	11;1	78.5421	in/acre/month	1
QReT	12;1	75.2742	in/acre/month	1
LRuT	1;1;1	2.38654	lbs/acre/month	1
LRuT	2;1;1	1.90926	lbs/acre/month	1

After filtering the "Data Difference" column for values of "1", we see that only the climate statistics (AvgAnnualPrecip and AvgTemp) and the monthly runoff and recharge hydrology and loadings statistics[8] (QRuT, QReT, LRuT, and LReT [not shown in above image]) differ between the scenarios.

[8] The statistics represent the monthly sum of runoff or recharge per acre for all land area for each managed set.

3.2.2 Compare Cost and Decision Variables Across Scenarios

Next, we look at the difference in decision variables across the scenario results. To do this, go to the Controls tab and select the "Compare Scenario Decisions" button under Step 2.



This button will generate the **Table_Comparison** tab, which displays all the cost and decision variables from the model results. Cost variables begin with a "C" and decision variables begin with a "D".

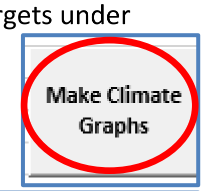
This table first shows the objective cost across scenarios, followed by the specific cost and decision variables. The image below shows the objective cost (total annual cost for watershed management) and the 16 HRU land use decisions for the baseline land area set. To the right of the scenario comparison, there is a "Data Difference" column, which can be used to filter varying values, and buttons to navigate back to the Controls tab or generate graphs that compare the objective cost to the climate statistics.

Variable	Description	Units	Baseline2002	Baseline_GCM-3.3	Baseline_GCM-3.7	Baseline_GCM-4.4	Baseline_GCM-5.0	Baseline_GCM-6.2	Data Difference
objective	Objective cost	$/yr	4524.5	4524.5	4524.5	4524.5	4524.5	4524.5	0
DALu11	Land Area - Land Area w/ Conservation, forest sand	ac	13647.0	13647.0	13647.0	13647.0	13647.0	13647.0	0
DALu21	Land Area - Land Area w/ Conservation, open nonres sand	ac	2296.4	2296.4	2296.4	2296.4	2296.4	2296.4	0
DALu31	Land Area - Land Area w/ Conservation, MLD res sand	ac	5948.7	5948.7	5948.7	5948.7	5948.7	5948.7	0
DALu41	Land Area - Land Area w/ Conservation, MHHD resid sand	ac	973.2	973.2	973.2	973.2	973.2	973.2	0
DALu51	Land Area - Land Area w/ Conservation, comindtr sand	ac	2536.9	2536.9	2536.9	2536.9	2536.9	2536.9	0
DALu61	Land Area - Land Area w/ Conservation, ag sand	ac	634.2	634.2	634.2	634.2	634.2	634.2	0
DALu71	Land Area - Land Area w/ Conservation, forest till	ac	12553.5	12553.5	12553.5	12553.5	12553.5	12553.5	0
DALu81	Land Area - Land Area w/ Conservation, open nonres till	ac	1082.6	1082.6	1082.6	1082.6	1082.6	1082.6	0
DALu91	Land Area - Land Area w/ Conservation, MLD res till	ac	2821.2	2821.2	2821.2	2821.2	2821.2	2821.2	0
DALu101	Land Area - Land Area w/ Conservation, MHHD resid till	ac	448.3	448.3	448.3	448.3	448.3	448.3	0
DALu111	Land Area - Land Area w/ Conservation, comindtr till	ac	1104.4	1104.4	1104.4	1104.4	1104.4	1104.4	0
DALu121	Land Area - Land Area w/ Conservation, ag till	ac	240.6	240.6	240.6	240.6	240.6	240.6	0
DALu131	Land Area - Land Area w/ Conservation, cranberry bog	ac	98.4	98.4	98.4	98.4	98.4	98.4	0
DALu141	Land Area - Land Area w/ Conservation, forested wetland	ac	6473.6	6473.6	6473.6	6473.6	6473.6	6473.6	0
DALu151	Land Area - Land Area w/ Conservation, nonforested wetlnd	ac	2132.3	2132.3	2132.3	2132.3	2132.3	2132.3	0
DALu161	Land Area - Land Area w/ Conservation, water	ac	1330.5	1330.5	1330.5	1330.5	1330.5	1330.5	0

