Impact of climate change on CSOs and SSOs in Milwaukee Watersheds

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Executive Summary

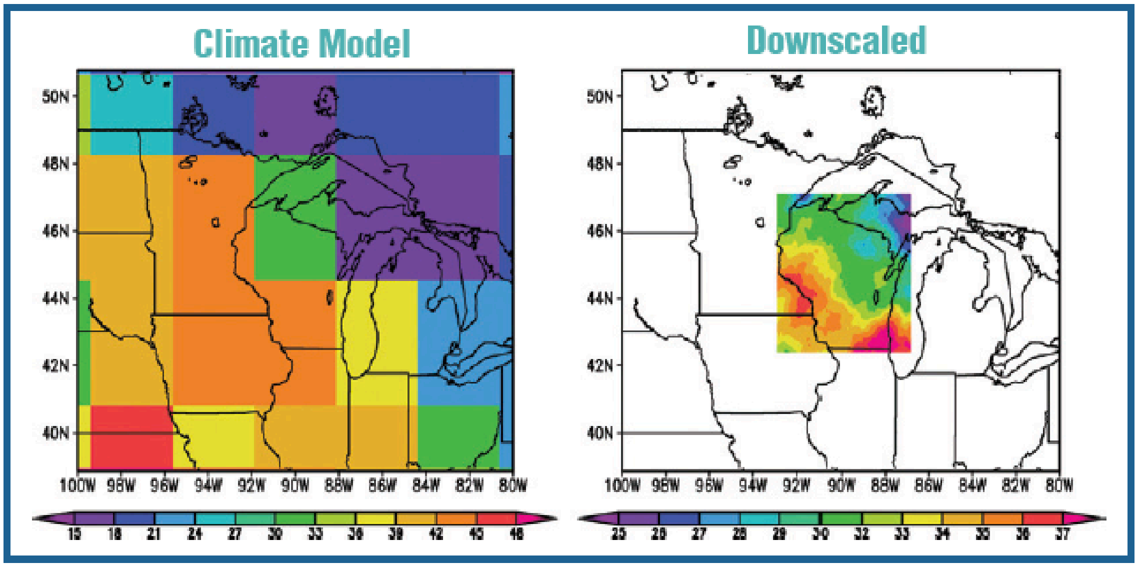
Climate change is predicted to alter precipitation and temperature trends in the Midwest and to result in increases in storm frequency and intensity, but only small to no changes in annual precipitation are expected. These changes would be expected to result in changes in the number, duration, and volume of combined sewer overflows (CSOs) and/or separate sewer overflows (SSOs). The impacts of climate change need to be assessed to plan adaptation strategies that will minimize negative outcomes for water quality and human health.

Approach. Because of the complex interrelationships between air temperatures and precipitation, a continuous simulation hydrologic model that specifically incorporates air temperature and precipitation time series was applied to estimate flows in the Milwaukee Metropolitan Sewerage District (MMSD) conveyance and storage system under climate change conditions. This project assessed the impact of projected mid-century (2050) climate trends on CSOs and SSOs through modeling and statistical analysis of the modeling output. Previous extensive facilities planning had employed a model of the MMSD conveyance and storage system (MACRO) to evaluate CSOs and SSOs with recommended facilities using historical climate conditions (January 1940 through June 2004). In this project, regional specific climate projections were used with the MACRO modeling procedure and the output was compared.

The overall goal of the project was to assess the impacts of climate change on CSOs and SSOs using the MACRO model as a tool to simulate climate change stressors. Specific objectives were:

1. Determine CSO/SSO frequency, duration, and volume under projected climate change conditions.
2. Evaluate driving forces related to climate parameters (e.g., rainfall and soil moisture).
3. Incorporate findings into the Milwaukee working group WICCI report.
4. Disseminate findings to Sweet Water Trust and develop fact sheets for public outreach.

Climate change projections. Climate change predictions based on global climate models (GCM) indicate that climate change will have a significant impact on the Midwest, but these predictions are not very specific for Wisconsin. The Wisconsin Initiative on Climate Change Impacts, Climate Working Group has developed methods to downscale GCM predictions to be region-specific. For example, the resolution of GCMs is in hundreds of km, but the downscaled models developed by the Climate Working Group have a resolution of approximately 10 km. For this project, the climate record from January 1940 through June 2004, or December 2010, depending on the issue being analyzed, was adjusted for climate predictions for mid century. Information on Wisconsin's changing climate and methods used to make these predictions can be found at http://www.wicci.wisc.edu.



Source: David Lorenz, Nelson Institute Center for Climatic Research, University of Wisconsin-Madison

Figure A. Example of downscaled climate data for the State of Wisconsin. GCM predict changes in units, or grids, of 200 km. Downscaling of these predictions improve resolution to a finer scale, so differences can be predicted between northern Wisconsin and Southeastern Wisconsin for example.

Overall, predictions for the Midwest include increased storm frequency and intensity with only small to no change in annual rainfall amounts. This means that periods of rainfall could have higher accumulations that could be offset by longer dry spells. For Wisconsin, an approximately 25% to 37% increase in the frequency of storm events with 2 and 3 inches, respectively, of rainfall in 24 hours is predicted for the mid-century period from 2046 through 2065. More storms are expected in the early spring time frame, which is when combined sewer systems are most vulnerable due to frozen ground conditions limiting infiltration of rainwater. Annual temperatures are also expected to increase, with the largest seasonal increases in spring and fall.

There are more than 14 GCM that vary in their projections, therefore, there is uncertainty associated with each. In this project, a “best case” and “worst case” scenario was used to bracket the range of projections. The scenarios were chosen base on the amount of spring rainfall because that is a sensitive variable in terms of CSOs and increases in spring rain was the variable most consistent among the 14 GCM examined for this project. Overall, 12 of 14 agreed spring rains would increase in frequency and intensity. Most analyses were divided into two time frames: Winter-Spring (November through April) and Summer-Fall (May through October).

MACRO Modeling results and statistical analysis

For the “worst case” scenario, there were 21 more CSOs over the 64 year time period and a 21% increase in volume projected for mid-century climate conditions using MACRO as a tool to model the MMSD storage and conveyance system. For this “worst case” scenario, there was also no notable change in the duration of CSOs or change in SSOs overall. For the "best" case scenario, there was a small decrease in the number of CSOs and a small decrease in the volume (e.g., <2%), which can be considered within the range of model variability. Similarly, SSOs did not change outside of what would be expected for model variability. Therefore, climate projections for mid century that estimate lesser changes in spring rains are not expected to add additional stress to the MMSD conveyance and storage system. All further analyses in this project considered only the "worst case" scenario.

Overall, 90% of the CSOs under current climate conditions occurred when there was 1.7 inches or less of rainfall in 24 hours. This threshold was similar for the Winter-Spring time frame as the Summer-Fall time frame. Under current climate conditions, the MACRO model simulated 17% of the CSOs in Winter-Spring occurred with low rainfall (<1.0 inch), whereas under projected climate conditions, there was a higher threshold. For projected climate 20% of the CSO events simulated in the model occurred when there was less than 1.3 inches in the previous 24 hours. The projected climate conditions include increased temperatures in winter and spring, which may reduce instances of a combination of rainfall and frozen ground and/or snow melt that results in CSOs. While these actual rainfall amounts are based on a model simulation and not actual occurrence, they do reveal the important influence of temperature in the Winter-Spring time frame.

Blending is used in the model MACRO model to maintain storage capacity within the deep tunnel, and as a result, model output shows 58 blending events per year under current climate conditions, which is much higher than actual operating procedures. This number is slightly less under projected climate conditions. Comparison of real time operating procedures with model operations might provide insight into the most important variables to track for the most effective real time controls.

Logistic regression was used to investigate combinations of parameters that were significantly correlated to CSOs. Rainfall amounts or rainfall with air temperature did not show significant correlations, demonstrating the complex interplay of variables. For MACRO inputs, HSPF is used to simulate runoff into the conveyance and storage system represented in the MACRO model. Change in one HSPF model parameter was significantly correlated with CSOs. For this result, a rapid change (e.g. steep gradient) in upper zone storage, which is the storage capacity in macropores in the upper soil layer, at the beginning of a tunnel event was predictive of a CSO event also occurring. These results confirm importance of soil moisture in combination with rainfall amounts.

The MACRO model was also used to compare existing facilities with planned facilities in terms of changes in CSOs and SSOs under current climate conditions. The model output showed a large reduction in SSO frequency, from 0.56 per year to 0.14 per year (75% reduction), and volume from 112 MG per year to 18 MG per year (84% reduction), which was the goal of implementing the planned facilities. This is in comparison to the 10% increase in CSO frequency and 21% increase in CSO volume when historic climate is interchanged with a "worst case" scenario climate change record. It is difficult to directly compare the outcome of improved facilities with the negative effect of climate change, but these results do provide a benchmark for the effect of infrastructure improvements and climate change.

The long term trend in CSOs and SSOs was also examined using current climate conditions

Conclusions and Recommendations

With no improvements in MMSD facilities beyond current plans and no adaptation strategies, CSOs may increase in the Winter-Spring time frame by mid-century due to climate change. This increase is very small ("best case" scenario) to moderate ("worst case" scenario) and these impacts should be considered in the context of ongoing improvements and additional stressors such as aging infrastructure and urban development.

Winter and spring time frames are most sensitive to CSOs, where under current climate conditions, the model output showed 20% of the simulated CSOs were triggered with 1.0 inches of rainfall or less and 90% of the CSOs were triggered by 1.7 inches. Combinations of frozen ground and/or snow melt and small amounts of rainfall triggered CSOs in the MACRO model, which may not actually occur in practice. Under climate change conditions, the increase in air temperature reduced the number of CSOs occurring with very low amounts of precipitation. Mitigation strategies to reduce climate impact could target reducing runoff in the winter and spring time frames because rainfall amounts that trigger some CSOs may be more manageable. Further projected increased rainfall in winter and spring are more certain than the increased storm frequencies and intensities projected for summer and fall.

Steep increases in Upper Zone Storage (UZS) at the beginning of storm events were correlated with CSOs. UZS is a compartment in the HSPF model and reflects the amount of storage in macropores of the upper layer of soil (e.g., soil moisture). Currently real time soil moisture measurements or predictions are not available, but such measurements could provide useful supplemental information for real time operation of the ISS during storm events

Continued improvements to MMSD conveyance and storage facilities are important for preserving and protecting water quality and protecting human health under current climate conditions. When considering improvements, the potential additional benefit for adapting to climate change should be considered.

Stakeholders are interested in information that quantifies the effect of climate change. This project offered the opportunity to quantify climate change impacts using sophisticated water resource planning tools. These results will be of interest to the broader water resource community and will be made available.

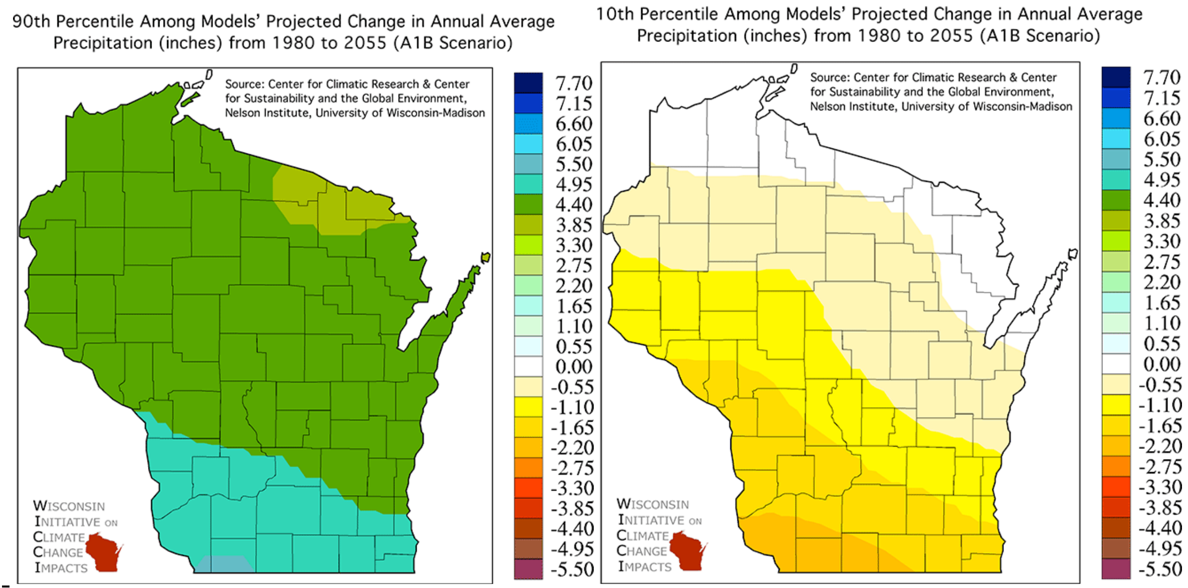
Impact of Climate Change on CSOs and SSOs in Milwaukee Watersheds

INTRODUCTION

Climate Change and Water Resources. Sewage overflows impact water resources and pose a serious health risk due to the introduction of pathogens into the environment. Combined sewers are located in the older parts of the MMSD service area in an approximately 24-square mile portion of the City of Milwaukee and the Village of Shorewood. Such sewers receive both wastewater and stormwater and convey them in the same system of pipes. Combined sewer overflows (CSOs) occur when the conveyance and storage system exceeds capacity during periods of heavy rain. Separate sanitary sewers only directly receive wastewater, but during wetter periods, stormwater finds its way into sanitary sewers through cracks in public sanitary sewer manholes, pipes, and private laterals (infiltration) and through inflow to manholes from flooded streets and inflow to private laterals from foundation and/or roof drains sewer pipes. Thus, sanitary sewers also may overflow during times of heavy rainfall, resulting in a sanitary sewer overflow (SSO). Climate change predictions project an increase in the intensity and frequency of larger rain events, particularly in spring when sewage overflows occur with lower amounts of rainfall compared with other times of the year since spring rainfall often occurs on frozen or saturated ground. These alterations in storm patterns could potentially increase the number of sewage overflows despite capital improvements or implementation of management strategies directed at reducing sewage overflows.

