**NOAA Sectoral Applications Research Program (SARP)**

# Climate Change Risks and Impacts on Urban Coastal Water Resources in the Great Lakes

Final Report

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Sandra McLellan, Ph.D. (Lead PI),
School of Freshwater Sciences, University of Wisconsin-Milwaukee

Hector Bravo, Ph.D. (Co-PI),
Department of Civil Engineering and Mechanics, UW-Milwaukee

Michael G. Hahn, P.E., P.H. (Co-PI)
Southeastern Wisconsin Regional Planning Commission

Contributions by Kevin Kratt and Jon Butcher, P.H., Ph.D.
Tetra Tech

# EXECUTIVE SUMMARY


Climate change can affect water resources in a number of ways. Altered rainfall patterns can affect runoff and pollutant loads to rivers and coastal waters. Climate change can also affect circulation patterns in the Great Lakes, which drive transport of bacteria and other pathogens in coastal waters. The planning for infrastructure renewal, allocation of resources for public health, recreation and restoration efforts requires the prediction of those effects of climate change. The three main objectives in this project were to:

1) Develop and incorporate a climate change impact component into watershed and nearshore models to improve predictive capabilities applicable to urban coastal regions.

2) Create a framework for interactive decision support among university scientists (research sector), engineers (planning sector), regulatory agencies and municipal governments (policy sector) through the Milwaukee Working Group of the Wisconsin Initiative on Climate Change Impacts.

3) Create and communicate methodologies to develop public awareness by interfacing with our regional watershed based partnership (Sweet Water Trust).

In this study the Center for Climatic Research at UW Madison created downscaled climate change data for meteorological stations around Milwaukee and Lake Michigan. The Southeastern Wisconsin Regional Planning Commission (SEWRPC) and Tetra Tech implemented a watershed hydrologic model (Hydrologic Simulation Program – Fortran HSPF) that predicts flows and bacteria loads for the watersheds and rivers that contribute to Lake Michigan around Milwaukee, under current or baseline and climate change conditions. Using results from the watershed hydrological model, a lake hydrodynamic and bacteria transport model for Lake Michigan around Milwaukee was implemented for this study. The authors believe that this is the first study that incorporates downscaled climate change data paired with watershed and lake models to study flows, bacteria loads and transport in Lake Michigan coastal waters.

One of the challenges addressed in this study was to adequately represent physically correct climate change scenarios to study impacts on water resources. We developed a strategy for the selection of the time periods to be simulated and how to address uncertainty in climate change predictions. We focused on spring rainfall as a criterion for choosing watershed climate scenarios because spring rainfall is a sensitive variable that influences water quality, meaning changes in spring rainfall patterns potentially have a large impact. Our strategy was to include a "best case" and "worst case" scenario for this variable. When assessing 14 global circulation (GCM) model predictions for spring rainfall, there was good agreement overall all among model predictions, with 12 models predicting increases. This agreement among models was how we assessed the certainty (or uncertainty). We took a similar approach for lake modeling and focused on the spring timeframe with a best and worst case scenario chosen for changes in wind, a primary driver of bacterial transport in the nearshore.

*Watershed Modeling*

Watershed hydrological modeling performed by Tetra Tech demonstrated an overall reduction in pollutant loads under climate change conditions for the five rivers leading to Lake Michigan and the Lake Michigan direct drainage area. This included fecal coliforms (FC), total phosphorous (TP), total nitrogen (TN), total suspended solids (TSS) and copper. The only exception was increased TSS in the Menomonee and Kinnickinnic Rivers, which are heavily urbanized. These findings were surprising considering that the predicted annual precipitation increased slightly from baseline levels of 32.5 inches per year to 33.4 inches per year in the worst case scenario (**Table ES1**). However modeling predicted a more arid future overall. Based on projected increases in air temperature under climate change conditions, potential evapotranspiration (PET) is estimated to increase by 25 to 38 percent, exceeding the change in annual precipitation and resulting in a net decrease in average annual flow accompanied by changes in seasonal timing that together result in lower annual loads of some pollutants. Results are described in full in **Appendix 1**: *Tetra Tech Final Technical Memo Milwaukee Climate Change Risk Modeling (September 17, 2012)*

**Table ES1. Comparison of 2050 Climate Scenarios to 1988 – 1997 Baseline**

| | **Baseline (1988 – 1997)** | **10th Percentile ("Best Case")** | **90th Percentile ("Worst Case")** |
|---|---|---|---|
| Precipitation (in/yr) | 32.5 | 33.2 | 33.4 |
| Average Temperature (°F) | 47.7 | 53.3 | 56.4 |
| Potential Evapotranspiration (in/yr) | 30.4 | 37.5 | 42.1 |

The projected changes in flow associated with increased PET do not account for potential mitigating effects of increased atmospheric $CO_2$ concentrations on plant transpiration. We further explored these finding by examining the complex interaction between temperature and actual evapotranspiration (ET). Tetra Tech prepared a detailed summary of the issues associated with ET and performed additional modeling in one of the watersheds, the Menomonee River watershed, partially offsetting the predicted increase in PET under climate change conditions by including a term that accounts for increased plant stomatal closure due to increased $C0_2$ concentrations. Stomatal structures are present on plant leaves and open to exchange $CO_2$ and water vapor with the atmosphere. Higher ambient $CO_2$ concentrations result in a reduced need to maintain open stomata to obtain the $CO_2$ needed for photosynthesis, which in turn can reduce water losses and offset some of the effects of higher air temperature on ET. Plant growth is not directly simulated in the HSPF model, and therefore the effect of $C0_2$ on plant transpiration could not be simulated directly; however, it can be accounted for by modifications to the parameters controlling ET from soil moisture stores consistent with the Penman-Monteith energy balance equations for ET. The net result is a reduction in predicted ET relative to that obtained from estimates of PET based only on changes in temperature and other meteorological factors, accompanied by a corresponding increase in flow. These results are described in full in **Appendix 2**: Tetra Tech Report entitled *"Simulating the impacts of increased stomatal closure under future $C0_2$ concentrations in the Menomonee River watershed climate response model."*

**Figure ES1A** shows predicted increases in fecal coliform (FC) concentrations over baseline levels at all assessment points (original modeling simulations with no adjustment for effects of increased $CO_2$ on ET), and **Figure ES1B** shows subsequent modeling results for Menomonee assessment points adjusted for increased atmospheric $CO_2$. As seen in **Figure ES1B**, annually there is little difference between "best case" and "worst case" scenarios based on adjustments for ET – in both cases about 17% of the Menomonee assessment points have FC increases over baseline levels. Seasonal results, however, do show differences based on ET adjustments. In the adjusted "best case" scenario the number of assessment points that show an FC increase drop by 10% after ET adjustment, largely due to increased dilution during non-storm event conditions. In the adjusted "worst case" scenario, there are about 5% fewer assessment points showing an increase in fecal coliform concentrations. Although not modeled, we suspect that the other urbanized watersheds (Kinnickinnic and Oak Creek) would be similarly impacted by ET adjustments to modeling. More rural watersheds (Milwaukee and Root River) could be expected to show a greater response to ET adjustments, as the landscape that surrounds them is more densely vegetated and thus subject to greater fluctuations in ET. The rural watersheds (**Figure ES1A**) did show a much higher percentage of assessment points with predicted increases in FC concentrations, so it will be interesting to see how ET adjustments affect those results in future models.