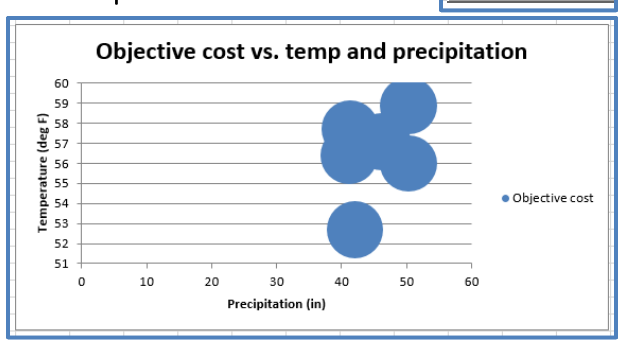
Return to Controls

Make Climate Graphs

For this table, when we try to filter the "Data Difference" column for varying values, we find that there are no differences across the scenarios for the objective cost and all of the other variables. This result is not surprising because there were no management targets (flow or loadings) set for any of the scenarios in the baseline run. We used the baseline run to determine the flows and costs associated with the watershed and model time period, and checked whether we could achieve the same targets under future climate scenarios.



Next, using the "Make Climate Graphs" button, we generated three climate graphs to compare the objective costs across the scenarios. This button produces a new tab titled **ClimateGraph_objective**, which has a table of the climate statistics and the objective cost for all scenarios, and three graphs: 1) Objective cost vs. precipitation, 2) Objective Cost vs. temperature, and 3) Objective cost vs. temperature and precipitation. The Objective cost vs. temperature and precipitation graph shows a bubble plot of the objective cost, where the size of the bubble is related to the magnitude of the objective cost and graphed with the temperature statistics on the y-axis and the precipitation statistic on the x-axis, to show how costs vary by climate. In this example, the objective cost bubbles are uniform because the objective costs do not vary by scenario.



3.2.3 Compare Time Series Variables Across Scenarios

Finally, we look at the comparisons available for the results time series variables. Under Step 3, on the Controls tab, you can select one or more variables you would like to compare on their own tab. Select the variables of interest in the "Series Variables" column, and click the "Create Tables and Graphs from Selected Variables" button to generate a new tab for each variable. In this case, we selected DQSwExt, the flow time series of surface water flowing outside the watershed. The flow regime from surface water to the external watershed is an indicator of watershed health because it represents the volume of water available to the stream and downstream watersheds after the water is used for human demand.

Step 3. Compare time series across scenarios.

Series Variables (select below)	Category	Description
COmAsr	O&M Costs	Aquifer storage and recovery (ASR)
COmESep	O&M Costs	Enhanced septic treatment
COmGwPump	O&M Costs	Groundwater pumping
COmIbtW	O&M Costs	Interbasin transfer (IBT) potable water
COmIbtWw	O&M Costs	IBT wastewater
COmNpdist	O&M Costs	Nonpotable distribution system
COmOS	O&M Costs	Operation cost of offline storage use
COmRes	O&M Costs	Reservoir management
COmSwPump	O&M Costs	Surface water pumping
COmWrf	O&M Costs	Water reuse facility (WRF)
COmWtp	O&M Costs	Water treatment
COmWwtp	O&M Costs	Wastewater treatment
DQCSOS	Flow	Combined sewer to offline storage
DQGwExt	Flow	Groundwater to external
DQGwMake	Flow	Groundwater deficits
DQGwWtp	Flow	Groundwater to water treatment plant
DQIbtWUseNp	Flow	IBT potable water to nonpotable water use
DQIbtWUseP	Flow	IBT potable water to potable water use
DQOSWwtp	Flow	Offline storage to wastewater treatment plant
DQResAsr	Flow	Reservoir to ASR
DQResWtp	Flow	Reservoir to water treatment plant
DQSwAsr	Flow	Surface water to ASR
DQSwExt	Flow	Surface water to external
DQSwWtp	Flow	Surface water to water treatment plant