Wisconsin's Changing Climate. Climate change data from global climate models (GCM) for the Great Lakes are not very specific. For example, the resolution of predictions in GCM is across hundreds of km. The Wisconsin Initiative on Climate Change Impacts (WICCI) Climate Working Group has recently developed methodology to downscale global climate models to a regional scale. This allows for higher resolution predictions that are specific to Southeastern Wisconsin. Climate predictions are also dependent on future greenhouse gas emissions. Climatologists use three standard scenarios, A2, A1B, and B1, that represent high, medium and low increases, respectively, in greenhouse gasses. For more information on methods and predictions see: http://wicci.wisc.edu/workinggroups/climate/index.htm.

Climate change is predicted to alter the precipitation and temperature trends in the Midwest and to result in an increase in storm frequency and intensity, but only small to no change on annual precipitation. Overall, we do not expect to see higher amounts of annual rainfall, but there will be an increased frequency of heavy rain events in southeastern Wisconsin and subsequently more summer droughts (ref WICCI report). **Figure 1** shows the annual change in rainfall for two GCMs, one in the 10th percentile in terms of predicted change, and one in the 90th percentile. **Figure 2** shows the predicted spring rainfall increases averaged for 14 GCMs. Early spring rains are predicted to increase and a slight increase in winter precipitation is also anticipated; however, increased temperatures may cause some precipitation to be in the form of rain or freezing rain instead of snow. Specifically, Wisconsin is predicted to have increases in the frequencies of 24-hour rainfalls of up to 12% for one-inch rains, up to 25% for two-inch rains, and up to about 37% for three-inch rains (**Figure 3**). Southeastern Wisconsin's temperatures are projected to increase in spring and fall with the least amount of warming in the summer. Southeastern Wisconsin will experience more extreme hot days in the summer and less cold nights in the winter (WICCI, 2011).



90th Percentile Among Models' Projected Change in Annual Average Precipitation (inches) from 1980 to 2055 (A1B Scenario)

10th Percentile Among Models' Projected Change in Annual Average Precipitation (inches) from 1980 to 2055 (A1B Scenario)

Source: Center for Climatic Research & Center for Sustainability and the Global Environment, Nelson Institute, University of Wisconsin-Madison

Figure 1: Projected annual average precipitation changes from 1980 to 2055 in the 90th percentile (left) and 10th percentile (right) (WICCI, 2011).

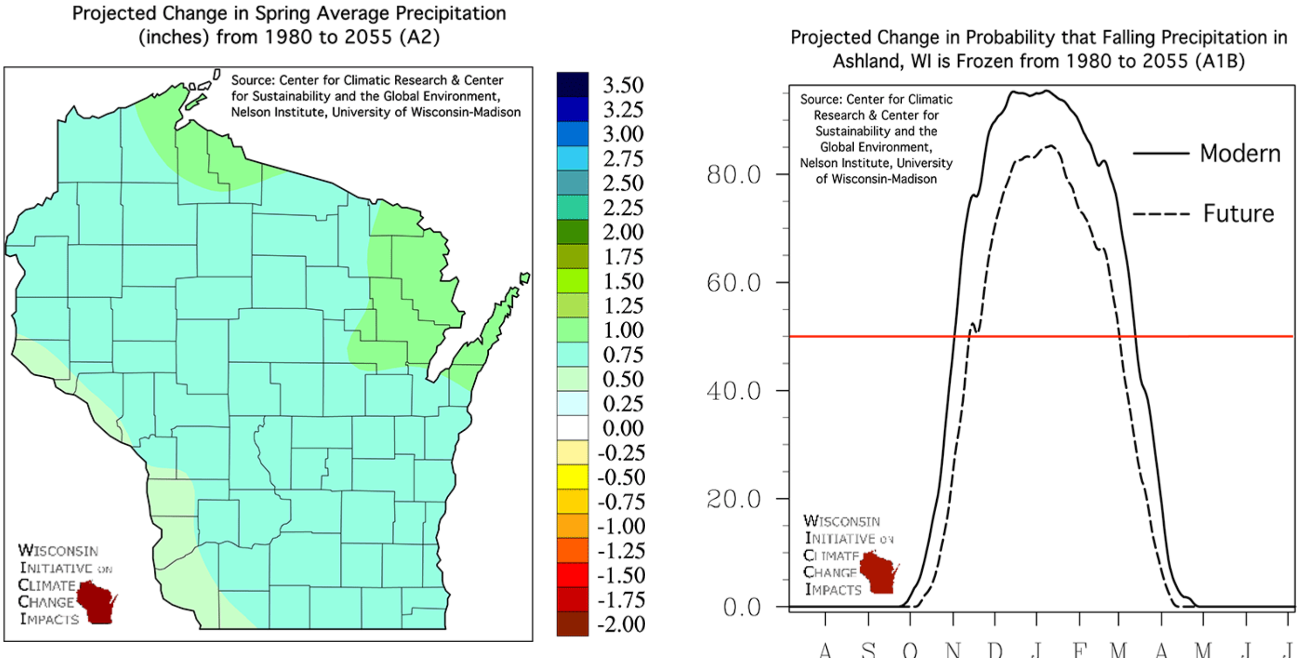


Figure 2: Figure 2. Projections for increased spring rain and increased rain *vs*. snow. (A) Increase in spring rain fall as an average of 14 GCMs. (B) Probability of frozen precipitation in different months during the year for Ashland WI under baseline (modern) and predicted (future) conditions (WICCI, 2011).

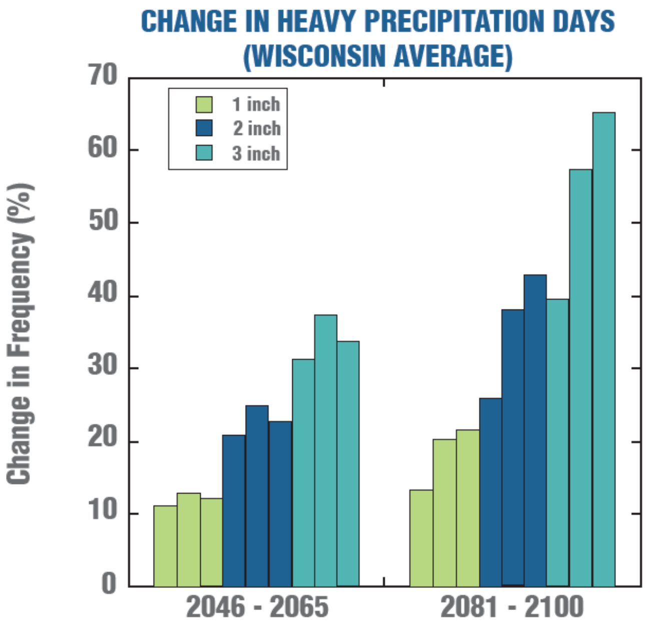


Figure 3. Percent change in precipitation for mid and end of century. The three bars for each rainfall amount represent the three emission scenarios, A2, A1B, and B1. Data from the Wisconsin Initiative on Climate Change Assessment Report (2011).

GOALS AND OBJECTIVES

From 2004 through 2007, SEWRPC and MMSD conducted a cooperative effort to update the MMSD 2020 facilities plan and to prepare that plan within a broader watershed-based framework as documented in SEWRPC Planning Report No. 50, *A Regional Water Quality Management Plan Update for the Greater Milwaukee Watersheds*, December 2007. (http://www.sewrpc.org/SEWRPCFiles/Publications/pr/pr-050_part-1_water_quality_plan_for_greater_mke_watersheds.pdf). This effort included modeling of the MMSD conveyance and storage system to evaluate the frequency of CSOs and SSOs and creation of a watershed model to assess pollution sources throughout the greater Milwaukee watersheds.[1] The models used in these assessments relied on current climate conditions. The need for longer range planning beyond the 2020 time horizon to address the possible effects of climate change has been identified, and the relatively recent availability of downscaled climate data makes consideration of climate change effects more feasible.

This project addresses how climate change alters the response of the MMSD system by incorporating projected temperature and precipitation values and computing their effects on groundwater storage amounts and wet weather flows to the MMSD conveyance and storage system. Downscaled time-series climate data from UW-Madison were applied in the MACRO model (Brown and Caldwell) to address these objectives:

- Determine CSO/SSO frequency, duration, and volume under projected climate change conditions.
- Evaluate driving forces related to climate parameters (e.g., rainfall and soil moisture).
- Incorporate findings into the Milwaukee working group WICCI report.
- Disseminate findings to Sweet Water Trust and develop fact sheets for public outreach.

METHODOLOGY

Downscaled Data. The statistical downscaling consists of two stages. First, the statistical relationship between the large-scale atmospheric state and local temperature /precipitation at the National Weather Service General Mitchell International Airport weather station is determined for each calendar month from the observational record (1940-2004). Second, this established statistical relationship is applied to predict the local temperature / precipitation given a climate model's large-scale atmospheric state.

Typically, statistical downscaling is used to relate the large-scale atmospheric state to one specific value of the temperature / precipitation at a point. With this approach, however,

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[1] *The greater Milwaukee watersheds include the Kinnickinnic, Menomonee, Milwaukee, and Root River watersheds; the Oak Creek watershed; the Lake Michigan Direct drainage area; the Milwaukee Harbor estuary; and the Lake Michigan nearshore area from the City of Port Washington in Ozaukee County to the Village of Wind Point in Racine County.*

the downscaled variability and extremes at the point will be too small unless the relationship between the large-scale and the point is artificially inflated (von Storch 1999), which then artificially exaggerates the climate change resulting from changes in the large-scale. Therefore, in order to both simulate the variability and extremes and to properly account for the effect of the large-scale on the weather at a point, the large-scale atmospheric state is related to the Probability Density Function (PDF) of temperature / precipitation at a point instead of a single value of temperature / precipitation. This approach takes into account that the large-scale atmospheric state does not completely specify the evolution of the atmosphere at small scales, instead the large-scale specifies the range and likelihood of particular outcomes at a point. A gridded precipitation/temperature product is created by interpolating the parameters of the PDFs from the weather station to a 0.1 ° x 0.1° grid. By interpolating the PDF parameters instead of the raw variables, the reduction in variance and extremes between stations that typically occurs when one interpolates the raw data is basically eliminated (Notaro et al, in press).

Given the "time series" of PDFs from the downscaling methodology described above, one way to create a downscaled time series of temperature / precipitation at a point is to draw random numbers from the particular PDF for each individual day in the record. Alternatively, one could use knowledge of the PDFs to create a monotonically increasing function that maps the particular value of temperature / precipitation on a particular day in the observed record to a new temperature / precipitation corresponding to a similar event under climate change. This scheme is called "remapping". Advantages of remapping over random number generation are 1) the covariances between variables and over time and space more accurately reflect nature and 2) the differences between present and future are more easy to discern because the changes only reflect the change due to global warming since the natural component of variability is exactly the same between the present and the remapped version of present. To calculate the function that maps the present to the future, first the time-mean Cumulative Distribution Function (CDF) is found from the time series of PDFs. Lastly, the CDF in the present and in the future is used to map the x^{th} percentile in the present to the x^{th} percentile in the future.