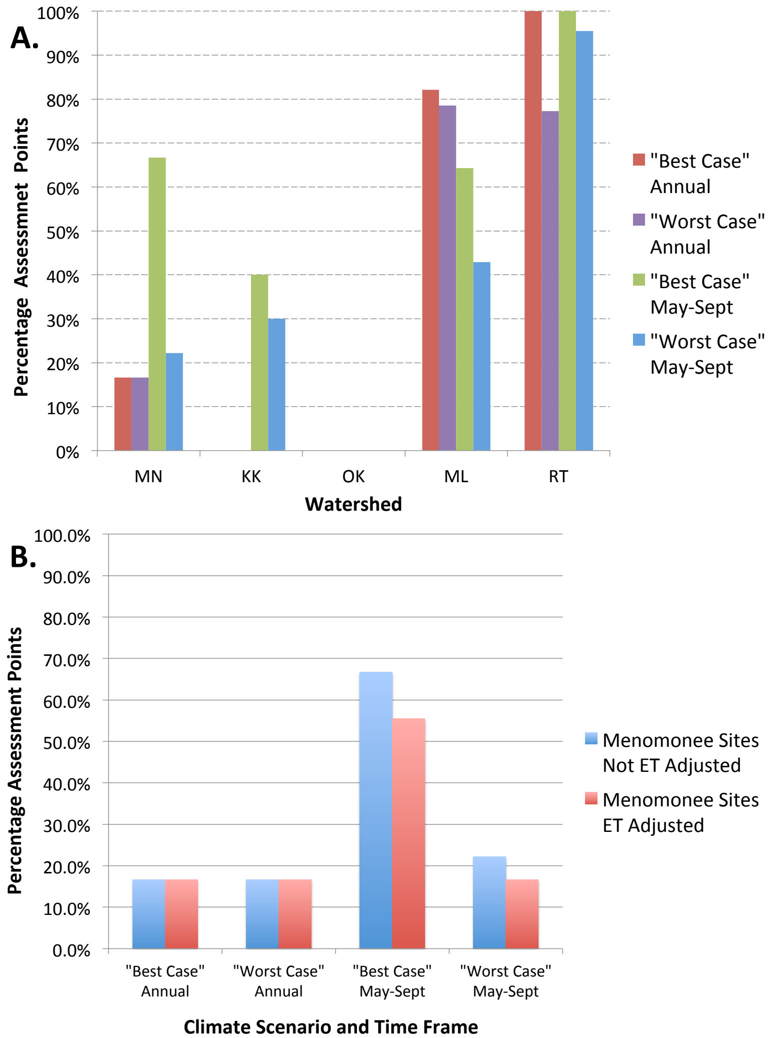


**Figure ES1. Percentage of assessment points that show increases over average baseline concentrations of FC with comparisons of "best case" and "worst case" climate scenarios for annual and seasonal time frames. A) All Watersheds (results are not adjusted for effects of increased atmospheric $CO_2$ on evapotranspiration (ET)). Abbreviations are Menomonee River (MN), Kinnickinnic River (KK), Oak Creek (OK), Milwaukee River (ML), Root River (RT). B) Menomonee Watershed with annual and seasonal results "Not ET adjusted" and "ET adjusted" for effects of increased atmospheric $CO_2$ on ET.**

The results we observed in the watershed model simulations highlight a major challenge in predicting impacts from climate change. Some outcomes, such as increased water temperature as a result of increased air temperature are straightforward, but other outcomes filter the climate signal through multiple and complex interactions. As ET is the largest term in the watershed water balance, future research is needed to better constrain the estimates of all ET fluxes in runoff models in respect to changes in temperature, $C0_2$, and other controlling variables (wind fields, humidity, cloud cover, etc.). Because of these complications, the results presented here should not be construed as providing definitive predictions of future conditions, but do serve as a useful tool to estimate the potential range, scale, and direction of changes to which adaptation may be needed.

*Lake Modeling*

The Lake Michigan model and the Milwaukee nested model were run for baseline scenarios and climate change scenarios and the hourly bacterial concentrations at critical stations were counted, including two beach sites and two drinking water intakes.

Climate change scenarios for lake modeling were developed using the arguments that bacteria loads to Lake Michigan are most sensitive to the spring season, and transport in coastal waters is most sensitive to changes in wind speed and direction. Therefore, we chose to focus on the spring time frame (to match the time frame of interest in the watershed modeling). Uncertainty in climate change predictions was dealt with by using the climate projections that yielded the 10$^{th}$ and 90$^{th}$ percentile changes in spring-season wind speed at the Milwaukee Airport station to define the worst-case and best-case climate change scenarios, respectively. Sets of downscaled climate change data for 11 ASOS stations around Lake Michigan were interpolated over Lake Michigan and used as meteorological forcing for baseline and climate change scenarios.

Because baseline modeling was generated as part of other projects, the time series available for watershed models and lake models were different. It was challenging to link these models, however, we developed a useful approach that captured changes in lake dynamics that we could quantify. The watershed model was developed for a previous study using as a baseline the existing 1988 through 1997 complete observations data set at the Milwaukee weather station. A complete observation data set was not available for the 1988-1997 period at the 11 ASOS stations around Lake Michigan, so we could not directly use the watershed model output as input into a lake model. Rather, we developed a parameter that described fecal coliform concentrations and used this as input into the hydrodynamic lake model. The Center for Climatic Research then used the existing 2001-2012 period of complete observations at the 11 ASOS stations around Lake Michigan to develop climate change projections for hydrodynamic modeling. We then assigned loads using the parameter describing the relationship between flow and fecal coliforms.

The SEWRPC/ Tetra Tech watershed model showed the largest tributary flows and fecal coliform bacteria loads for the year 1990. TetraTech developed baseline and projected flow and loads for 1990. A complete dataset could be assembled for that year for the 11 ASOS stations around Lake Michigan. Meteorological forcing over the lake was developed, and whole lake model and the nested model described below were run for 1990 using SEWRPC/ Tetra Tech watershed loads. The year 1990 was the only year when simulations were run using concurrent watershed forcing, over-lake meteorological forcing, and modeled watershed loads. The hydrodynamic and transport model was run using 1990 lake meteorological forcing and both the baseline and projected loads for the Milwaukee River and Oak Creek. The purpose of those runs was to test the effect of different loads under the same lake hydrodynamics. The transport of baseline and projected fecal coliform at relevant sites showed negligible effect of using those two different loads for the same lake hydrodynamics.

The patterns of bacteria transport showed significant changes under climate change conditions, with more fecal pollution north of the estuary discharge under the worst case scenario (**Table ES2**). At one beach site, the number of hours with fecal coliforms above recreational water quality limits increased by 2.5 fold. The best case scenario showed minimal changes. Climate change predictions showed significant changes in the number of violations of concentration at relevant locations in the Lake Michigan coast around Milwaukee.

**Table ES2. Predicted number of hours with fecal coliform concentration larger than 1,000 CFU/100 ml at relevant locations, for baseline and worst-case scenario. Sites: main gap (MG), south gap (SG), north gap (NG), Bradford Beach (BB), South Shore Beach (SSB), and the Linnwood (LI) and Howard Avenue (HA) intakes.**

| Station | Baseline condition | Worst-case scenario |
|---|---|---|
| MG | 121 | 201 |
| NG | 156 | 223 |
| SG | 86 | 43 |
| SSB | 129 | 58 |
| BB | 35 | 74 |
| LI | 0 | 0 |
| HA | 0 | 0 |

Future work to couple climate change projections, watershed and hydrodynamic models may need to first generate baseline time series that are synchronized. As noted in the watershed modeling, additional variables that can be adjusted for climate, and downscaled for regional applicability would be of value.

*Decision support tools*

The modeling framework explored in this project lays a sound foundation to further build decision support tools. In this project, the PIs interacted closely with each other, Tetra Tech engineers, and climatologists to develop the best approach to modeling the effects of climate change. The modeling exercise serves as the primary decision support tool, but more importantly this project helped us identify where critical knowledge gaps are (i.e. PET estimates, time series that can be coupled directly in models) that will improve the certainty and estimations moving forwards. The Milwaukee Metropolitan Sewerage District (MMSD) is already using our results as the basis for examining vulnerability to their resources (watercourse, conveyance systems and WWTP infrastructure). Our findings are guiding their prioritization and ranking of potential risks.

*Dissemination of results*

The progress throughout the grant has been shared through a variety of venues. All of the PIs have presented at multiple scientific meetings. Presentations have been made to citizen groups, The Wisconsin Initiative on Climate Change Impacts, the Technical Advisory Team at the MMSD, to Southeastern Wisconsin Watersheds Trust, Inc. (Sweet Water), and the PIs have participated in an experts workshop hosted by MMSD to help them develop an assessment of facility vulnerabilities to climate change. Discussion and consideration of the possible implications of this study were key components of that vulnerability assessment exercise. In addition, the PIs have given interviews to the government accountability board and NGOs interested in the impacts of climate change on water resources.

# 1 Introduction

Climate is intricately tied to the health and integrity of our water resources. Rainfall, drought, intense storms, wind patterns and other variables impact the amount of pollutants entering surface waters and the distribution of those pollutants from watersheds into coastal waters. Changes in our climate are expected to impact water resources in a number of ways. Altered rainfall patterns can affect runoff and pollutant loads to rivers and coastal waters and have implications for meeting water quality standards. Climate change can also affect circulation patterns in the Great Lakes, which drive transport of bacteria and other pathogens in coastal waters, which in turn could alter the amount of pollutants reaching recreational beaches and drinking water sources. The planning for infrastructure renewal, allocation of resources for public health, and recreation and restoration efforts requires the prediction of those effects of climate change.