Create Tables and Graphs from Selected Variables

Clear Tables and Graphs

After selecting the button, a new tab is created entitled **Table_DQSwExt**. On the left side of this tab, there is a table of the time series for all scenarios, as well as the minimum, average, and maximum statistics for the time series, and a time step count threshold. The count threshold defaults to zero, but it can be edited to calculate the count of time steps above a certain value. In the example below, we can see that the flow out of the watershed exceeds zero for all days in the time period.

Surface water to exter	Baseline2002	Baseline_GCM-3.3	Baseline_GCM-3.7	Baseline_GCM-4.4	Baseline_GCM-5.0	Baseline_GCM-6.2		
MIN	4.91604281	4.923838995	4.923838995	4.852392972	4.629905929	4.890133854		
AVERAGE	113.7807581	140.0302234	140.0302234	124.4070025	105.762474	136.9017693		
MAX	394.1073415	486.2379146	486.2379146	439.6757833	382.8236989	483.7298046		
COUNT > 0	365	365	365	365	365	365	Count Threshold (edit):	0
1/1/2002	131.4222063	131.1075806	131.1075806	131.3151699	131.2154625	131.1097389		
1/2/2002	98.65000245	98.94297298	98.94297298	98.70411448	98.82435458	98.80215908		
1/3/2002	105.5583947	105.3437909	105.3437909	105.1340121	105.0347991	105.0600119		
1/4/2002	99.60279215	99.29465405	99.29465405	98.97426677	98.91342454	98.89097536		
1/5/2002	93.50104626	93.18199199	93.18199199	92.67792243	92.67217684	92.67959862		
1/6/2002	92.91998335	93.10734564	93.10734564	92.24913241	92.28638843	92.52314579		
1/7/2002	129.9370666	141.3680892	141.3680892	134.5667786	126.534404	140.5475422		

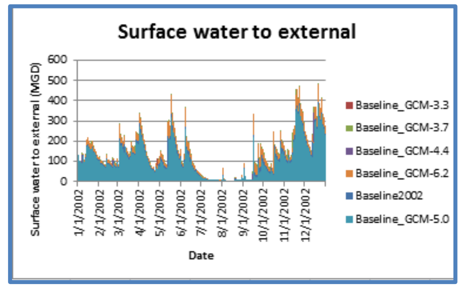
As an example, we changed the count threshold to 114 MGD (the average flow of the baseline scenario) and found that the majority of the scenarios had more time steps with flow out of the watershed exceeding the baseline average compared to the baseline. However, the GCM 5.0 to -1.7 scenario did not follow this trend, with fewer time steps exceeding the baseline average compared to the baseline scenario.

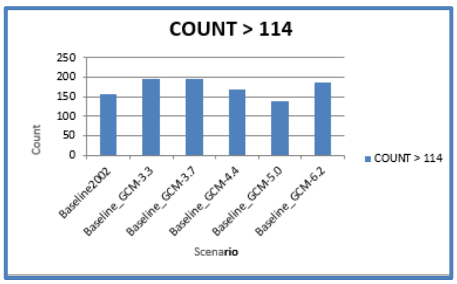
Surface water to exteri	Baseline2002	Baseline_GCM-3.3	Baseline_GCM-3.7	Baseline_GCM-4.4	Baseline_GCM-5.0	Baseline_GCM-6.2		
MIN	4.91604281	4.923838995	4.923838995	4.852392972	4.629905929	4.890133854		
AVERAGE	113.7807581	140.0302234	140.0302234	124.4070025	105.762474	136.9017693		
MAX	394.1073415	486.2379146	486.2379146	439.6757833	382.8236989	483.7298046		
COUNT > 114	155	196	196	168	137	186	Count Threshold (edit):	114

3.2.3.1 *Time Series Graphs*

The time series comparison tab also has graphing functions available. On the right side of this tab, there are three graphs: 1) a time series graph, 2) a count threshold histogram, and 3) a box plots graph.