One difficulty with the present application is that the climate change prediction data is only available at daily time scales while hourly (and/or 15 minute) time scale data are required for this project. Therefore, to remap the current climate hourly data, the daily precipitation and maximum and minimum temperature data was first calculated from the hourly data. Next the daily data was remapped to make future daily data. Finally, for precipitation, the observed hourly data was multiplied by the ratio of daily precipitation in the future to daily precipitation in the present. For temperature, the change in the hourly temperature is a weighted average of the change in maximum and minimum temperature. The weights are simply linearly related to the actual hourly temperature such that hours when the temperature is close to the minimum temperature, the change is close to the change in the minimum temperature, and vice versa.

Downscaled projections have been produced for three different emissions scenarios (the A2, A1B, and B1, which represent high, medium and low increases, respectively, in greenhouse gasses), and for all models contributing daily data to the World Climate

Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset, used in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR4). For the results here, we use the A1B scenario.

***Scenario development*.** There are more than 14 global climate models, each with different predictions, which reflect that there is uncertainty associated with any predictive model. To account for uncertainty in this project, a "best case" and "worst case" scenario was defined using increased spring rainfall as the metric. This parameter was chosen based thresholds for SSOs/CSO's in the past 10 years. In the case of spring rainfall, the models were generally in agreement that rainfall would increase, where as the 14 GCM did not agree on changes in summer rainfall (**Figure 4**). In summer months, SSOs/CSOs generally occur when there is greater than 2 inches of rainfall in 24 hours. In spring months, these events occur with 1 inch of rainfall. Of the 14 GCMs available, the two that have projections in the upper 90 percentile and lower 10 percentile for increases in the number of spring precipitation events larger then 1 inch were chosen for use in the U.S. Environmental Protection Agency/ U.S. Geological Survey Hydrologic Simulation Program-Fortran (HSPF) continuous simulation model, which was used to develop flow inputs to MACRO. The choice of a particular distribution for rescaling the 1940-2004 data was estimated by interpolating the two models closest to either the 10th or the 90th percentile of a particular stressor (for a best case, or worst case, respectively).

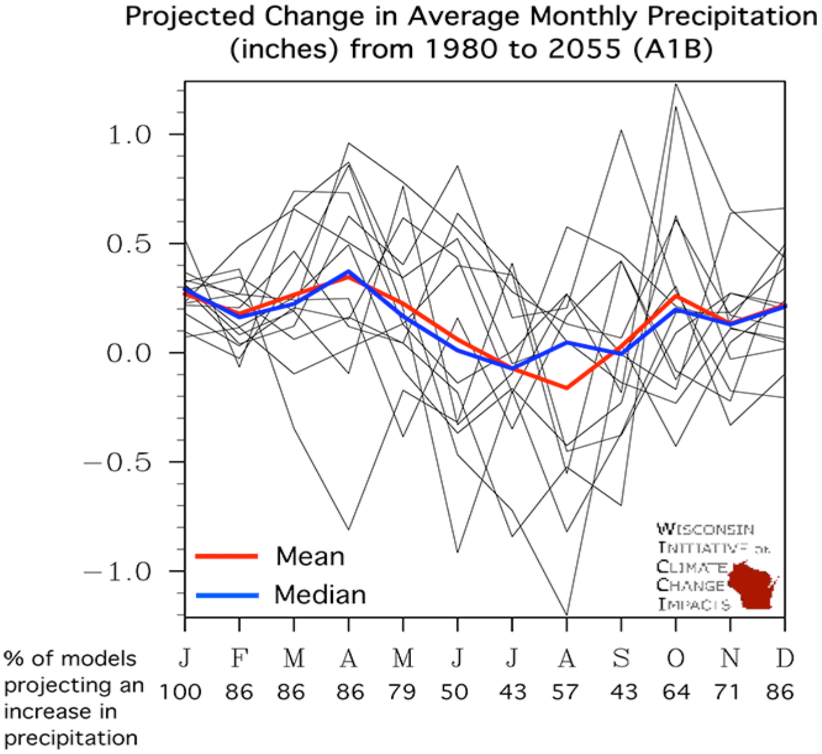


Figure 4. Change in precipitation plotted by month. The 14 GCM generally show increases in spring rains, with 12 of 14 climate models predicting increases in March and April rainfall amounts, and 11 of 14 climate models with increases in May. The models have variable predictions for changes in summer rainfall.

Modeling. Using the downscaled meteorological data provided by the WICCI Climate working Group, Brown and Caldwell modeled the hydrological conditions in response to temperature and precipitation changes (HSPF model) and the response of the MMSD system (MACRO model). The MACRO model was previously developed as part of the MMSD facility planning effort and takes into account the recommended facilities through 2020. For additional details, see Appendix A for Technical Memo provided by Brown and Caldwell.

Brown and Caldwell simulated conditions for three MACRO runs:

1. Current (current conditions with no change in climate)
2. Best case climate change scenario (DSN 10%)
3. Worse case climate change scenario (DSN 90%)

***Statistical Approach**.* Brown and Caldwell provided the HSPF and MACRO outputs for the three scenarios to the Great Lakes WATER Institute. A variety of statistical approaches were used to identify important benchmarks and correlating factors that lead to changes in CSO/SSO frequency, duration, and volume. These parameters were analyzed in terms of the full record (1940-2004) and seasonally. We defined Winter-Spring as November 1st to April 31st and Summer-Fall as May 1st to October 31st.

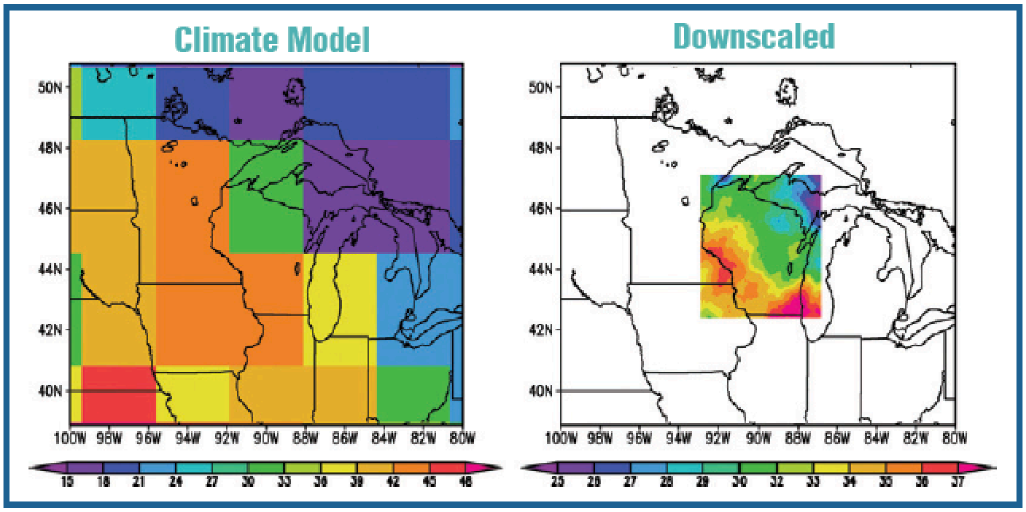
RESULTS

1. CLIMATE DOWNSCALING

Global climate predictions are made across a large spatial scale, therefore more specific predictions for Southeastern Wisconsin were generated as described in the methods section. An illustration of the improved resolution is shown in **Figure** 5 that highlights maximum daily temperature as predicted over a 200 km grid (left), and as predicted with higher spatial resolution over a 10 km grid (right). Global predictions will give only a single value for the very large grid area, whereas downscaling the data to a higher resolution allows for different predictions over a smaller area to be calculated, resulting in regional specific (e.g. Milwaukee Metro area) projections. We compared the current climate record of 1940-2004 and the adjusted records based on the “best” and “worst” case scenarios.

For the best case climate change scenario (i.e., DSN 10%) the average changes in average annual temperature and rainfall were 5.7°F and 0.7 inches, respectively. The change in Winter-Spring rains (Nov-Apr) was 0.9 inch and the change in Summer-Fall rains (May-Oct) was -0.2 inch.

Under worst case climate change conditions (DSN 90%) the average annual rainfall increased by 1 inch. The change in Winter-Spring rains (Nov-Apr) was 1.5 inches and the change in Summer-Fall rains (May-Oct) was -0.5 inch The most dramatic change was average temperature, which increased by 8.7 degrees. See Brown and Caldwell memo in Appendix A for detailed discussion.



Source: David Lorenz, Nelson Institute Center for Climatic Research, University of Wisconsin-Madison

Figure 5. Example of downscaled climate data (maximum daily temperature shown) for the State of Wisconsin. GCM predict changes in units, or grids, of 200 km. Downscaling of these predictions improve resolution to a finer scale, so differences can be predicted between northern Wisconsin and Southeastern Wisconsin for example.

2. MACRO MODEL OUTPUTS

MACRO Output. The recommended 2020 FP improvements were designed to provide a specified level of protection against SSOs, while meeting current permit conditions related to the frequency of CSOs. The MACRO model was used to estimate potential outcomes of changing climates, but the specific outcomes (e.g. increases in blending events, increases in CSOs) are influenced by the operating procedures that the model assumes (e.g., to meet the goal of a 5-year level of protection against SSOs). For example, blending events are used in the MACRO model as much as possible. Whenever the flow to Jones Island exceeds the plant capacity, blending is started and continues until the flow recedes to a rate that is less than the plant capacity. Therefore, the frequency of blending events is very high (**Table 1**). However, real time control and actual operating procedures would likely consider additional factors (e.g., weather forecast) before blending would be initiated. Overall, the increased blending and CSO events reflect additional pressures on the conveyance system due to projected climate change.

The MACRO model outputs for current climate and DSN 90% projected climate conditions are summarized in Table 1. There was only minimal change between the baseline conditions and the DSN 10% scenario, therefore, analysis of MACRO outputs only compared baseline and the worse case DNA 90% scenario. The output includes the numbers of CSO and SSO events and their volumes and durations, which were analyzed in relation to various parameters to assess the effect of increased rain amounts and frequencies during winter and spring time frames, and the effect of the combination of increased temperatures with increased rainfall during this same time frame. The winter and spring was the primary focus of this project because that was the time frame with the most agreement in projections (13 of 14 GCM predict higher rainfall totals and more intense storms). The scenarios used for this project projected an average decrease in rainfall in the summer and fall time frame, with some increase in specific storm amounts, which was reflected in only a slight increase in CSO and SSOs when comparing current conditions to projected conditions. In general, the analyses were divided into two seasons, winter and spring (referred to as Winter-Spring) and summer and fall (referred to as Summer-Fall).

Volume, Duration, and Pathogen Loads. We examined the relationships between rainfall amounts and the duration and volume of CSOs. As expected, there is a relationship between rainfall amount and volume of discharge (r2= 0.7). However, there is no relationship between rainfall amount and duration of event or duration of event and volume of discharge. Duration of an event may be linked to intensity of rainfall or the capacity of the soil for runoff infiltration and was investigated in a logistic regression model discussed below.

The distinction between volume *vs.* duration is important to note when considering potential health risks. A higher volume of CSO discharge during a given duration (e.g. 24 hours) is due to higher amounts of stormwater and therefore not necessarily a higher risk to human health. In some cases, pathogen concentration measured in the estuary leading to Lake Michigan is actually lower during CSO-dominated events compared to some storm events where stormwater is the major input into rivers (Newton et al., in press), which illustrates the possible effect on CSOs of dilution caused by large amounts of stormwater. However, the total load is likely higher when considering the higher stream discharges during a CSO in combination with long durations. Higher stream discharges also affect the dynamics of plume dispersion into Lake Michigan and could impact how likely it is that CSO-contaminated water will reach beach areas. Overall, a longer duration CSO is of high concern because the combined sewer area releases human fecal waste generated within the combined sewer area over the CSO duration, regardless of the volume of stormwater that dilutes the discharge. Longer durations have higher pathogen loads and a higher risk to human health. Therefore, when exploring CSO impacts we should consider both duration and volume of discharge. Potential exposure to pathogens in surface waters through recreational activities are less during Winter-Spring compared to Summer-Fall periods because there is little human contact with the water bodies during these months.

CSO Events. CSO frequency increases under projected worst case (DSN90%) climate change conditions (Appendix A and Table 1). Importantly, there was a 37% increase in the frequency of Winter-Spring CSOs, increasing from an average of 0.84 per year to 1.15 per year. There is also a 60% increase in Winter-Spring CSO volume with no increase in duration. There was essentially no increase in the frequency of Summer-Fall CSOs.

SSO Events. Overall, MACRO output demonstrated only slight increases in annual SSO frequency (0.14 to 0.16 per year) under worst case climate change conditions, with a small decrease in SSO volume. These small changes were within the range of variability expected in the MACRO model.