This study brings together multiple collaborators from different sectors and disciplines. The University of Wisconsin-Milwaukee School of Freshwater Sciences, the University of Wisconsin-Milwaukee Department of Civil Engineering and Mechanics, the University of Wisconsin-Madison Center for Climate Research, Tetra Tech consultants, and the Southeastern Wisconsin Regional Planning Commission (SEWRPC) have contributed to this study. The overall objective of this project was to create a decision support tool for understanding climate impacts on water resources within the greater Milwaukee watersheds, which include the Kinnickinnic, Menomonee, Milwaukee, and Root River watersheds and the Oak Creek watershed as shown on **Map 1**.

The decision support tool was created by linking downscaled climate change predictions that are applicable to the Milwaukee area (climate model) to a model of pollutant runoff and flows in local rivers (watershed model). Distribution of these pollutant loads in nearshore waters were also examined with a nested and whole hydrodynamic model that used climate adjusted variables to drive circulation (lake model). Extensive water quality work in our region allows us to "layer" these modeling activities over baseline results to compare. The results of this project will be disseminated through the Wisconsin Initiative on Climate Change Impacts Milwaukee Working Group to both water resources managers for planning purposes, to our regional watershed based partnership and to the public to increase awareness of the potential consequences of climate change.

*The objectives for this study included:*

1) Develop and incorporate a climate change impact component into watershed and nearshore models to improve predictive capabilities applicable to urban coastal regions.

2) Create a framework for interactive decision support among university scientists (research sector), engineers (planning sector), regulatory agencies and municipal governments (policy sector) through the Milwaukee Working Group of the Wisconsin Initiative on Climate Change impacts.

3) Create and communicate methodologies to develop public awareness by interfacing with our regional watershed based partnership (Sweet Water).

Map 1

# THE GREATER MILWAUKEE WATERSHEDS

| Watershed | Area (square miles) |
|---|---|
| Kinnickinnic River | 24.7 |
| Menomonee River | 135.8 |
| Milwaukee River | 700.0 |
| Oak Creek | 28.2 |
| Root River | 197.6 |
| Lake Michigan Direct Drainage Area | 40.7 |
| Total | 1,127.0 |



Source: SEWRPC.

# 2 Watershed Modeling

The project analyses include simulation of both the greater Milwaukee watersheds draining to Lake Michigan and the nearshore waters of Lake Michigan. The watershed modeling component was conducted by Tetra Tech under contract to SEWRPC. The nearshore modeling used the watershed model output as boundary conditions and was conducted at the University of Wisconsin-Milwaukee.

## 2.1 Approach

Watershed flow and water quality modeling uses the calibrated and validated continuous simulation models developed by Tetra Tech in support of the Milwaukee Metropolitan Sewerage District 2020 facilities plan and SEWRPC regional water quality management plan update for the greater Milwaukee watersheds (collectively referred to as the Water Quality Initiative or WQI). These models are documented in Milwaukee Metropolitan Sewerage District, *MMSD 2020 Facilities Plan*, June 2007 and SEWRPC Planning Report No. 50 (PR No. 50), *A Regional Water Quality Management Plan Update for the Greater Milwaukee Watersheds*, December 2007. The watershed models simulate instream pollutant concentrations accounting for streamflow; nonpoint source loads of fecal coliform bacteria, total phosphorus, total nitrogen total suspended solids, and copper; and point source loads. Models for the Kinnickinnic River, Menomonee River, Root River, and Oak Creek watersheds were built using the U.S. Environmental Protection Agency (USEPA) Hydrologic Simulation Program – FORTRAN (HSPF) (Bicknell et al., 2005), while the Milwaukee River model (the largest individual model) uses a recompiled version of HSPF called Loading Simulation Program in C++ (LSPC), developed by Tetra Tech (Tetra Tech, 2009).

The original HSPF and LSPC watershed water quality model runs from the WQI were developed for the 10-year meteorological period from 1988 through 1997, which was determined to approximate normal conditions in the absence of major climate change influences. For this study, the watershed representation (independent of climate change) is provided by the models for revised 2020 baseline population and land use and recommended regional water quality management plan conditions with 1988 through 1997 climate. The models simulate water quality conditions continuously at 15-minute intervals throughout the 10-year analysis period except for the Milwaukee River watershed model, which simulates at a one-hour interval.

## 2.2 Climate Scenarios

Potential climate impacts are estimated based on expected conditions at mid-century (from 2046 through 2065). The envelope of potential impacts is estimated by comparing “best case” and “worst case” climate change conditions for rainfall, air temperature, and potential evapotranspiration to current conditions, where current conditions are represented by the 1988 through 1997 meteorological time series. To provide a consistent basis for comparison, the future weather series were based on perturbations of the 1987 – 1997 time series (allowing a year for model spin-up). Specifically, the UW-Madison Center for Climate Research created statistically downscaled versions of 1987 through 1997 precipitation and temperature representing the 10$^{th}$ percentile and 90$^{th}$ percentile of predicted climate statistics for mid-century under the A1B emissions scenario (which projects emissions for a future world of very rapid economic growth, low population growth and rapid introduction of new and more efficient technology). The underlying ensemble is derived from the suite of archived output from 14 general circulation models (GCMs) contained in the World Climate Research Programme’s CMIP3 multi-model dataset, statistically downscaled to the local scale using the CRU CL 2.0 20th century climate dataset. Results were provided at a 15-minute time step. For the initial water quality analyses of each of the greater Milwaukee watersheds, potential evapotranspiration (PET) was computed using the Penman Pan Evaporation formula along with some localized monthly adjustments. An additional water quality simulation for the Menomonee River watershed, accounting for the effect of increased carbon dioxide on plant growth, and the resulting effect on transpiration, is set forth below in Section 4.

The climate models are generally in agreement that spring rainfall will increase in the Milwaukee area. The "best case" (10th percentile) and "worst case" (90th percentile) scenarios for mid-century were defined relative to the spring rainfall thresholds associated with SSO and CSO events over the past ten years (McLellan et al., 2011). The future climate scenarios provide output for the Milwaukee – General Mitchell International Airport (GMIA) weather station. Specifically, the choice of a particular distribution for rescaling the historical precipitation and temperature records was based on interpolating the two models closest to the upper 90th percentile and the two closest to the lower 10th percentile for increases in the number of spring precipitation events larger than one inch in 24 hours. For the watershed model application, the two scenarios represent an increase of from 5.6 to 8.7 degrees Fahrenheit in annual average temperature relative to the 1988 through 1997 baseline (**Table 1**). While the two scenarios were selected to describe the potential range of frequency of large spring rainfall events, the resulting differences in annual average precipitation are small. On the other hand, based on projected increases in air temperature under climate change conditions, PET is estimated to increase by 25 to 38 percent, with predictions for a more arid future in which average annual PET exceeds precipitation.

**Table 2. Comparison of 2050 Climate Scenarios to 1988 – 1997 Baseline**

| | **Baseline (1988 – 1997)** | **10th Percentile ("Best Case")** | **90th Percentile ("Worst Case")** |
|---|---|---|---|
| Precipitation (in/yr) | 32.5 | 33.2 | 33.4 |
| Average Temperature (°F) | 47.7 | 53.3 | 56.4 |
| Potential Evapotranspiration (in/yr) | 30.4 | 37.5 | 42.1 |

### 2.3 Watershed Simulation Results

The WQI recommended plan (i.e., the model reflects best management measures recommended for abatement of stormwater runoff pollution and point source pollution control measures that are recommended to be implemented by the year 2020) simulation models were executed three times for each watershed: once using existing climate, and once each using the 10 percent and 90 percent mid-century climate scenarios.

### 2.4 Load and Concentration Summaries

Annual average loads delivered from each watershed and concentrations of the pollutants of interest were simulated. Significant decreases in annual flow are predicted for both the "best" and "worst" case climate scenarios for 2050. This occurs because PET is predicted to increase at a much faster rate than precipitation. In many, but not all cases, annual pollutant load is also predicted to decrease due to lower total volumes of storm runoff. This is offset by the observation that both the "best" and "worst" case scenarios predict an increase in the frequency of large spring rainfall events – resulting in less total storm runoff but more high runoff events. The predicted effects on total suspended solids (TSS) loads reflect the complex interplay between upland loading rates and channel scour/resuspension events. In the Menomonee and Kinnickinnic watersheds the TSS load is greater than the recommended plan TSS load under both climate scenarios, whereas net reductions are predicted under both climate scenarios for the Milwaukee River, Oak Creek, and Root River watersheds.