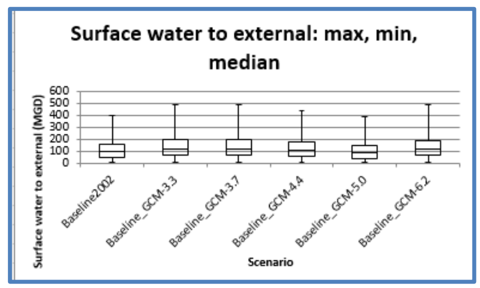
The time series graph (right) shows the flow or loadings time series for the model period and all scenarios. Depending on the number of scenarios, you may need to change the order of the time series to better see the comparison between flows. In this example, we brought the baseline and GCM 5.0/-1.7 to the forefront to see the magnitude of the flows in comparison to scenarios with larger flows, like GCM 6.2/19.4.



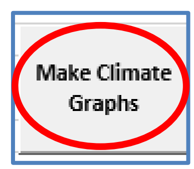


The count threshold histogram (left) shows a column chart of the number of threshold exceedances for each scenario. The histogram changes whenever the count threshold is edited.

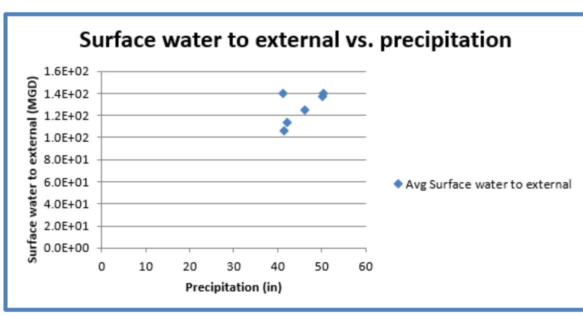
The box plots graph (right) shows box plots displaying the minimum, first quartile, median, third quartile, and maximum flows for each scenario. It shows how the distribution of flow magnitudes vary by scenario. We see that the GCM 3.3/19.5 scenario has the largest spread, though it is similar to other scenarios.

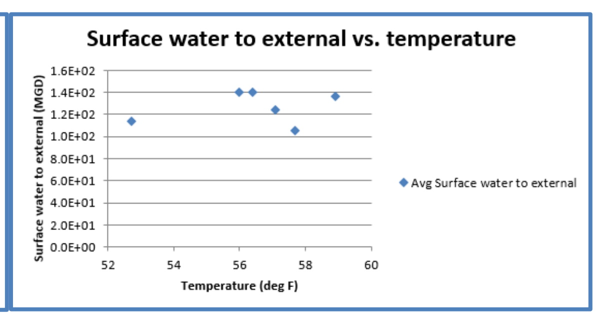


3.2.3.2 *Climate Graphs*



The time series comparison tab also has climate graphing functionality. On the right side of the tab, you can use the "Make Climate Graph" button, to create a new tab titled **ClimateGraph_DQSwExt**. This tab creates a similar tab as seen in Section 3.2.2, with three climate graphs showing the average time series value for all scenarios versus the climate statistics (average annual precipitation and average temperature).





The images above show the average flow out of the watershed compared to precipitation and temperature. In the precipitation graph, we see a trend with increasing annual precipitation and larger flows, although the GCM $\Delta T = +3.7°F/\Delta P = -2.2\%$ appears to be an outlier. We see no clear trend between temperature and flows, which indicates that annual precipitation likely has a larger effect on streamflows.