The frequency of CSOs is offset by the large increase in blending events. Due to the optimal operating procedures that the model assumes, i.e. near misses could easily be tipped into the direction of a CSO and the frequency of blending events is far greater than normal operating procedures. In contrast to actual operating procedures, blending events are used in the MACRO model as much as possible. Whenever the flow to Jones Island exceeds the plant capacity, blending is started and continues until the flow recedes to a rate that is less than the plant capacity. On the other hand, some small events could be avoided because MMSD operators are able to apply real-time judgment, rather than using the fixed rules of the MACRO model. Therefore, the frequency of blending events is very high in this simulation compared to the number of actual blending events that currently occur.

Overall, the frequency, volume, or duration of CSO and SSOs did not differ substantially between the current conditions and the "best case" climate change scenario, DSN 10% (see Appendix A, data not shown for duration in DSN 10% scenario). The most change occurred during worse case scenario, DSN 90%. ***Therefore, all additional statistical analyses compared current climate conditions with the "worst case" climate conditions.*** However, the DSN 10% and 90% bracket the range of projections for increased spring rains and either could occur.

Table 1: Frequency, Duration, and Volume of CSO, SSO, and Blending events between 1940-2004 under current climate conditions and worse case projected climate conditions. Winter-Spring is November 1st to April 31st and Summer-Fall is May 1st to October 31st.

Current	**CSO Frequency (events/yr)**	**CSO Volume (MG/yr)**	**CSO Duration (hrs/yr)**	**SSO Frequency (events/yr)**	**SSO Volume (MG/yr)**	**SSO Duration (hrs/yr)**	**Blending Frequency (events/yr)**	**Blending Volume (MG/yr)**	**CSO Volume (MG/event)**	**CSO Duration (hrs/event)**	**SSO Volume (MG/event)**	**SSO Duration (hrs/event)**
Winter-Spring	0.84	150	7.2	0.06	10	0.7	27	361	180	9	160	12
Summer-Fall	2.29	620	13.2	0.08	9	0.7	28	341	270	6	117	9
TOTAL	**3.13**	**771**	**20.4**	**0.14**	**19**	**1.5**	**58**	**702**	**246**	**7**	**136**	**10**

Projected												
Winter-Spring	1.15	240	8.0	0.05	5	0.4	25	257	209	7	110	8
Summer-Fall	2.31	694	13.3	0.11	12	1.0	28	345	300	6	115	9
TOTAL	**3.46**	**934**	**21.3**	**0.16**	**18**	**1.4**	**53**	**651**	**270**	**6**	**113**	**9**

STATISTICAL ANALYSIS

Rainfall and CSO/SSO occurrence. Because there were only small changes in CSOs under the DSN 10% scenario, the DSN 90% was used to compare MACRO output under current and projected climate conditions. The rainfall amounts that corresponded with CSO events were examined to determine rainfall thresholds. Under current conditions approximately 15% of Winter-Spring CSOs were triggered by 0.6 inches of rain or less in the preceding 24 hours and 17% of Winter-Spring CSOs were triggered by 1.0 inch or less. In addition, 90% of CSOs were triggered by less than 1.7 inches of rain in 24 hours (**Figure 6**). However, under projected climate conditions, 20% of Winter-Spring CSOs were triggered by rain below 1.3 inches in 24 hours and 90% of CSOs were triggered by rain below 2 inches. Likewise, in Winter-Spring all SSOs were triggered by 1 inch or more of rain under current climate conditions and 2 inches or more rain under projected climate conditions (data not shown).

Overall, under projected climate conditions the amount of rain that triggers a CSO event increases for the Winter-Spring time frame. Importantly, there are fewer CSOs triggered by very small rain amounts. CSO and SSO events may be not be triggered by small amounts of rain under projected climate conditions because of other factors such as differences in temperature and soil moisture values between the current climate and DSN 90% scenarios (warmer weather may cause the ground to thaw sooner, allowing infiltration of water creating less runoff).

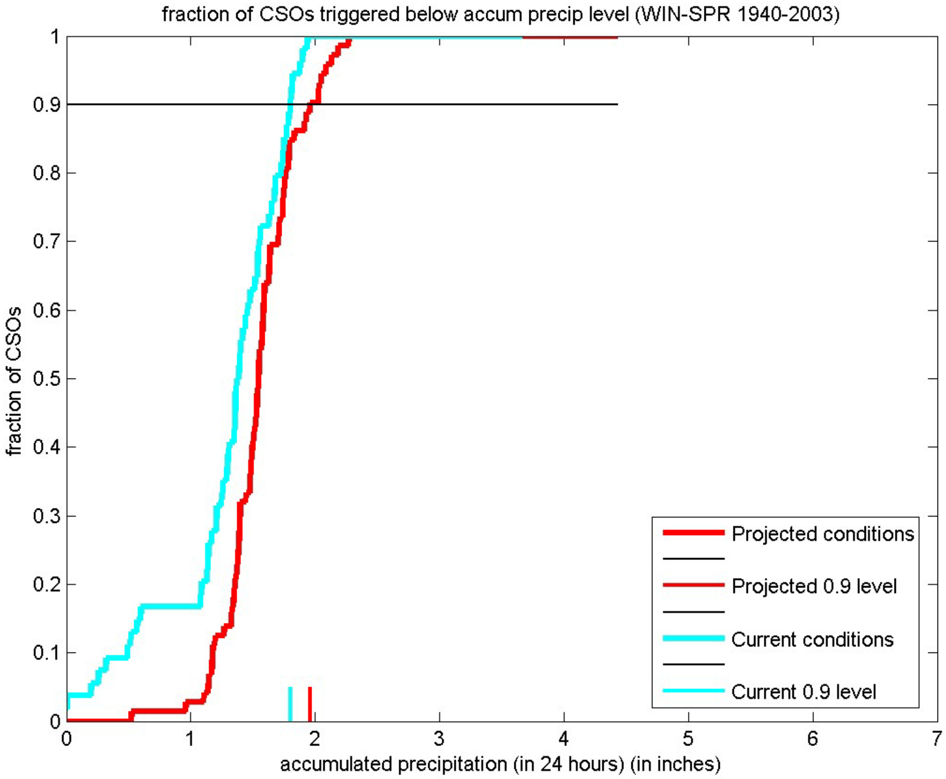


Figure 6: The fraction of CSOs triggered by a given amount of rain in 24 hours under current and projected climate conditions in Winter-Spring.

The Summer-Fall thresholds for CSO events were similar to Winter-Spring. The amount of rainfall that triggered 20% of the CSOs was 1.3 inches for both current and projected climate conditions. The rainfall amounts that triggered 90% of the CSOs was also nearly identical for current and projected conditions, and was 1.7 and 1.8 inches, respectively, similar (**Figure 7**). Figure 6 and 7 illustrate a small shift to the right in the Summer-Fall CSO occurrence compared with Winter-Spring occurrence under current climate conditions (e.g., CSOs occurred with smaller rainfall totals in Winter-Spring).

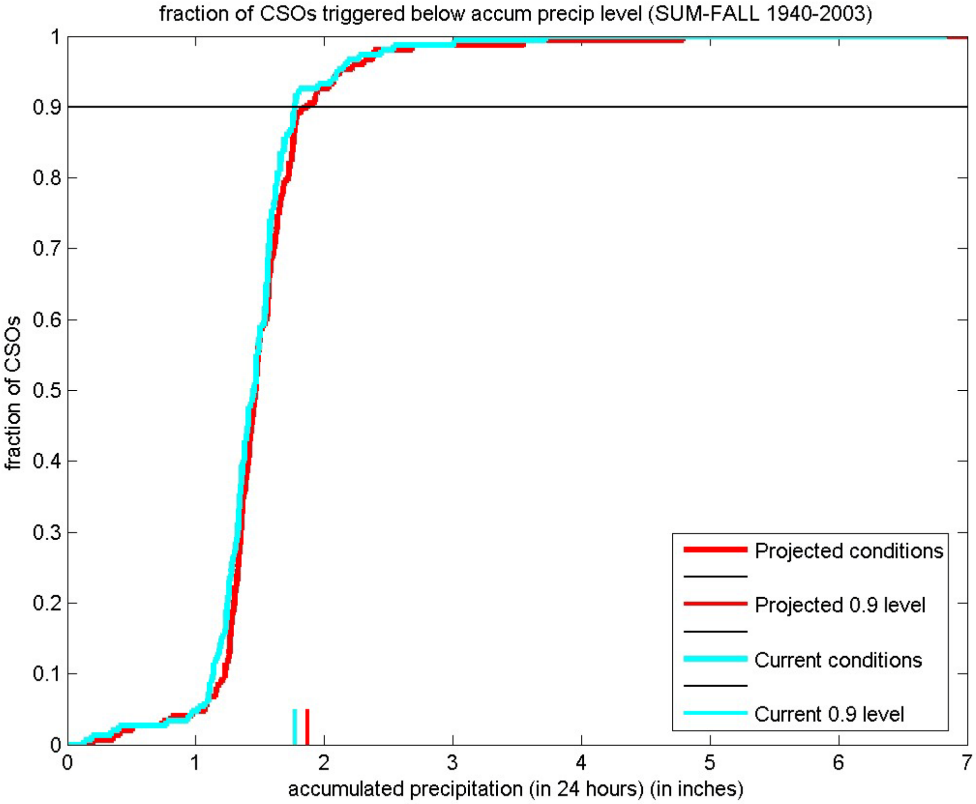


Figure 7: The fraction of CSOs triggered by a given amount of rain in 24 hours under current and projected climate conditions in Summer-Fall.

The probability that a CSO will occur under current climate conditions with varying rainfall intensities and amounts was also examined. Overall, for most rainfall intensities, there is a higher probability of a CSO in Winter-Spring compared with Summer-Fall, demonstrating that Winter-Spring is a more sensitive/vulnerable time frame. **Table 2** shows the probability for CSOs under different intensities for the Winter-Spring time frame and **Table 3** shows the probabilities of a CSO for the Summer-Fall time frame. There is a low probability of a CSO with 0.6 inches of rain occurring in from 4 through 24 hours in Winter Spring, whereas in Summer-Fall, this probability is 0. For intermediate intensities of rain, e.g. 0.8 to 2.0 inches over 4 to 24 hours, there is a higher probability of a CSO if this rainfall occurs in Winter-Spring compared with summer. In contrast, over 2 inches of rain in less than 24 hours results in a CSO regardless of season.

Table 2: Winter-Spring rainfall intensities. The probability that a CSO will occur at rainfall intervals in different time spans under current climate conditions.

Rainfall Intervals (inches)											
Time Span (hr)	0.0-0.2	0.2-0.4	0.4-0.6	0.6-0.8	0.8-1.0	1.0-1.2	1.2-1.4	1.4-1.6	1.6-1.8	1.8-2.0	2-2.2
2	0.13%	2.65%	21.59%	47.83%	83.33%	100%	100%				
4	0.07%	0.46%	4.58%	18.80%	81.00%	92.31%	100%	100%			100
8	0.09%	0.21%	1.04%	2.50%	10.64%	48.28%	91.67%	100%	100%	100%	100
12	0.10%	0.20%	0.91%	2.65%	1.39%	10.26%	62.50%	100%	100%	100%	100
24	0.11%		0.82%	0.64%	2.47%	5.66%	14.29%	50%	69.2%	76.9%	100

Table 3: Summer-Fall rainfall intensities. The probability that a CSO will occur at rainfall intervals in different time spans under current climate conditions.

Rainfall Intervals (inches)											
Time Span (hr)	0.0-0.2	0.2-0.4	0.4-0.6	0.6-0.8	0.8-1.0	1.0-1.2	1.2-1.4	1.4-1.6	1.6-1.8	1.8-2.0	2-2.2
2	0	0	6%	21.43%	43%	80%	100%	100%	100%	100%	100
4	0	0	0	5.1%	25.5%	55.17%	89%	100%	100%	100%	100
8	0	0	0	0	1.9%	19.35%	76.13%	90%	100%	100%	100
12	0	0	0	0	2%	14.29%	58.62%	88%	100%	100%	100
24	0	0	0	0	0	2.6%	27%	50%	86%	94%	100

Contributing factors to CSO occurrence: The MACRO model is driven by HSPF, a runoff model that includes various storage compartments, which are influenced by precipitation, evapotransportation, and groundwater levels. Preliminary data analysis that characterized CSOs with various soil moisture variables and accumulated precipitation shows a marked effect of the Upper Zone Storage (UZS) variable on CSO occurrence, while no structuring effect can be seen with the other soil moisture variables. UZS is the component in the model that simulates the storage capacity within the macropores of soil. Moreover, the effect of UZS seems to be more pronounced in the Winter-Spring seasons, when CSOs occurred only at high (>=1.1 inches) UZS values, indicating conditions characterized by large amounts of water already in storage and little room available to store more, leading to higher runoff amounts.