Effects on pollutant concentration reflect the combined impact of changes in flow and load. If both flow and load decrease, average concentration can go up or down depending on which component changes more. For TSS, there is a tendency in the more urban parts of the Menomonee River, Kinnickinnic River, and Oak Creek watersheds for average concentrations to increase while the median concentration decreases. This reflects a situation in which concentrations are generally predicted to decrease in the future, but the averages are higher due to a small number of large, scouring events.

## 2.5 WATER QUALITY CONDITION COMPARISON

Instream water quality summary statistics were developed for annual mean and median concentrations of fecal coliform bacteria, total phosphorus, total nitrogen, total suspended solids, and copper. Also, in the case of fecal coliform bacteria, dissolved oxygen, and total phosphorus, for which there are numerical water quality criteria promulgated by the State of Wisconsin, the average annual amount of time that instream concentrations were modeled to be in compliance with the criteria was determined. Water quality conditions were simulated at multiple locations in each of the five watersheds. In general, the changes associated with future climate are small, as is the difference between the best case (10$^{th}$ percentile) and worst case (90$^{th}$ percentile) climate scenarios. Full results are available in Appendix A.

Both the best case and worst case climate scenarios can result in prediction of a slight improvement or slight degradation of water quality conditions relative to the existing baseline as seen in **Tables 2** and **3**, which set forth average annual flow volumes and pollutant loads at the downstream end of each watershed and average annual flow rates and pollutant concentrations at the downstream end of each watershed, respectively. The result depends on the balance between changes in load and flow, especially the tradeoff between more intense events (which increase load) and lower frequency of events (which decreases load and concentration).

The downstream station on the Kinnickinnic River provides an example of the complexities of the modeled relationships. At this station, both total flow volume and total phosphorus load are predicted to decrease under both future scenarios, while average annual total phosphorus concentration increases. Despite the overall decrease in flow and load, the highest flows increase under the future scenarios, as do the highest phosphorus concentrations. For TSS, both loads and concentrations increase under the future scenarios.

**Table 2. Average Annual Flow Volume and Pollutant Load by Watershed**

| Watershed | Parameter | Recommended Plan based on GMIA Weather Inputs | Recommended Plan under Best-Case (10%) Climate Change Scenario | Recommended Plan under Worst-Case (90%) Climate Scenario |
|---|---|---|---|---|
| Milwaukee River | Flow (AF/yr) | 451,927 | 379,457 | 348,428 |
| | Fecal Coliform Bacteria (#/yr) | 4.13E+15 | 3.41E+15 | 3.01E+15 |

| | | | | |
|---|---|---|---|---|
| | Total Phosphorus (MT/yr) | 95.05 | 83.68 | 84.72 |
| | Total Nitrogen (MT/yr) | 878.8 | 706.1 | 686.7 |
| | Total Suspended Solids (MT/yr) | 14,270 | 12,611 | 13,236 |
| | Copper (kg/yr) | 4,395 | 4,002 | 3,811 |
| Menomonee River | Flow (AF/yr) | 97,117 | 85,877 | 81,391 |
| | Fecal Coliform Bacteria (#/yr) | 7.21E+15 | 6.59E+15 | 6.12E+15 |
| | Total Phosphorus (MT/yr) | 15.65 | 14.36 | 14.23 |
| | Total Nitrogen (MT/yr) | 124.8 | 110.4 | 107.5 |
| | Total Suspended Solids (MT/yr) | 5,251 | 5,338 | 5,544 |
| | Copper (kg/yr) | 825 | 768 | 733 |
| Kinnickinnic River | Flow (AF/yr) | 18,766 | 17,244 | 16,614 |
| | Fecal Coliform Bacteria (#/yr) | 2.18E+15 | 2.10E+15 | 2.01E+15 |
| | Total Phosphorus (MT/yr) | 4.52 | 4.13 | 4.01 |
| | Total Nitrogen (MT/yr) | 27.0 | 24.2 | 23.2 |
| | Total Suspended Solids (MT/yr) | 1,779 | 1,814 | 1,892 |
| | Copper (kg/yr) | 209 | 197 | 187 |

| | | | | |
|---|---|---|---|---|
| Oak Creek | Flow (AF/yr) | 20,581 | 18,128 | 17,202 |
| | Fecal Coliform Bacteria (#/yr) | 1.52E+15 | 1.46E+15 | 1.42E+15 |
| | Total Phosphorus (MT/yr) | 3.10 | 2.88 | 2.80 |
| | Total Nitrogen (MT/yr) | 25.8 | 24.0 | 23.3 |
| | Total Suspended Solids (MT/yr) | 1,122 | 1,086 | 1,093 |
| | Copper (kg/yr) | 188 | 179 | 174 |
| Root River | Flow (AF/yr) | 119,550 | 92,897 | 83,781 |
| | Fecal Coliform Bacteria (#/yr) | 3.28E+15 | 2.94E+15 | 2.64E+15 |
| | Total Phosphorus (MT/yr) | 21.93 | 16.63 | 15.84 |
| | Total Nitrogen (MT/yr) | 262.5 | 190.5 | 179.3 |
| | Total Suspended Solids (MT/yr) | 11,502 | 8,882 | 8,960 |
| | Copper (kg/yr) | 148 | 128 | 118 |
| Lake Michigan Direct Drainage | Flow (AF/yr) | 31,596 | 27,479 | 25,757 |
| | Fecal Coliform Bacteria (#/yr) | 2.69E+15 | 2.57E+15 | 2.44E+15 |
| | Total Phosphorus (MT/yr) | 7.030 | 6.016 | 5.767 |
| | Total Nitrogen (MT/yr) | 57.18 | 48.28 | 45.92 |
| | Total Suspended Solids (MT/yr) | 2617 | 2591 | 2705 |
| | Copper (kg/yr) | 286.2 | 259.5 | 245.1 |

**Table 3 Average Annual Flow Rate and Downstream Pollutant Concentration by Watershed**

| Watershed | Parameter | Recommended Plan based on GMIA Weather Inputs | Recommended Plan under Best-Case (10%) Climate Change Scenario | Recommended Plan under Worst-Case (90%) Climate Scenario |
|---|---|---|---|---|
| Milwaukee River | Flow (cfs) | 623.7 | 523.7 | 480.9 |
| | Fecal Coliform Bacteria (#/100 ml) | 460 | 420 | 373 |
| | Dissolved Oxygen (mg/L) | 9.915 | 9.215 | 8.756 |
| | Total Phosphorus (mg/L) | 0.109 | 0.109 | 0.114 |
| | Total Nitrogen (mg/L) | 1.384 | 1.328 | 1.312 |
| | Total Suspended Solids (mg/L) | 55.67 | 43.11 | 44.19 |
| | Copper (mg/L) | 0.040 | 0.045 | 0.048 |
| Menomonee River | Flow (cfs) | 134.0 | 118.5 | 112.3 |
| | Fecal Coliform Bacteria (#/100 ml) | 3,835 | 3,437 | 3,209 |
| | Dissolved Oxygen (mg/L) | 11.13 | 10.79 | 10.59 |
| | Total Phosphorus (mg/L) | 0.136 | 0.149 | 0.160 |
| | Total Nitrogen (mg/L) | 1.150 | 1.191 | 1.243 |
| | Total Suspended Solids (mg/L) | 13.09 | 13.55 | 13.54 |
| | Copper (mg/L) | 0.045 | 0.044 | 0.043 |

| **Watershed** | **Parameter** | **Recommended Plan based on GMIA Weather Inputs** | **Recommended Plan under Best-Case (10%) Climate Change Scenario** | **Recommended Plan under Worst-Case (90%) Climate Scenario** |
|---|---|---|---|---|
| Kinnickinnic River | Flow (cfs) | 25.90 | 23.80 | 22.93 |
| | Fecal Coliform Bacteria (#/100 ml) | 2,928 | 2,571 | 2,263 |
| | Dissolved Oxygen (mg/L) | 11.05 | 10.66 | 10.43 |
| | Total Phosphorus (mg/L) | 0.180 | 0.188 | 0.200 |
| | Total Nitrogen (mg/L) | 1.398 | 1.401 | 1.442 |
| | Total Suspended Solids (mg/L) | 10.41 | 10.63 | 10.70 |
| | Copper (mg/L) | 0.038 | 0.035 | 0.033 |
| Oak Creek | Flow (cfs) | 28.41 | 25.02 | 23.74 |
| | Fecal Coliform Bacteria (#/100 ml) | 3,696 | 3,181 | 2,918 |
| | Dissolved Oxygen (mg/L) | 11.22 | 10.91 | 10.74 |
| | Total Phosphorus (mg/L) | 0.070 | 0.068 | 0.068 |
| | Total Nitrogen (mg/L) | 0.811 | 0.803 | 0.810 |
| | Total Suspended Solids (mg/L) | 13.19 | 14.29 | 14.94 |
| | Copper (mg/L) | 0.047 | 0.046 | 0.048 |