3.3 Land Use Optimization Scenarios

In this section, we discuss the two land use optimization scenarios developed for the Wading-Threemile watershed, the optimal stormwater BMP and the optimal riparian zone implementation, as well as how to compare and analyze land management variables within ScenCompare.

3.3.1 Compare Robustness of Land Management Variables Decisions Across Scenarios

The second and third comparison types for this case study, the optimal stormwater BMP and optimal riparian zone implementation, were developed to test the robustness of the WMOST land use management decisions in future climate scenarios, i.e., whether the optimal set would change in the future. We show how the model decisions varied by climate scenario for each run in the following sections.

3.3.1.1 Stormwater BMP Optimization Scenarios

For the stormwater BMP comparison, we modeled a fixed set of stormwater land use BMPs optimized for the historical baseline run with a stream loadings target, and modeled the five future climate scenarios with the stormwater land use BMPs fixed at the 2002 solution and with no stream loadings target. For the future climate scenarios, although WMOST had no decision variables with respect to BMP implementation, there were still decision variables related to meeting water demand. The optimal stormwater BMP selected was 1,088 acres of infiltration basins with a 0.6” design depth on Commercial/Industrial/Transportation land use on a till and fine-grained deposits soil type. Using this stormwater BMP set, we found that the optimization models for the future climate scenarios determined a least-cost objective value of about $6,414/year, which is slightly lower than the historical baseline scenario objective value of $6,430/year.

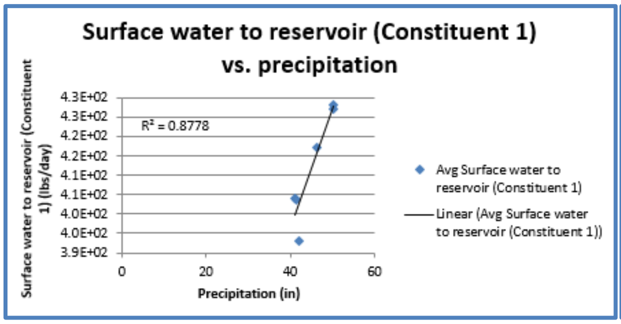
Variable	Description	Units	OptBMPs_Baseline	OptBMPs_GCM-3.7	OptBMPs_GCM-4.4	OptBMPs_GCM-5.0	OptBMPs_GCM-6.2	optbmps3.39.5	Data Difference
objective	Objective cost	$/yr	6430.9395	6414.6307	6414.6307	6414.6307	6414.6307	6414.6307	1
CGwPump	Total cost of groundwater pumping	$/yr	490.0586873	291.19066	291.19066	291.19066	291.19066	291.19066	1
CSwPump	Total cost of surface water pumping	$/yr	117.8049938	124.0212959	124.0212959	124.0212959	124.0212959	124.0212959	1
CIbtW	Total cost of IBT potable water	$/yr	362.3837596	538.7266703	538.7266703	538.7266703	538.7266703	538.7266703	1

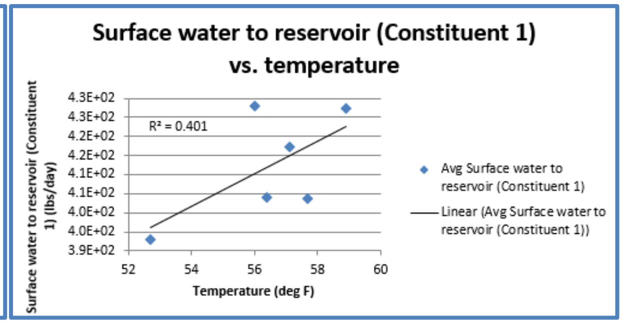
The cost difference between the baseline and climate scenarios occur in the model’s usage of groundwater pumping, surface water pumping, and interbasin transfer of potable water.