A number of CSOs in Winter-Spring are triggered by very little precipitation (<0.6 inches), but high UZS values. In the Summer-Fall seasons the distribution of CSOs with respect to UZS values is more spread, and there are large rain events triggering CSOs at lower UZS values. These observations suggest that the UZS variable and accumulated precipitation are major contributing factors in CSOs (which is hardly surprising), and that temperature might also have an effect. These results clearly illustrate that soil moisture plays a large modulating factor for runoff and therefore, CSO occurrence.

From a management standpoint it might be desirable to find a combination of variables that might predict the occurrence of a CSO in a particular tunnel event. While maxUZS and total precipitation are not such variables, the change of UZS at the beginning of a tunnel event was considered. Under current climate conditions, 75.9% of Winter-Spring CSOs occur with the average UZS gradient above 0.0105 in/hr for the first 3 hours of the tunnel event. 77.4% of Summer- Fall CSOs happen with the UZS gradient above 0.0196 in/hr for the first hour of the tunnel event. Under projected climate conditions, 76.8% of Summer-Fall CSOs happens with the UZS gradient above 0.0222 in/hour for the first hour of the tunnel event. 81.9% of Winter-Spring CSOs happen with the average UZS gradient above 0.013 in/hour for the first 3 hours of the tunnel event. These results again underscore the importance of the UZS variable in CSO occurrence.

We built a logistic regression model for the onset of CSOs for all four quadrants of the data (Winter-Summer/ Current conditions-worse case climate conditions), that originally considered all soil moisture variables, current and averaged over tunnel events, their maximum and minimum values, and one and three hour gradients together with accumulated (2, 4, 8, 12, 24 hours) precipitation, total precipitation in a tunnel event and accumulated precipitation until a CSO would occur. Forward, backward and random variable selection methods were performed. Results showed no significant difference between current conditions and the climate model, but a seasonal separation was detected. In the Summer-Fall season, a good regression model can be built using the maximum of the UZS variable during a tunnel event together with the total precipitation during the tunnel event. Alternatively, a good model is provided by the accumulated precipitation until a CSO would occur and the one hour UZS gradient at the beginning of tunnel events. Both models are deemed adequate based on goodness of fit tests, and an empirical check on the data. The latter model may prove to be more useful from the management standpoint, if real-time tracking of these variables is feasible. Similarly, in the Winter-Spring season we can build a regression model using the maximum of the UZS variable during a tunnel event together with the total precipitation during the tunnel event. Comparing this model to its Summer-Fall counterpart, we see the increased influence of the upper zone storage variable supporting our earlier observations. In the Winter-Spring a good model is also given by the accumulated precipitation until a CSO would occur and the three hour UZS gradient at the beginning of tunnel events (which again may provide more predictive capabilities - as they can be determined before the onset of a CSO). While goodness of fit tests support both models, an empirical check on the data reveals the latter model fitting observations slightly better.

Table 4. Logistic regression models that are predictive of CSO occurrence current conditions and (climate modeled conditions).

	Summer-Fall		Winter-Spring	
Predictor	Coefficient	P-value	Coefficient	P-value
Constant	-18.693 (-16.078)	0.0 (0.0)	-48.209 (-36.383)	0.0 (0.0)
maxUZS	9.716 (7.996)	0.0 (0.0)	36.541 (25.815)	0.0 (0.0)
Total precip.	5.274 (4.928)	0.0 (0.0)	3.020 (3.901)	0.0 (0.0)

	Summer-Fall	
Predictor	Coefficient	P-value
Constant	-9.571 (-9.465)	0.0 (0.0)
First hour UZS gradient	4.362 (4.511)	0.0 (0.0)
Accumulated prec. till CSO	6.337 (6.103)	0.0 (0.0)

	Winter-Spring	
Predictor	Coefficient	P-value
Constant	-6.432 (-7.630)	0.0 (0.0)
Three hour UZS gradient	14.599 (8.706)	0.002 (0.007)
Accumulated prec. till CSO	3.731 (4.552)	0.0 (0.0)

The logistic regression may be hard to use as a predictor since measuring soil moisture in real-time is a challenge and the MACRO models are not running in real-time and therefore cannot handle real-time soil moisture values. However, future operational models may make this feasible. Realistically, the logistic regression is most useful as verification of the operating protocols MMSD currently uses. For instance, when soil moisture is high, there is a higher risk of CSO occurrence. Therefore more volume should be reserved in the ISS system for runoff during this time.

In summary, rainfall alone is not a good predictor of CSO occurrence. MMSD has a large storage system and service area so rainfall does not correlate with excess wastewater volume (MMSD Facilities Plan, 2007). Under current climate conditions in the Winter-Spring time frame, CSOs occur during very small rain events (0.6 inches or below), but this does not occur in the Summer-Fall time frame. During large rain events, e.g., 2 inches of rain in less than 24 hours, there is a 100% probability of CSO regardless of season (**Table 2 and 3**). Because the effects of climate change are being evaluated using a simulation of the conveyance and storage system, CSOs and SSOs may not actually occur under conditions of very low or no rainfall and this result could be a model anomaly. Alternatively, CSO occurrence during very small rain events could be caused by rare meteorological conditions (e.g. excessive rainfall in the preceding week, very large snow melt). Regardless of the likelihood of an actual occurrence, the MACRO model does simulate more stressors on the conveyance and storage system in Winter-Spring compared with Summer-Fall time frames.

Part 2: EXTENSION OF MODELLING 1940-2010

Two additional MACRO model runs were added to this project:[2]

1. 2010 MMSD Facilities, 1940-2010, baseline (i.e. current) climate conditions
2. Recommended MMSD facilities under the 2020 facilities plan (FP), 1940-2010, baseline (i.e. current) climate conditions

Facility Improvements. The Recommended MMSD facility improvements under the 2020 FP significantly decrease SSO average annual frequency and volume (from 0.56 events/yr to 0.14 events/yr and about a 140 MG/yr reduction in volume) (**Appendix B**, Brown and Caldwell memo 3/21/11).[3] Overall, there was a 75% reduction in frequency and 84% reduction in volume. The recommended 2020 FP improvements were designed to provide a specified level of protection against SSOs, while meeting current permit conditions related to the frequency of CSOs. While it is difficult to make a direct comparison between SSO reduction due to improved facilities and a potential increase in CSO frequency (10% increase) and volume (21% increase) under worst case climate change conditions (see Table 1), it does appear that system improvements under the 2020 FP would be expected to offset, but not completely eliminate, CSO volume and frequency increases under worst case climate change conditions. Further, SSOs contain concentrated amounts of human fecal pollution, while CSOs are diluted with rainwater. This analysis was performed to

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[2] *The simulation period was extended to 2010 to enable consideration of large storms that occurred since mid-2004 and to allow for computation of 10-year averages to analyze trends.*

[3] *Because the current climate conditions applied for the evaluation of the effects of climate change are based on a January 1940 through June 2004 climate condition, and the current climate conditions applied for the analysis set forth in Appendix B are based on a simulation period from January 1940 through December 2010, the "current" climate condition results differ somewhat between the two analyses.*

benchmark the effect of facilities improvements compared with the effects of climate change. Continued improvements in facilities are critical to offset projected increases in rainfall intensity or frequencies in the future.

CSO/SSO Trends. We have observed a trend towards an increased number of CSOs and SSOs in the past years so we further explored this using the modeled current climate conditions under the recommended 2020 FP improvements. A 10-year moving average was used to determine if there is a trend towards an increased number of CSOs and SSOs within the past 71 years (**Figure 8**). Starting in the mid- 1960's we see a statistically significant shift towards more CSOs (t-test, p≤0.05). Assuming that 2010 MMSD facilities are in place, the climate from the mid-1960s through late 1990's appear to exhibit a trend toward conditions that increase CSOs and SSOs, but it is unclear if this trend is within the normal cyclic nature of climate patterns or if it reflects long term trends.

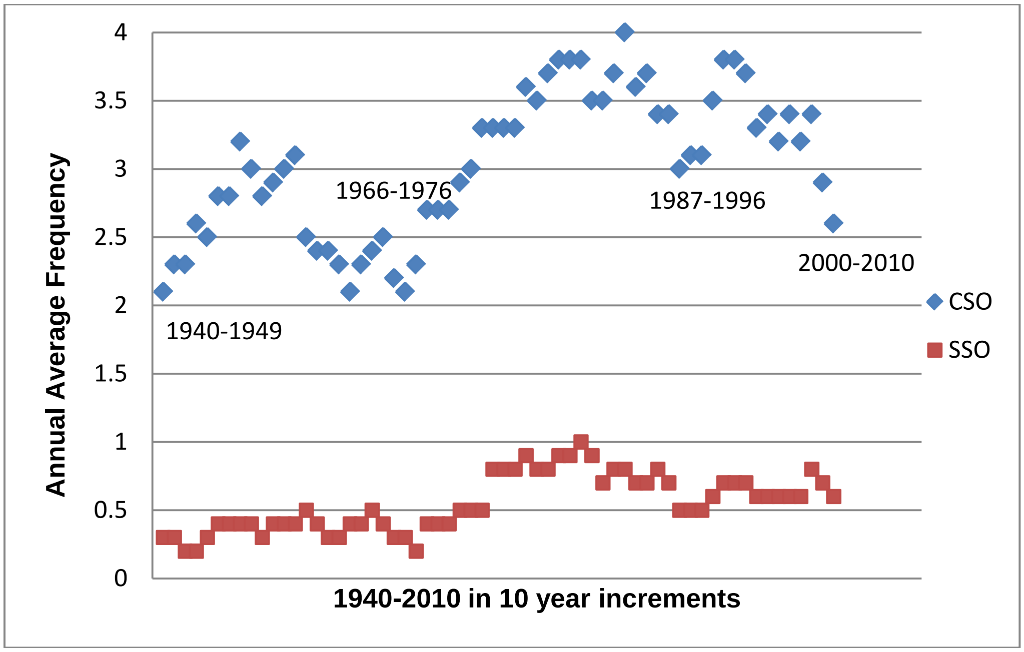

Figure 8: The 10 year moving average of occurrence of CSOs and SSOs between 1940-2010 under current climate conditions (i.e., first diamond represents 1940-1949, second diamond represents 1941-1950).

Conclusions and Recommendations

With no improvements in MMSD facilities beyond current plans and no adaptation strategies, CSOs may increase in the Winter-Spring time frame by mid-century due to climate change. This increase is very small ("best case" scenario) to moderate ("worst case" scenario) and these impacts should be considered in the context of ongoing improvements and additional stressors such as aging infrastructure and urban development.

Winter and spring time frames are most sensitive to CSOs, where 20% of the CSOs were triggered with 1.0 inches of rainfall and 90% of the CSOs were triggered by 1.7 inches. Combinations of frozen ground and/or snow melt and small amounts of rainfall triggered CSOs in the MACRO model, which may not actually occur in practice. Under climate change conditions, the increase in air temperature reduced the number of CSOs occurring with very low amounts of precipitation. MACRO model output showed the Summer-Fall timeframe also had a threshold of 1.7 inches of rainfall associated with 90% of the CSOs. Mitigation strategies to reduce climate impact could target reducing runoff in the winter and spring time frames because rainfall amounts that trigger some CSOs may be more manageable. Further projected increased rainfall in winter and spring are more certain than the increased storm frequencies and intensities projected for summer and fall.

Steep increases in Upper Zone Storage (UZS) at the beginning of storm events were correlated with CSOs. UZS is a compartment in the HSPF model and reflects the amount of storage in marcopores of the upper layer of soil (e.g., soil moisture). Currently real time soil moisture measurements or predictions are not available, but such measurements could provide useful supplemental information for real time operation of the ISS during storm events

Continued improvements to MMSD conveyance and storage facilities are important for preserving and protecting water quality and protecting human health under current climate conditions. When considering improvements, the potential additional benefit for adapting to climate change should be considered.

Stakeholders are interested in information that quantifies the effect of climate change. This project offered the opportunity to quantify climate change impacts using sophisticated water resource planning tools. These results will be of interest to the broader water resource community and will be made available

Education and Outreach

Milwaukee Working Group. The WICCI Milwaukee Working Group started in February 2008 to facilitate a multidisciplinary approach to address the impacts that climate change will have on the most urbanized area in the state of Wisconsin and Lake Michigan. The goals of this working group are to (1) organize a critical mass of researchers, professionals, and policy makers that span a wide range of disciplines (e.g., water resources, hydrology, public health, engineering, urban planning, economics); (2) explore the impact of recent climate changes on the urban environment and relevant infrastructure; (3) detail how future climate change is likely to influence the Milwaukee urban environment; and (4) formulate recommendations for adaptive management strategies. The Milwaukee working group has identified the following areas that could be sensitive to climate change: water resources, the built environment, and public health. Specifically, the group identified the frequency of CSOs and SSOs and water quality as potential sensitivities to climate change (ref WICCI report) and recommended that detailed analyses be conducted to evaluate the level of sensitivity and the potential outcomes for a range of climate scenarios to aid in the development of adaptation strategies.