| Watershed | Parameter | Recommended Plan based on GMIA Weather Inputs | Recommended Plan under Best-Case (10%) Climate Change Scenario | Recommended Plan under Worst-Case (90%) Climate Scenario |
|---|---|---|---|---|
| Root River | Flow (cfs) | 165.0 | 128.2 | 115.6 |
| | Fecal Coliform Bacteria (#/100 ml) | 2,836 | 3,280 | 3,373 |
| | Dissolved Oxygen (mg/L) | 11.11 | 10.90 | 10.75 |
| | Total Phosphorus (mg/L) | 0.100 | 0.105 | 0.114 |
| | Total Nitrogen (mg/L) | 1.191 | 1.158 | 1.183 |
| | Total Suspended Solids (mg/L) | 22.08 | 19.69 | 19.37 |
| | Copper (mg/L) | 0.012 | 0.014 | 0.014 |

Of the relatively rural Milwaukee River and Root River watersheds, Root River has the most upstream stations with predicted increases in average fecal coliform (FC) concentrations and, as seen in **Table 3**, is the sole watershed that shows a downstream increase in average FC concentration. Under both climate change scenarios, it is predicted that FC concentrations will decrease at most downstream watershed stations, although, increases are predicted for many upstream assessment points in those same watersheds (**Figure 1**). Since an average is more sensitive to outliers than a geometric mean, which flattens them, we used average FC concentrations to capture changes due to spikes in runoff caused by large spring rainfall events. The more urban Menomonee River, Kinnickinnic River and Oak Creek watersheds have fewer predicted increases in the upstream reaches for average FC levels, but this is not unexpected in climate change scenarios. Impervious surfaces of urbanized landscapes combined with more large spring rainfall events would increase storm runoff flow to rivers and dilute the fecal coliform concentrations seen at local assessment points. On the other hand, in more rural watersheds stormwater is absorbed by the landscape and a substantially smaller volume ends up as river-diluting runoff – making the concurrent input of FC a measurable increase in concentration.

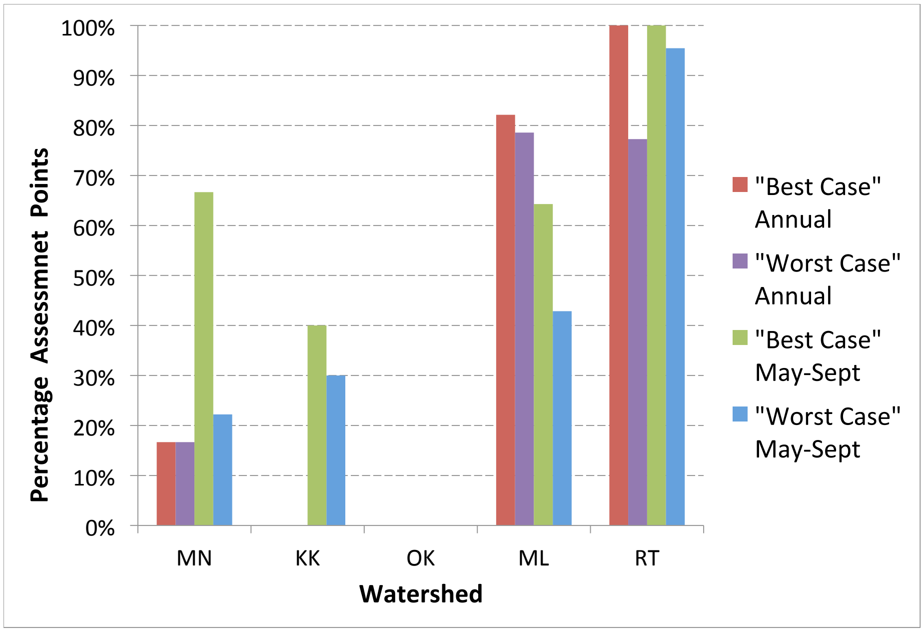


**Figure 1. Percentage of assessment points in each watershed predicted to increase in average fecal coliform concentration. Annual and May-September predictions for "Best" and "Worst" case scenarios are compared. Watersheds: Menomonee River (MN), Kinnickinnic River (KK), Oak Creek (OK), Milwaukee River (ML), Root River (RT).**

### 2.6 Impacts on Temporal Distribution of Loads

Future climate may result in changes in the timing as well as the magnitude of flows and pollutant loads. Seasonal results for flow are striking as average flow is predicted to decline in all months except for the winter, with the largest reduction in spring flows. There does not appear to be a pronounced shift in the timing of flows in response to climate scenarios; however, there is a systematic difference between watersheds as a result of impervious area cover, with the more urban watersheds exhibiting relatively higher summer runoff.

Monthly patterns of nutrient loads generally follow flow volume. In contrast, the TSS loads are more closely related to the frequency of intense events. The highest rainfall intensities under the 90$^{th}$ percentile climate change scenario are found in May through August, while June and August have the greatest frequency of intense rainfall as well as the largest sediment loads – even though the total flow volume for August is relatively low compared to the spring.

Nutrient loads tend to decline more than TSS loads under future climate because the nutrient loads are focused more toward the early part of the year when the flow reductions are greater.

## 3 Additional Analyses Considering Effects of Increased Carbon Dioxide on Actual ET

An important, but sometimes ignored, aspect of climate change is the predicted increase in ground level carbon dioxide ($CO_2$) concentrations. Plants require $CO_2$ from the atmosphere for photosynthesis. An important effect of $CO_2$ fertilization is increased stomatal closure, as plants do not need to transpire as much water to obtain the $CO_2$ they need for growth. This effect can potentially counterbalance predicted increases in temperature and potential evapotranspiration. Recent research, particularly the FACE experiments summary (Leakey et al., 2009), seems to confirm that significant evapotranspiration reductions do occur at the ecosystem level under $CO_2$ fertilization. This feedback effect from increased $CO_2$ may in part offset the predicted increase in PET. Carbon dioxide fertilization, and the resultant increased stomatal closure, were not initially represented in the water quality models, and are not reflected in the results presented above. However, additional simulations that account for the projected effects of increased stomatal closure under climate change conditions were performed for the Menomonee River watershed.

Review of the watershed water quality model results for the five greater Milwaukee watersheds indicated some counterintuitive outcomes in that the simulations under projected climate change conditions indicated the possibility of 1) significant reductions in flow volumes and rates; 2) in many cases, significant reductions in pollutant loads, 3) and, in some cases, reductions in instream pollutant concentrations. The additional analyses were undertaken to determine if refining the representation of plant transpiration to reflect the effect of $CO_2$ fertilization on increased stomatal closure in plants would yield significantly different results than those for the initial simulation.

The refinement to the Menomonee River water quality model was accomplished through appropriate adjustment of the model parameter that affects monthly plant transpiration from the lower soil zone moisture store.

### 3.1 Hydrology Differences with Adjusted Plant ET

In general, accounting for the effects of $CO_2$ enrichment on stomatal closure in the Menomonee River model results in a small increase in total flow volume for future climate scenarios; however, the total flow remains less than under current baseline conditions. Results for the 90th percentile scenario show a reduction in lower zone ET of from 6 to 8.5 percent on an annual basis compared to the simulation without correction for stomatal closure, and a corresponding total runoff increase of from 3.6 to 6.6 percent. Results for the 10th percentile scenario show slightly larger decreases in lower zone ET (6.7 to 8.9 percent) but slightly smaller increases in total runoff from the pervious land segments (3.5 to 5.7 percent).

Total runoff from the entire Menomonee River watershed also includes runoff generated by impervious surfaces, which is not affected by increased $CO_2$. As a result, the percentage increases in total flow in the River are projected to be smaller than the increases in flow from pervious land segments. Over the entire 10-year simulation period, average annual flow at the mouth of the Menomonee River increases by 2.6 percent under the 10th percentile scenario, and by 2.8 percent under the hotter and slightly wetter, 90th percentile scenario.