We used the “Create Tables and Graphs from Selected Variables” button to tabulate and graph the loadings time series LSwRes, which is the loadings flow from the stream to the reservoir, and the flow upon which the stream loadings target is based. By changing the Count Threshold to 1,156 lbs (the baseline stream loading target), we found that the stream loadings for two of the five future climate scenarios achieved the baseline loadings target. The other three scenarios exceeded the loadings target on only one time step in the model period.

Surface water to resen	OptBMPs_Baseline	OptBMPs_GCM-3.3	OptBMPs_GCM-3.7	OptBMPs_GCM-4.4	OptBMPs_GCM-5.0	OptBMPs_GCM-6.2		
MIN	42.59782234	138.3093323	131.7356999	134.8816899	131.3388132	138.0435979		
AVERAGE	392.9978659	428.0723073	404.0083285	417.1245325	403.8378292	427.2204664		
MAX	1147.533395	1188.52981	1150.731899	1172.097451	1151.979989	1189.114321		
COUNT > 1156	0	1	0	1	0	1	Count Threshold (edit):	1156

When comparing the loadings in the surface water to the climate statistics, we found that, in general, the average surface water loadings increased with increasing precipitation and increasing temperature. As shown in the images below, the linear relationship between stream loadings and precipitation is stronger than the relationship between stream loadings and temperature, with an r^2 value of 0.8778 for precipitation versus an r^2 value of 0.401 for temperature.





3.3.1.2 Riparian Buffer Optimization Scenarios

For the riparian buffer run, we modeled a selection of 10 potential riparian buffer land conversions from developed land to forest with the same climate scenarios and stream loadings targets as the stormwater BMP run (i.e., with a loading target for the historical baseline run and no loadings target for the future climate scenarios). The optimization model selected the optimal riparian buffer land use conversion with the least cost.

We found that the model selected all of the same riparian conversion sets, except the baseline run did not select the conversion from HRU 4 (medium/high-density residential on sand-and-gravel soil type) to HRU 1 (forest on sand-and-gravel soil type) for loads group three, as indicated by the zero value for CRipSet133, which resulted in a lower total riparian conversion cost (CRipTotal).