The Milwaukee Working Group, along with 12 other groups in WICCI submitted an assessment report; Wisconsin's Changing Climate: Impacts and Adaptations. The report was published in January 2011 and can found on the WICCI website, http://www.wicci.wisc.edu/publications.php. This report was written for dissemination to the public, decision-makers, resource managers, and scientists to be used in future management and policy decisions. This report identifies the vulnerabilities and sensitivities in Milwaukee area along with ideas on how to develop adaptation strategies. The use of modeling in conjunction with the climate projections for future facility planning efforts is highlighted in this report. Future WICCI reports will summarize the findings of this project so that it could act as a framework for others to duplicate these efforts.

The Sweet Water Trust is a collaborative effort responsible for promoting and implementing projects to improve water quality in the greater Milwaukee watersheds. The results and implications of this study will be disseminated through the Executive Council and the Science Advisory Committee of the Sweet Water Trust of which Sandra McLellan and Mike Hahn are members.

The results of this study have also been presented by Sandra McLellan at the AAAS Annual Meeting in February 2011 in Washington D.C. (When It Rains, It Pours: Climate and Waterborne Disease Transmission in Urban Coastal Ecosystems). Dr. McLellan also discussed the project on Wisconsin Public Radio (UW-Milwaukee professor researches effects of climate change on local sewer systems) and was interviewed for National Geographic (Three surprising ways global warming could make you sick). In June 2011, Dr. McLellan presented at Capitol Hill Oceans Week in Washington, D.C. on a panel entitled "*Emerging Public Health Impacts of a Changing Ocean and Great Lakes".*

Public outreach tools such as fact sheets for public dissemination and updates to the McLellan Lab informational website on climate change will be developed within the next six months. These will be developed in collaboration with MMSD.

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Appendix A

Brown AND Caldwell

Technical Memorandum

250 East Wisconsin Avenue, Suite 1525
Milwaukee, WI 53202

Project No.: 139071

Project Title: Climate Change Impact on Overflows

Project Manager: David Bennett

HSPF Modeler: Julie McMullin

MACRO Modeler: David Perry

Client: Southeastern Wisconsin Regional Planning Commission

Team: Great Lakes Water Institute

Date: May 18, 2010

1. Background and Objectives

The Southeastern Wisconsin Regional Planning Commission (SEWRPC) in partnership with the Great Lakes Water Institute (GLWI) is evaluating the impacts of climate change on water quality in Southeastern Wisconsin. One of the elements of this study is an evaluation of potential changes in combined and separate sewer overflows (CSOs and SSOs) from the Milwaukee Metropolitan Sewerage District (MMSD) system. The objective of this analysis is to estimate changes in the frequency and volumes of CSOs and SSOs under a few climate change scenarios.

Key objectives of the analysis are:

- Simulate long term hydrologic conditions in response to changing precipitation and temperature scenarios.
- Simulate the long term response of the MMSD system to estimate SSO and CSO frequencies and volumes in response to changing climate scenarios.

2. Modeling Tools

Three cases have been simulated in this analysis: a current climate case and two climate change scenarios. Each case is analyzed using the Hydrologic Simulation Program – Fortran (HSPF) model and the MACRO model of the MMSD system.

The HSPF model is a tool to simulate the continuous hydrologic conditions in the soil in response to the input meteorological conditions (primarily rainfall and temperature). The hydrologic soil conditions are the runoff, infiltration, and soil moisture storage. The HSPF simulation results are used as input to the MACRO model.

The MACRO model is a water balance representation of the MMSD conveyance and storage system that was used for the MMSD 2020 Facilities Plan to compute the frequencies and volumes of CSOs and SSOs related to the operations of the Inline Storage System (ISS). Using the hydrologic results from HSPF, MACRO simulates the generation of flow in the sewer system and accounts for the volume of flow treated by the water reclamation facilities, stored in the ISS, and overflowing as CSOs and SSOs.

For this analysis, the MACRO model is configured to represent facilities recommended in the 2020 Facilities Plan. Noteworthy facilities in the plan include additional treatment capacity at the South Shore Water Reclamation Facility and additional ISS pumping capacity. The model also includes committed facilities such as the North 27th Street ISS extension and the harbor siphon upgrades.

3. Baseline Case Description

The baseline simulations use the meteorological conditions at the General Mitchell International Airport for the 64.5-year period from January 1940 through June 2004. This is the same 64.5-year period that was used in the 2020 Facilities Plan analysis. The flow generation parameters in the MACRO model represent the population and land use of the "Revised Future 2020" conditions as prepared by SEWRPC.

4. Climate Change Case Descriptions

The climate change cases have different precipitation and temperature time series that represent alternative climate change scenarios. The time series were developed by the meteorological team at UW-Madison and were provided to Brown and Caldwell by SEWRPC in the form of Water Data Management (WDM) files suitable for HSPF input. There is a unique WDM file for each climate change scenario.

Two climate change scenarios were evaluated. The first climate change scenario (abbreviated as DSN10%) has higher average annual temperatures but is otherwise similar to the baseline case in average precipitation amounts. The second climate change scenario (abbreviated as DSN90%) is more severe, having a significantly greater average annual temperature. The peak rainfall intensities of the large events are significantly greater than those of the baseline case, even though the average annual precipitation amounts are only slightly higher.

For the climate change simulations, model configuration parameters were assumed to have not changed from the baseline case. Therefore, Brown and Caldwell did not make any modifications to the HSPF calibration parameters or the MACRO model parameters. The precipitation and temperature input time series to HSPF were the only changes from the baseline model runs.

5. MACRO Simulations: CSO and SSO Frequency and Volume

The MACRO model simulates ISS-related overflows from the MMSD system. ISS-related overflows are the largest source of wastewater overflows in the MMSD service area. Overflows from the local collection systems and overflows from the MMSD system that are caused by restrictions in the conveyance system are not included in the MACRO model. However, these other sources of overflow are relatively small compared to the ISS-related overflows.

Before discussing the MACRO simulation results, the reader is reminded that the MACRO model is a screening level model that produces simulation results that are useful to study the impact of various system wide changes on the overall response of the MMSD system. The MACRO model was developed to quickly simulate the MMSD system response over a long simulation period using fundamental water balance principles. Therefore, MACRO is well suited to this study because it can show relative changes from a baseline.

Model results should not be interpreted as rigorously accurate model predictions. The absolute values of simulated overflow volumes or the frequency of overflows should be interpreted from the perspective of the intended level of model accuracy. This is particularly true of the simulated frequency of ISS-related SSO events because they are relatively rare in the 64.5 year period. For example, in the baseline case the ISS-related SSO frequency is 0.14 events per year because there are only 9 events in the 64.5 year simulation period.

Table 1 summarizes the average annual frequency and volume of overflows as simulated by the MACRO model. The table also summarizes the average annual temperature and rainfall depths, and the maximum rainfall intensity of the most intense hourly rainfall value in the period of record (for the August 1986 event). Figure 1 summarizes the results of Table 1 in bar graphs for CSO and SSO volume.

In general, the simulated response of the DSN10% climate change scenario is very similar to the baseline case. In the DSN10% scenario there is a decrease in average annual ISS-related SSO volume and a decrease in the ISS-related SSO frequency. The average annual CSO volume is 1% less than the baseline and the CSO frequency is still approximately 3 CSOs per year, as in the baseline case.

The simulated CSO volume of the DSN90% climate change scenario is 21% greater than the baseline, and the CSO frequency is greater than the baseline, changing from 3.1 to 3.5 CSOs per year. The SSO volume is essentially unchanged, but the simulated SSO frequency is slightly higher.

Figure 2 shows the simulated CSO volumes for each calendar year during the 64.5-year simulation period. Climate change scenario DSN90% produces greater CSO volumes than the baseline case in the larger events and is similar to the baseline case in the smaller events.

Figure 3 shows the simulated ISS-related SSO volumes for each calendar year. The largest simulated SSO in the baseline case is the March 1960 event, which was a snow melt event with significant rainfall. In the climate change cases (both DSN10% and DSN90%) the temperatures are warmer earlier in the year leading up to the March 1960 event. Consequently, the timing of the snow melt does not coincide with the March 1960 rainfall event, and there is no simulated SSO in 1960 for the climate change cases. In many of the other years, the simulated SSO volumes for the climate change cases are similar to the baseline results. The DSN90% case contains two additional SSO events (August 1986 and August 1987) that are not experienced in the baseline simulations. The simulated SSO volumes of the two additional events are approximately 50 MG.

Table 1 **Simulation Results**			
	Average Annual Temperature		
	Baseline	DSN 10%	DSN 90%
Average Temperature (degrees F)	46.6	52.3	55.3
Temperature Std Deviation (degrees F)	20.7	19.6	19.6
	Average Annual Rainfall		
	Baseline	DSN 10%	DSN 90%
Average Depth (inches/year)	31.8	32.5	32.8
Max Hourly Intensity (inches/hour) (August 1986 event)	3.06	2.90	3.94
	Average Annual Overflow Volumes		
	Baseline	DSN 10%	DSN 90%
ISS-related SSO (MG/year)	19	12	18
ISS-related CSO (MG/year)	771	761	934
Total Overflow (MG/year)	790	773	952
	Average Annual Overflow Frequencies		
	Baseline	DSN 10%	DSN 90%
ISS-related SSO Frequency (events/year)	0.14	0.12	0.16
ISS-related CSO Frequency (events/year)	3.13	3.05	3.46