A comparison of the percentage difference in flows relative to the simulation without modification for increased stomatal closure suggests that the percentage changes are greatest in the fall and winter, with lesser changes in the summer months. Importantly, the adjustment to transpiration has the greatest impact on baseflow, which predominates in the fall and early winter month low-flow period.

### 3.2 Water Quality Differences with Adjusted ET

The model simulations indicate that projected pollutant loads could increase with the $CO_2$ adjustment, but only by a small amount, and, with the exception of TSS, they would still be less than under the baseline condition assuming current climate conditions. While pollutant loads could increase slightly, pollutant concentrations tend to decrease (and dissolved oxygen concentrations increase) in the models with the adjustment for increased $CO_2$. This again reflects the role of decreased lower zone transpiration in increasing baseflow, and thus diluting the average pollutant concentration.

### 3.3 $CO_2$ AND ET CONCLUSION

The results of the Menomonee River watershed simulations indicate that accounting for the effects of decreased transpiration resulting from increased $CO_2$ levels would not be projected to change the relationship between flows, pollutant loads, and instream pollutant concentrations under climate change relative to those parameters under climate change conditions without accounting for decreased transpiration. Given the level of accuracy of precipitation, air temperature, and potential evapotranspiration under climate change, the relative changes projected without consideration of decreased transpiration for the Kinnickinnic, Milwaukee, and Root River watersheds and the Oak Creek watershed would still likely be generally valid based on the results of the additional analyses for the Menomonee River watershed.

To illustrate the effect of ET on modeling results, **Figure 2** shows predicted increases in average FC concentrations at Menomonee River assessment points adjusted for reduced plant ET due to increased plant stomatal closure ("MN-ET Adjusted") under future ambient $CO_2$ concentrations. Annually there is little difference between "best case" and "worst case" scenarios based on adjustments for ET – in both cases about 17% of the Menomonee assessment points have FC increases over baseline levels. Seasonal results, however, do show differences based on ET adjustments. In the adjusted "best case" scenario the number of assessment points that show an FC increase drop by 10% after ET adjustment. In the adjusted "worst case" scenario, there are about 5% fewer assessment points showing an increase in FC concentrations. Although not modeled, we suspect that the other urbanized watersheds (Kinnickinnic and Oak Creek) would be similarly impacted by ET adjustments to modeling.

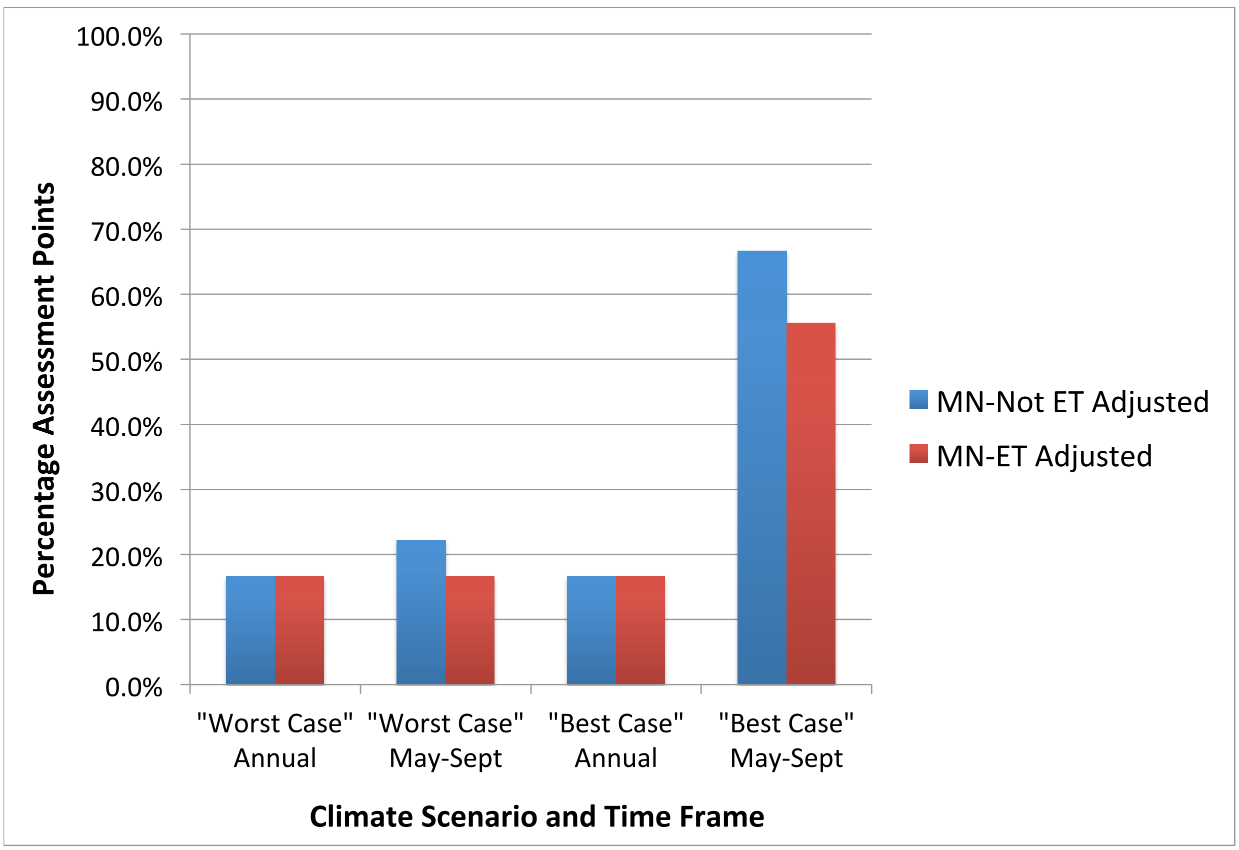


**Figure 2. Percentage of assessment points in Menomonee Watershed predicted to increase in average FC concentration. ET adjustments are compared for annual and May-September predictions for "Best" and "Worst" case scenarios**.

Urban land uses comprise about 64 percent of area of the Menomonee River watershed and rural uses comprise about 36 percent. The Oak Creek watershed has a similar urban (61 percent)/rural (39 percent) relationship and the Kinnickinnic is more highly urbanized (92 percent urban and 8 percent rural). The effects of decreased transpiration would be less prominent in watersheds with more impervious area (such as the Kinnickinnic, Menomonee, and Oak). It can reasonably be concluded that the general conclusions regarding flow, pollutant load, and pollutant concentration for the Menomonee River watershed under the reduced transpiration scenario would be similar for the Oak Creek and Kinnickinnic River watersheds. It is also possible that, with reduced transpiration under climate change, flows and pollutant loads and concentrations in the more rural Milwaukee (21 percent urban and 79 percent rural) and Root (33 percent urban and 67 percent rural) River watersheds with greater relative pervious areas could be reduced less, or in some cases, increased a small amount, in comparison to the baseline existing climate condition.

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# 4 Lake modeling and distribution of fecal coliforms in the nearshore

## 4.1 Introduction

Climate change can affect the patterns of circulation and transport of bacteria and other pathogens in Great Lakes coastal waters. In this study the Center for Climatic Research at UW Madison created downscaled climate change data for meteorological stations around Milwaukee and Lake Michigan. The Southeastern Wisconsin Regional Planning Commission (SEWRPC) and Tetra Tech implemented a (Hydrologic Simulation Program – Fortran HSPF) hydrologic model that predicts flows and bacteria loads for the watersheds and rivers that contribute to Lake Michigan around Milwaukee, under current or baseline and climate change conditions developed by the Center for Climatic Research at UW Madison (SEWRPC 2013). A hydrodynamic and bacteria transport model for Lake Michigan around Milwaukee was implemented for this study. The authors believe that this is the first study that incorporates downscaled climate change data to study flows, bacteria loads and transport in Lake Michigan coastal waters.

One of the challenges addressed in this study was the representation of physically correct climate change scenarios to study the impacts on circulation on the whole Lake Michigan, and on flows, bacteria loads and transport in coastal waters around Milwaukee. Other relevant challenges were the selections of periods to be simulated and how to address uncertainty in climate change predictions.