Variable	Description	Unit	OptRipa	OptRipa	OptRipa	OptRipa	OptRipa	OptRipa	Data Difference
objective	Objective cost	$/yr	574.0	5533.1	5533.1	5533.1	5533.1	5533.1	1
CRipSet111	LU Conv: From HRU2 To HRU1 - Cost of riparian buffer land use conversion set for loads group 1	$/yr	3.6	3.6	3.6	3.6	3.6	3.6	0
CRipSet112	LU Conv: From HRU2 To HRU1 - Cost of riparian buffer land use conversion set for loads group 2	$/yr	62.0	62.0	62.0	62.0	62.0	62.0	0
CRipSet113	LU Conv: From HRU2 To HRU1 - Cost of riparian buffer land use conversion set for loads group 3	$/yr	0.0	0.0	0.0	0.0	0.0	0.0	0
CRipSet121	LU Conv: From HRU3 To HRU1 - Cost of riparian buffer land use conversion set for loads group 1	$/yr	3.6	3.6	3.6	3.6	3.6	3.6	0
CRipSet122	LU Conv: From HRU3 To HRU1 - Cost of riparian buffer land use conversion set for loads group 2	$/yr	210.0	210.0	210.0	210.0	210.0	210.0	0
CRipSet123	LU Conv: From HRU3 To HRU1 - Cost of riparian buffer land use conversion set for loads group 3	$/yr	0.0	0.0	0.0	0.0	0.0	0.0	0
CRipSet132	LU Conv: From HRU4 To HRU1 - Cost of riparian buffer land use conversion set for loads group 2	$/yr	79.5	79.5	79.5	79.5	79.5	79.5	0
CRipSet133	LU Conv: From HRU4 To HRU1 - Cost of riparian buffer land use conversion set for loads group 3	$/yr	0.0	48.0	48.0	48.0	48.0	48.0	1
CRipSet141	LU Conv: From HRU5 To HRU1 - Cost of riparian buffer land use conversion set for loads group 1	$/yr	1.1	1.1	1.1	1.1	1.1	1.1	0
CRipSet142	LU Conv: From HRU5 To HRU1 - Cost of riparian buffer land use conversion set for loads group 2	$/yr	184.0	184.0	184.0	184.0	184.0	184.0	0
CRipSet143	LU Conv: From HRU5 To HRU1 - Cost of riparian buffer land use conversion set for loads group 3	$/yr	0.0	0.0	0.0	0.0	0.0	0.0	0
CRipSet152	LU Conv: From HRU6 To HRU1 - Cost of riparian buffer land use conversion set for loads group 2	$/yr	12.5	12.5	12.5	12.5	12.5	12.5	0
CRipSet153	LU Conv: From HRU6 To HRU1 - Cost of riparian buffer land use conversion set for loads group 3	$/yr	44.7	44.7	44.7	44.7	44.7	44.7	0
CRipSet161	LU Conv: From HRU8 To HRU7 - Cost of riparian buffer land use conversion set for loads group 1	$/yr	4.1	4.1	4.1	4.1	4.1	4.1	0
CRipSet162	LU Conv: From HRU8 To HRU7 - Cost of riparian buffer land use conversion set for loads group 2	$/yr	62.0	62.0	62.0	62.0	62.0	62.0	0
CRipSet163	LU Conv: From HRU8 To HRU7 - Cost of riparian buffer land use conversion set for loads group 3	$/yr	0.0	0.0	0.0	0.0	0.0	0.0	0
CRipSet171	LU Conv: From HRU9 To HRU7 - Cost of riparian buffer land use conversion set for loads group 1	$/yr	12.9	12.9	12.9	12.9	12.9	12.9	0
CRipSet172	LU Conv: From HRU9 To HRU7 - Cost of riparian buffer land use conversion set for loads group 2	$/yr	122.3	122.3	122.3	122.3	122.3	122.3	0
CRipSet173	LU Conv: From HRU9 To HRU7 - Cost of riparian buffer land use conversion set for loads group 3	$/yr	0.0	0.0	0.0	0.0	0.0	0.0	0
CRipSet181	LU Conv: From HRU10 To HRU7 - Cost of riparian buffer land use conversion set for loads group 1	$/yr	1.9	1.9	1.9	1.9	1.9	1.9	0
CRipSet182	LU Conv: From HRU10 To HRU7 - Cost of riparian buffer land use conversion set for loads group 2	$/yr	45.8	45.8	45.8	45.8	45.8	45.8	0
CRipSet183	LU Conv: From HRU10 To HRU7 - Cost of riparian buffer land use conversion set for loads group 3	$/yr	0.0	0.0	0.0	0.0	0.0	0.0	0
CRipSet191	LU Conv: From HRU11 To HRU7 - Cost of riparian buffer land use conversion set for loads group 1	$/yr	1.6	1.6	1.6	1.6	1.6	1.6	0
CRipSet192	LU Conv: From HRU11 To HRU7 - Cost of riparian buffer land use conversion set for loads group 2	$/yr	103.4	103.4	103.4	103.4	103.4	103.4	0
CRipSet193	LU Conv: From HRU11 To HRU7 - Cost of riparian buffer land use conversion set for loads group 3	$/yr	0.0	0.0	0.0	0.0	0.0	0.0	0
CRipSet1102	LU Conv: From HRU12 To HRU7 - Cost of riparian buffer land use conversion set for loads group 2	$/yr	5.5	5.5	5.5	5.5	5.5	5.5	0
CRipSet1103	LU Conv: From HRU12 To HRU7 - Cost of riparian buffer land use conversion set for loads group 3	$/yr	0.0	0.0	0.0	0.0	0.0	0.0	0
CRipTotal	Total cost of applying riparian buffer land management sets	$/yr	960.6	1008.5	1008.5	1008.5	1008.5	1008.5	1