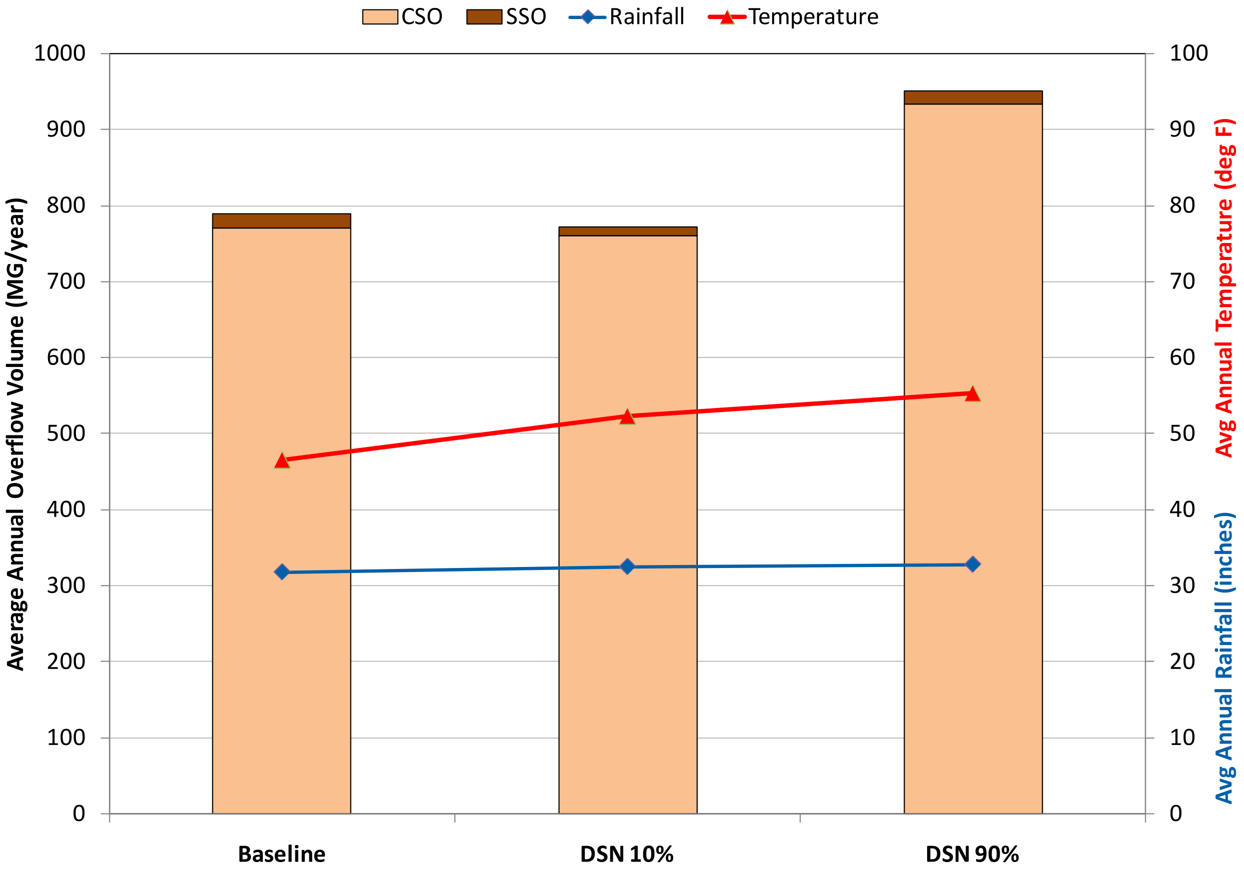

Figure 1: Average Annual Simulation Results

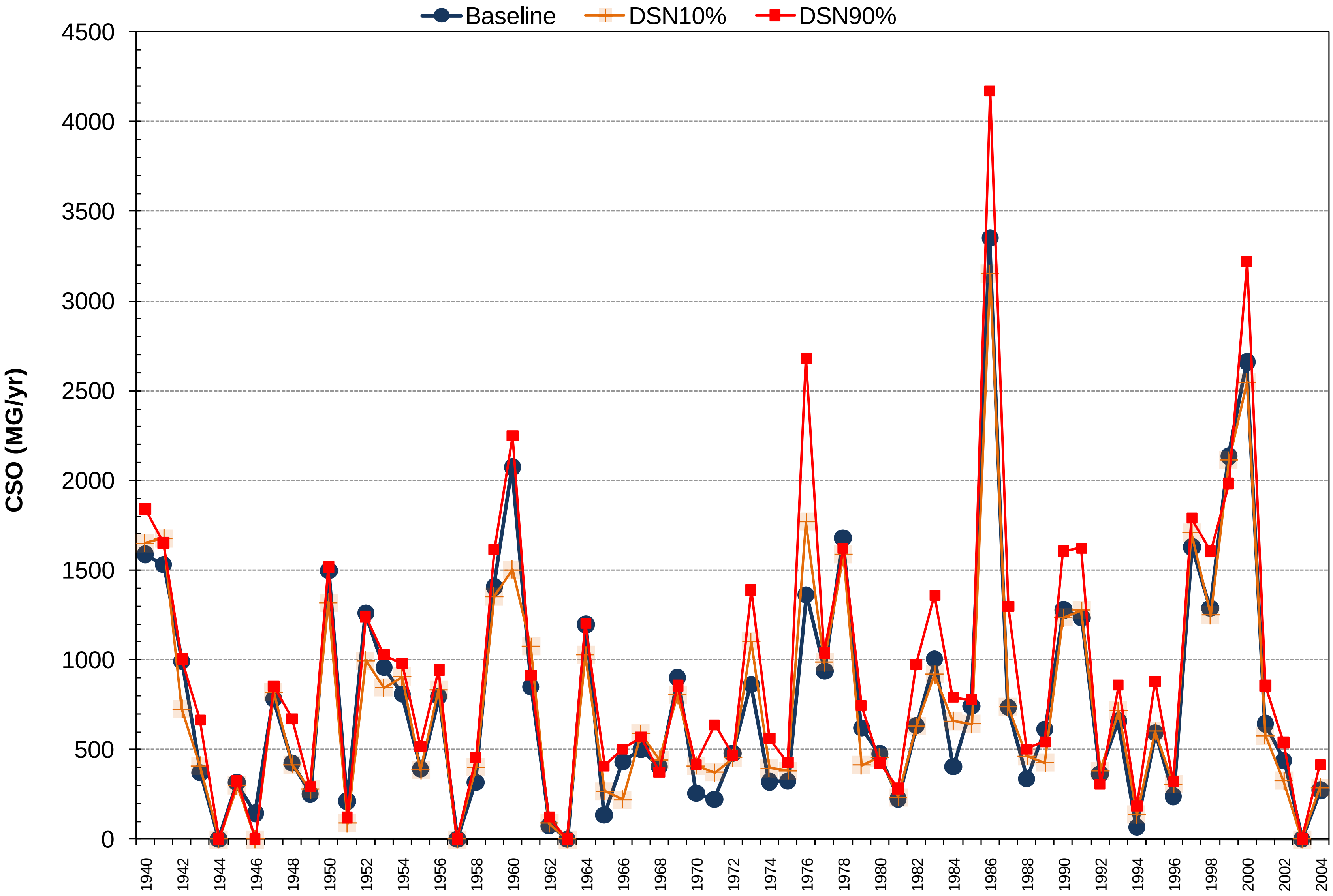

Figure 2: Simulated CSO Volume in Each Year

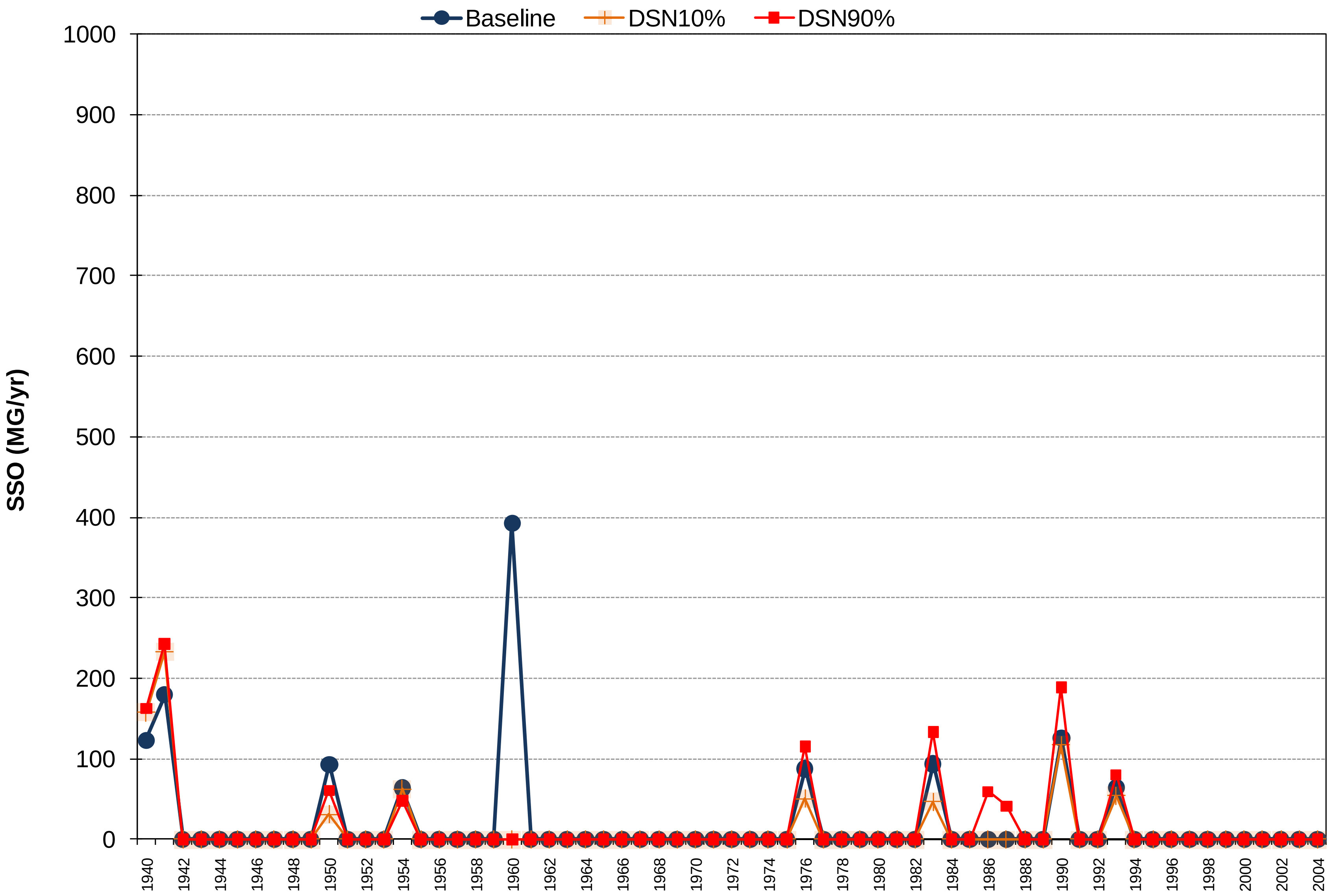

Figure 3: Simulated ISS-related SSO Volume in Each Year

Appendix B

Brown AND Caldwell

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Technical Memorandum

Project No.:	139071
Project Title:	Climate Change Impact on Overflows
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Client:	Southeastern Wisconsin Regional Planning Commission
Team:	Great Lakes Water Institute
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Subject:	Part 2: Extension of Modeling Using Historic Climate from 1940 to 2010

1. Introduction

The Southeastern Wisconsin Regional Planning Commission (SEWRPC) in partnership with the Great Lakes Water Institute (GLWI) is evaluating the impacts of climate change on water quality in Southeastern Wisconsin. One of the elements of this study is an evaluation of potential changes in combined and separate sewer overflows (CSOs and SSOs) from the Milwaukee Metropolitan Sewerage District (MMSD) system.

The first part of this study used a 64.5-year simulation period from January 1940 to June 2004 because this was the simulation period used in the MMSD 2020 Facilities Plan (2020 FP) analysis. The findings from the first part of the study were reported in the technical memorandum dated May 18, 2010.

This memorandum documents Part 2 of the analysis in which the historic climate record used for the model simulations was extended to 2010. These MACRO model simulations cover the 71-year period from January 1940 to December 2010. All of the simulations in Part 2 used the historic climate conditions instead of the climate change scenarios.

2. 2010 Facilities and Historic Climate from 1940-2010

One MACRO simulation was run with the model configured with 2010 facilities, the projected population and land use for the year 2020, and the historic climate from 1940-2010. The 2010 facilities are the MMSD facilities in operation in the year 2010 including facilities such as the North 27th Street ISS extension and the harbor siphon upgrades.

The projected values for population and land use for the year 2020 were defined by SEWRPC. (In the 2020FP these development projections were called the “revised future 2020” values.)

3. Recommended Facilities of the 2020 FP from 1940-2010

A second MACRO simulation was run with the model configured to represent facilities recommended in the 2020 Facilities Plan, the projected population and land use for the year 2020, and the historic climate from 1940 to 2010. Noteworthy facilities in the plan include additional treatment capacity at the South Shore Water Reclamation Facility and additional ISS pumping capacity. The recommended facilities in the 2020 FP were proposed to achieve a 5-year recurrence interval level of protection against SSOs under the historic climate conditions. (This model configuration was previously called the “baseline” case in the memorandum documenting the first part of the analysis.)

4. MACRO Simulations: CSO and SSO Frequency and Volume

The results documented below are extensions of the table and figures in the previous memorandum. The table and figures include the two additional simulations with the historic climate extended to 2010. Descriptions of the meaning of the various terms are given in the previous memorandum.

Table 1 summarizes the simulated average annual frequencies and overflow volumes. Figure 1 summarizes the results of Table 1 in stacked bar graphs for CSO and SSO volumes. The total overflow volume is the sum of the SSO and CSO volumes. The average annual overflow volume in the simulation of the 2010 facilities is greater than the average annual overflow volume in any of the climate change scenarios. The average annual total overflow volume is reduced by the recommended facilities in the 2020 FP; the reduction in total overflow volume is primarily due to the reduction in the SSO volume.

Figure 2 shows the simulated CSO volume for each calendar year. From year to year the simulated CSO volume is highly variable. The extension of the data from 2004 to 2010 resulted in simulated CSO volumes that were lower than average in 2005 and 2006 and higher than average values in 2008 and 2010.

Figure 3 shows the simulated ISS-related SSO volumes for each calendar year. The simulated SSO frequency for the recommended facilities in the 2020 FP is one fourth of the frequency of the SSOs with the 2010 facilities. Similarly, the simulated SSO volume with the recommend facilities is one sixth of the volume with 2010 facilities.