### 4.2 Methods

The three main research tasks in this study were climate change modeling, watershed hydrologic and bacteria load modeling, and hydrodynamic and bacteria transport modeling. This section summarizes the methods used in hydrodynamic and bacteria transport modeling, the links with climate change modeling and watershed hydrologic and bacteria load modeling, and the field data used to validate the hydrodynamic and bacteria transport model.

Because baseline modeling was generated as part of other projects, the time series available for watershed models and lake models were different. The climate model predictions used in watershed modeling and hydrodynamic modeling are not completely synchronized because a common baseline data set was not available. It was challenging to link these models, however, we developed a useful approach that captured changes in lake dynamics that we could quantify. The conceptual link between all models was done as follows. Watershed hydrologic and fecal coliform load modeling showed that bacteria loads to Lake Michigan are larger during the spring season. Hydrodynamic and fecal coliform transport showed that transport in coastal waters is most sensitive to changes in wind speed and direction. The effects of climate changes, particularly wind speed and direction, on hydrodynamic and fecal coliform transport were studied for the spring season, thus closing the links between the three main modeling components.

#### <u>Meteorological forcing for hydrodynamic modeling</u>

Meteorological forcing for the hydrodynamic models requires the variables of wind vectors, air temperature, dew point temperature and cloud cover at every model grid cell. These meteorological forcing variables are developed from observations at 11 National Weather Service (NWS) Automated Surface Observing System (ASOS) stations shown in the **Figure 3** and **Table 4**.

The observations are adjusted to convert overland measurements to over-water measurements, and then interpolated and smoothed over the lake using a procedure originally described by Beletsky and Schwab (2001). **Figure 3** shows also the locations of National Buoy Data Center (NBDC) buoys 45002 and 45007 used to verify the adjustment, interpolation and smoothing procedure.

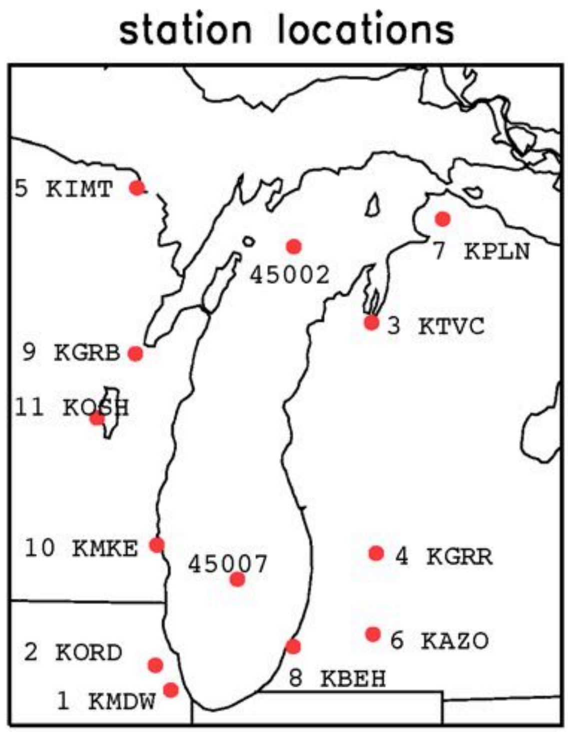



**Figure 3. Location of 11 ASOS stations and NBDC buoys**

**Table 4. Location of ASOS stations used to develop meteorological forcing over Lake Michigan**

| Station number | Station acronym | Station name | Longitude | Latitude |
|---|---|---|---|---|
| 1 | KMDW | Chicago Midway Airport | -87.75000 | 41.78333 |
| 2 | KORD | Chicago O'Hare International | -87.91666 | 41.98333 |
| 3 | KTVC | Cherry Capital Airport | -85.56667 | 44.73333 |
| 4 | KGRR | Gerald R. Ford International | -85.51667 | 42.88334 |
| 5 | KIMT | Iron Mountain Ford Airport | -88.11667 | 45.81667 |
| 6 | KAZO | Kalamazoo/Battle Creek Airport | -85.55000 | 42.23333 |
| 7 | KPLN | Pellston Regional Airport | -84.80000 | 45.56667 |
| 8 | KBEH | Southwest Michigan Regional | -86.41666 | 42.13334 |
| 9 | KGRB | Austin Straubel International Airport | -88.13333 | 44.48333 |
| 10 | KMKE | Gen Mitchell International Airport | -87.90000 | 42.95000 |
| 11 | KOSH | Wittman Regional Airport | -88.55000 | 43.96667 |

<u>Selection of climate change scenarios for hydrodynamic modeling</u>

The Lake Michigan model and the Milwaukee nested model described below were run for baseline scenarios and climate change scenarios summarized in **Table 5**. The table lists the spreadsheet appendices that contain calculated fecal coliform concentrations for the different scenarios. Two baseline scenarios for climate change were constructed based on 2001-2012 observations at the ASOS stations described above. Twelve years of observations (2001-2012) of air temperature, dew point, wind speed and direction were provided by the Nelson Institute's Center for Climatic Research. Cloud cover observations for the same period were obtained from the National Climatic Data Center (NCDC) website. Two climate change scenarios were constructed, namely a best-case scenario and a worst-case scenario. The critical variables for hydrodynamic and bacteria transport are wind speed and direction, and the chosen critical period is Spring (March-May), consistent with the watershed model.

Meteorological forcing for the climate change scenarios was established using remapped predictions of the baseline observation period. The UW-Madison's Center for Climatic Research remapped the baseline observations to two future periods, namely 2046-2065 (mid-century) and 2081-2100 (end of century), using 13 climate models. The 2046-2065 remapped predictions were used, in consistency with the watershed model. The Nelson Institute's Center for Climatic Research used 13 Global Circulation Models for remapping.

The data were created using the "cdf remapping" technique. This method uses the time-mean CDF in the 20c3m scenario and the time-mean CDF in a future scenario to map the nth percentile in the 20th century to the nth percentile in the future. This preserves all the covariances between the data. All this data is for the A1B scenario (middle–of-the-road scenario); unfortunately, the A2 scenario, which may be more realistic, only has 9 models.

**Table 5. Summary of baseline and climate change scenarios. The spreadsheet appendices that contain calculated fecal coliform concentrations are listed in parentheses for each scenario.**

| Baseline scenario | Climate change scenario |
|---|---|
| March-May 2005<br>(con_2005_base.xlsx spreadsheet) | Worst case: model cccma_cgcm3_1 projection for 2005 yielded second highest (approximately 10% quartile) March-May average wind speed for station KMKE (con_2005_cgcm3.xlsx spreadsheet) |
| March-May 2011<br>(con_2011_base.xlsx spreadsheet) | Best case: model mri_cgcm2_3_2a projection for 2011 yielded second lowest (approximately 90% quartile) March-May average wind speed for station KMKE (con_2011_mri.xlsx spreadsheet) |

The following rationale was used in the selection of baseline and climate change scenarios. The time-averaged wind varies significantly between the ASOS stations. The variability was clearly displayed for the average wind in the 20$^{th}$ and 21$^{st}$ centuries, for each ASOS station, averaged over all climate change models. For practical reasons we analyzed the change in wind speed and direction at the General Mitchell station, because the local wind has direct influence on transport of bacteria in Lake Michigan around Milwaukee.

The three-month (March-May) average wind speed and direction at the General Mitchell (KMKE) station was calculated for the baseline observation period (2001-2012), and for the observations projected to mid-century (2046-2065), for all 13 climate change models.

The model cccma_cgcm3_1 projection for 2005 (model mri_cgcm2_3_2a projection for 2011) yields the second highest, or approximately 10% quartile (second lowest, or approximately 90% quartile) March-May average wind speed for station KMKE. The model cccma_cgcm3_1 projections for 2005 (model mri_cgcm2_3_2a projections for 2011), for all 11 ASOS stations, were used to construct the worst-case (best-case) wind scenario.

Baseline and climate change scenarios for watershed and hydrodynamic modeling

Using a period that has a complete observation data set is a prerequisite for the development of climate change predictions by the Center for Climatic Research. The watershed model was developed for a previous study using as a baseline the existing 1988 through 1997 complete observations data set at the General Mitchell weather station. A complete observation data set was not available for the 1988-1997 period at the 11 ASOS stations around Lake Michigan. The Center for Climatic Research used the existing 2001-2012 period of complete observations at the 11 ASOS stations around Lake Michigan to develop climate change projections for hydrodynamic modeling. Therefore, the baseline and mid-century climate change projections for watershed and hydrodynamic model are not completely synchronized.