3.3.2 Compare Land Management Variables Across Scenarios

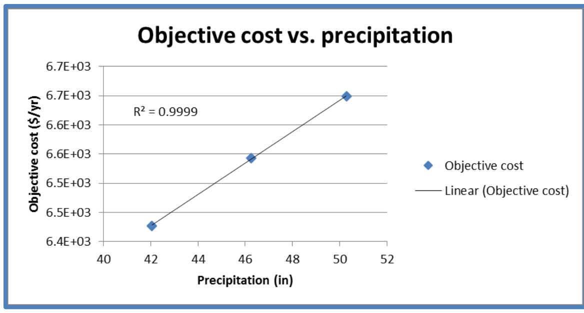
In this section, we provide an example of how to compare stormwater BMP decisions using the historical baseline and two future climate scenarios (GCM 4.4/10.1 [the median scenario] and GCM 6.2/19.4 [an extreme bounding scenario]) when the optimization model is allowed to decide how much land area to allocate to a stormwater BMP. In this run, the stream loadings target for TN was applied for all scenarios.

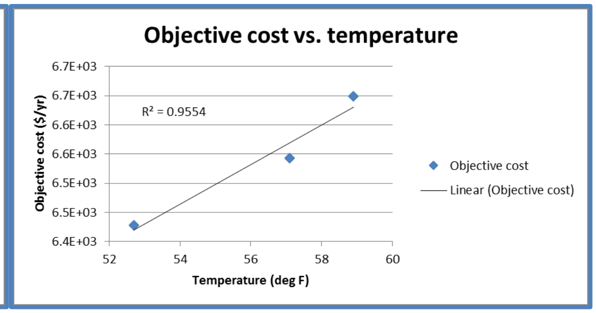
We found the different stormwater BMP decisions made by using the "Compare Scenario Decisions" button to create the **Table_Comparison** tab. After filtering the "Data Difference" column for values of "1", we found that, for all scenario runs, the model selected an Infiltration Basin with a design depth of 0.6" to be implemented on the Commercial/Industrial/Transportation land use on the sand-and-gravel soil type and till-and-fine-grained deposits soil type (DALu52 and DALu112, respectively).

Variable	Description	Units	BMPs_Baseline2002	BMPs_GCM-4.4	BMPs_GCM-6.2	Data Difference
objective	Objective cost	$/yr	6427.4676	6543.0085	6649.0394	1
DALu52	Land Area - 0.6" Infilt	ac	0.0000174	53.16350656	114.7482124	1
DALu112	Land Area - 0.6" Infilt	ac	1090.555717	1104.442104	1104.442104	1
CLuSet2	0.6" Infiltration Basi	$/yr	1894.536918	2010.916898	2117.786745	1
CGwPump	Total cost of groundv	$/yr	479.1857416	483.2004344	489.1591315	1
CSwPump	Total cost of surface	$/yr	120.8216609	121.1416244	121.4615879	1
CIbtW	Total cost of IBT pota	$/yr	362.3282006	357.1545276	350.0369083	1

When analyzing the decision variables more closely, we see that the land use allocation for this BMP changed between all three climate scenarios. The baseline scenario selected the BMP only on the till and fine-grained deposits soil type (the value for DALu52 is negligible), and the future climate scenarios selected the BMP for both the sand-and-gravel and till-and-fine-grained deposits soil types, with a larger allocation of overall land area for the BMP in the extreme climate scenario (GCM 6.2/19.4).

We also see that the objective cost increased from the baseline scenario to the future climate scenarios, with the highest objective cost occurring in the extreme climate scenario. The climate comparison graphs show an extremely close linear relationship between objective cost and increasing precipitation and temperature with r^2 values of 0.9999 and 0.9554, respectively.





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