Table 1
Simulation Results

	Model Configuration				
Facilities	2010 Existing	Recommended 2020FP 5-yr SSO LOP	Recommended 2020FP 5-yr SSO LOP	Recommended 2020FP 5-yr SSO LOP	Recommended 2020FP 5-yr SSO LOP
Population and Land Use	Projected 2020	Projected 2020	Projected 2020	Projected 2020	Projected 2020
Climate Scenario	Historic	Historic	Historic	10% Change	90% Change
Simulation Duration	71 years 1940-2010	71 years 1940-2010	64.5 years 1940-June 2004	64.5 years 1940-June 2004	64.5 years 1940-June 2004
	Part 2	*Part 2*	*Part 1* *Baseline*	*Part 1* *DSN 10%*	*Part 1* *DSN 90%*
	Average Annual Temperature				
Average Temperature (degrees F)			46.6	52.3	55.3
Temperature Std Deviation (degrees F)			20.7	19.6	19.6
	Average Annual Rainfall				
Average Depth (inches/year)			31.8	32.5	32.8
Max Hourly Intensity (inches/hour) (August 1986 event)			3.06	2.90	3.94
	Average Annual Overflow Volumes				
ISS-related SSO (MG/year)	112	18	19	12	18
ISS-related CSO (MG/year)	862	815	771	761	934
Total Overflow (MG/year)	974	833	790	773	952
	Average Annual Overflow Frequencies				
ISS-related SSO Frequency (events/year)	0.56	0.14	0.14	0.12	0.16
ISS-related CSO Frequency (events/year)	2.97	3.14	3.13	3.05	3.46

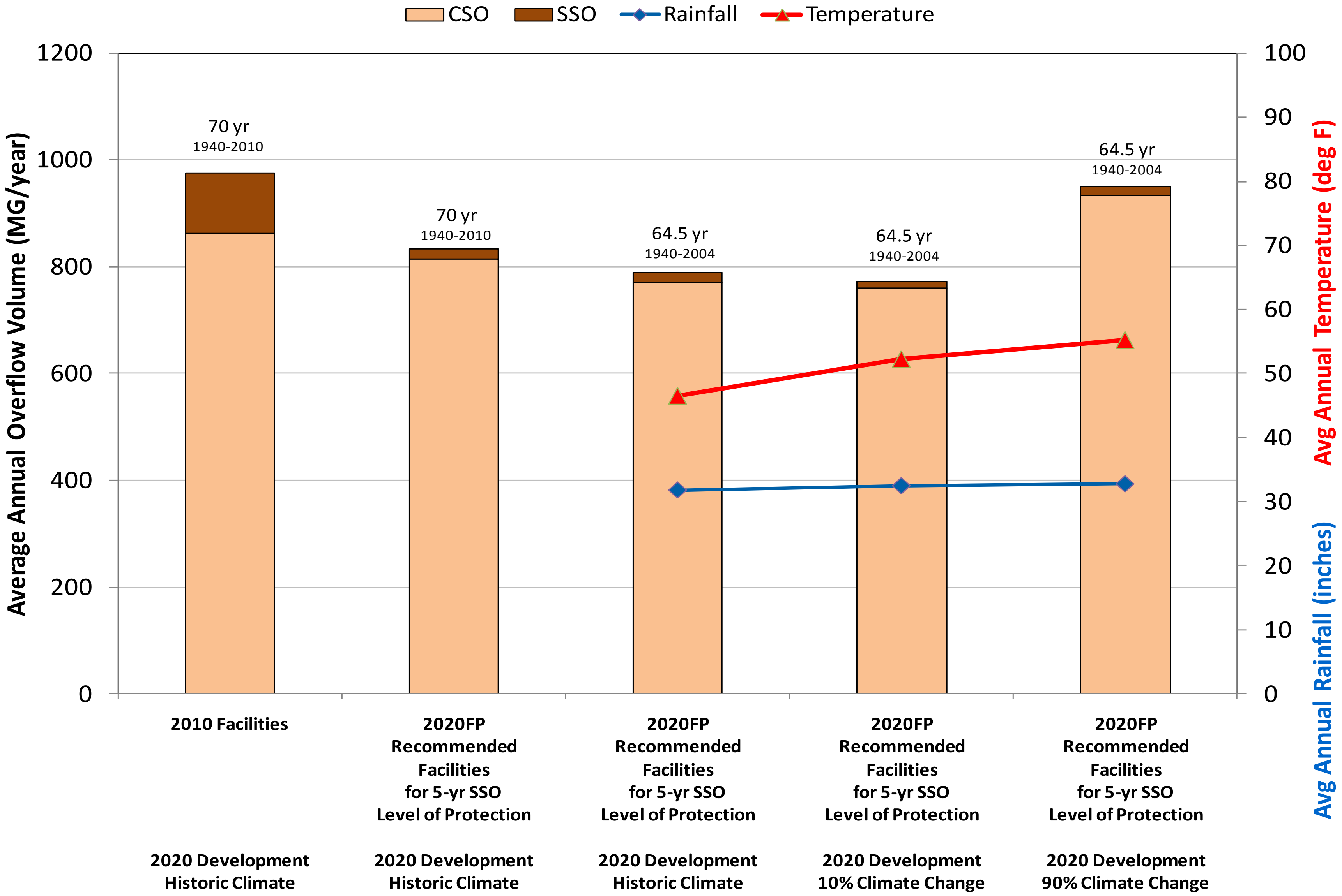

Figure 1: Average Annual Simulation Results

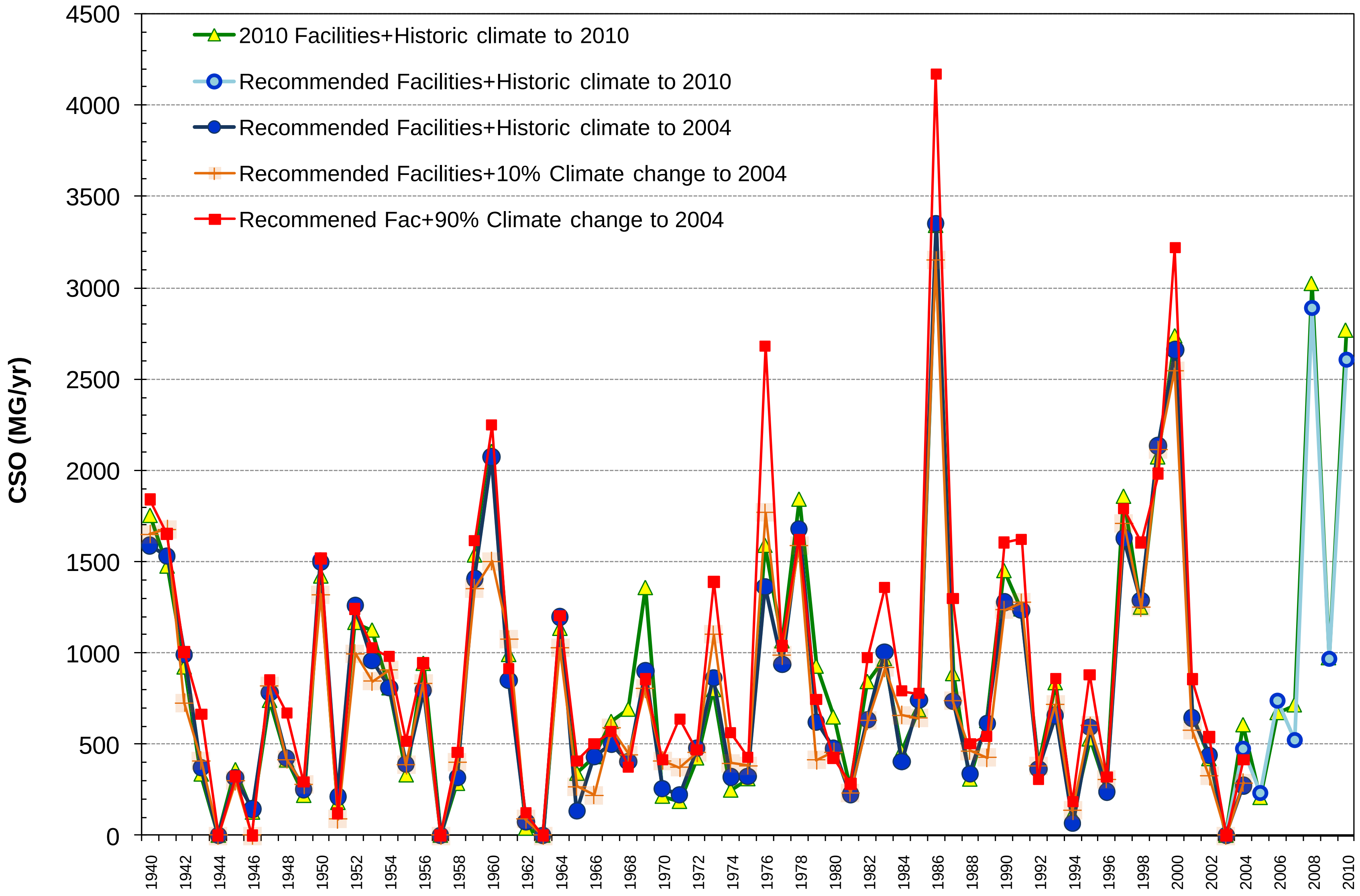

Figure 2: Simulated CSO Volume in Each Year

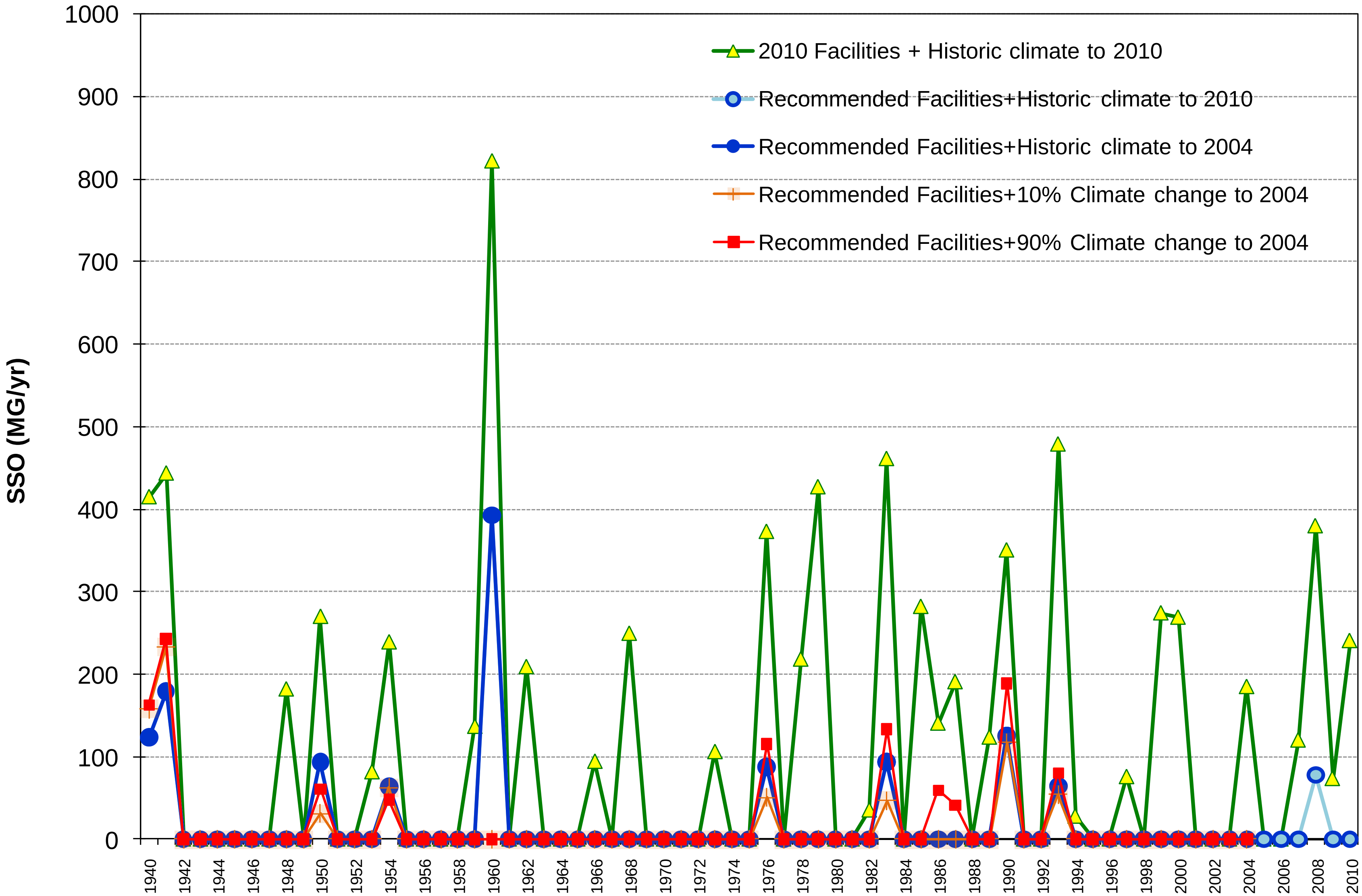

Figure 3: Simulated ISS-related SSO Volume in Each Year