The SEWRPC/ Tetra Tech watershed model showed the largest tributary flows and fecal coliform bacteria loads for the year 1990. A complete dataset could be assembled for that year for the 11 ASOS stations around Lake Michigan. Meteorological forcing over the lake was developed, and whole lake model and the nested model described below were run for 1990 using SEWRPC/ Tetra Tech watershed loads. The year 1990 was the only year when simulations were run using concurrent watershed forcing, over-lake meteorological forcing, and modeled watershed loads.

Tributary loads used in hydrodynamic modeling: Parameterization of tributary concentration vs. discharge

The hydrodynamic model included the flows and fecal coliform loads from the Kinnickinnic, Menomonee, and Milwaukee River watersheds and the Oak Creek watershed. The mid-century climate projections of watershed flows and fecal coliform bacteria loads, and meteorological forcing for hydrodynamic modeling are not completely synchronized. Therefore, we established an approach to estimate loads from the watershed based on the actual time series form 1988-1997. Watershed flows and fecal coliform bacteria loads for hydrodynamic modeling were estimated as follows. Tributary streamflows measured by the USGS in 2005 and 2011 were used for both the baseline and the corresponding climate change scenarios summarized in **Table 5**. Tributary fecal coliform loadings were developed using several sets of hourly measurements of fecal coliform loads (close to one thousand measurements) at the mouth of the Milwaukee River obtained by Corsi and McLellan (personal communication) between 2009 and 2011, and simultaneous streamflows measured by the USGS.

The hypothesis was made that streamflows and fecal coliform bacteria loads are both log-normally distributed, and can be represented by the equation $Y = \bar{Y} + z\, S_Y$, where $Y$ represents the logarithm of either streamflow or fecal coliform bacteria concentration, $\bar{Y}$ and $S_Y$ are the mean and standard deviation of $Y$, and $z$ represents the standard normal variate. The standard normal variate $z$ calculated using that equation for either streamflow or fecal coliform concentration values sampled simultaneously, as indicated by sample number, was plotted. The plot showed that $z$ for fecal concentration mimics quite well the values and timing of $z$ for streamflow, and therefore the hypothesis can be accepted. Concentration of fecal coliform was estimated for years 2005 and 2011 using that equation, the values of $\bar{Y}$ and $S_Y$ estimated from 2009-2011 measurements, and values of z for streamflow that can be calculated using the existing continuous streamflow measurements. A similar procedure was used to develop fecal coliform loads for Oak Creek.

Hydrodynamic and bacteria transport modeling

Two hydrodynamic models were used in this study, namely a version of Great Lakes Coastal Forecasting System (GLCFS) developed by NOAA GLERL, and a high resolution nested model. The hydrodynamic models solve governing equations to predict currents and temperature that result from effects of meteorological forcing functions, the Earth's rotation, and bathymetry. Both the GLCFS model and the nested model are based on a Princeton Ocean Model (POM, Blumberg and Mellor 1987) version adapted to the Great Lakes by NOAA GLERL (Schwab and Bedford 1994).

A bacteria transport module was added to the hydrodynamic model. The bacteria transport module simulates the processes of advection, dispersion or mixing, bacteria fall through the water column, light-dependent inactivation rate, and base mortality, as described by Thupaki et al. (2010). The bacteria transport module and the hydrodynamics module are solved simultaneously and use the same numerical methods. The simulation of the processes of advection and dispersion or mixing is described in Talarczyk (2012).

Field data

**Figure 4** and **Table 6** show the model bathymetry and the location of sampling sites. Continuous measurements of conductivity were obtained in 2008 at stations SG, HB and GC (Klump, personal communication). Fecal coliform was measured by the McLellan's lab at all stations during summer semi monthly cruises in 2006-2008. Several sets of hourly measurements of fecal coliform loads (close to one thousand measurements) were obtained between 2009 and 2011 at the mouth of the Milwaukee River using ISSCO samplers (Corsi and McLellan, personal communication).

### 4.3 Lake Modeling Results

Verification of hydrodynamic and bacteria transport models

Comparison of model predictions with specific conductivity measured continuously in 2008 at stations HB, SG and GC showed that the model does a good job of reproducing the timing and range of values, demonstrating the validity of the advection and dispersion modeling.

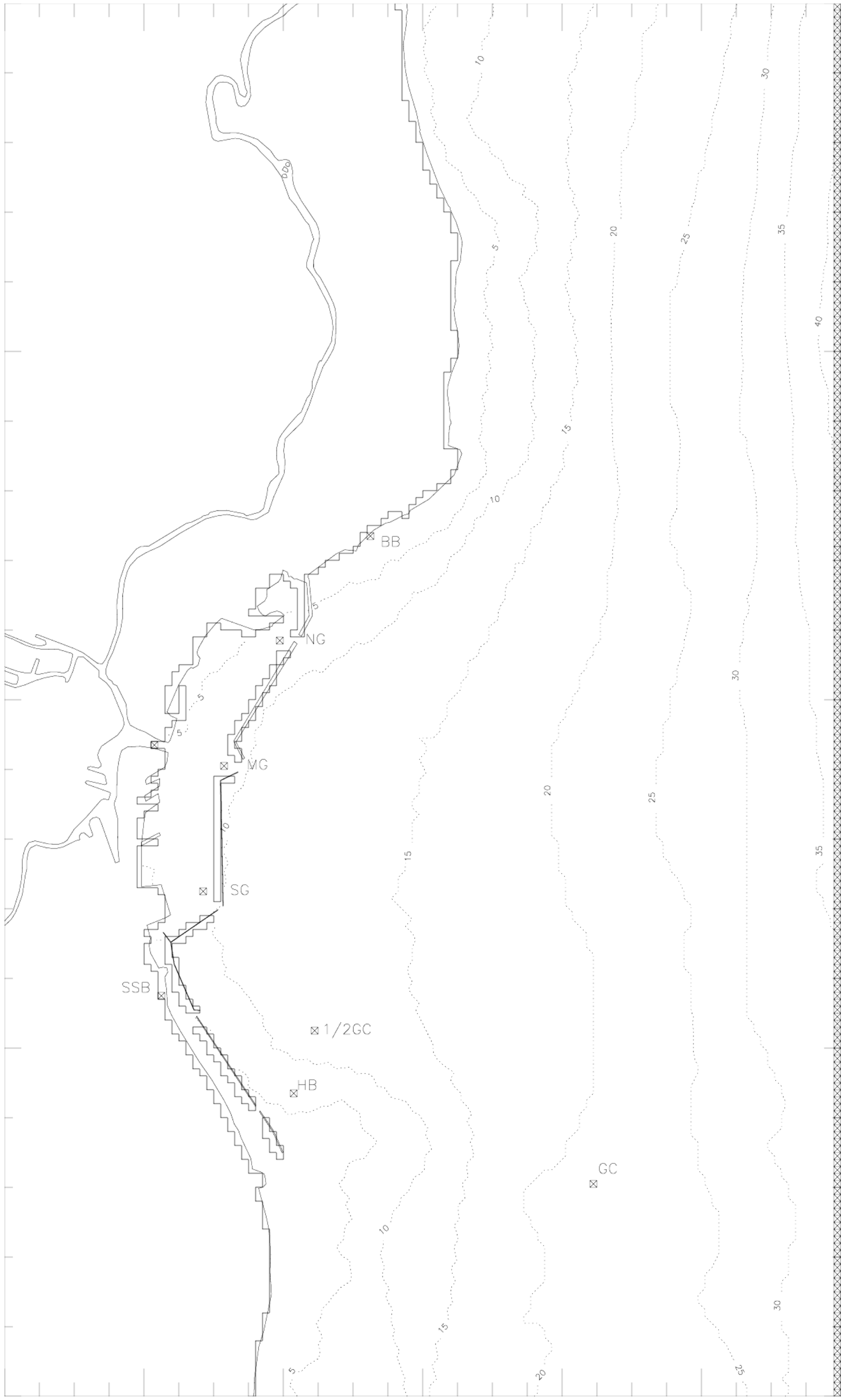



**Figure 4. Model geometry around the Milwaukee Harbor and locations of sampling stations.**

**Table 6. Location of sampling stations and measurement type (CO=conductivity, FC=fecal coliform).**

| Station | Longitude | Latitude | Measurement |
|---|---|---|---|
| BB | -87.87276 | 43.06129 | FC |
| NG | -87.88168 | 43.04462 | FC |
| GC | -87.79829 | 42.99147 | CO, FC |
| 1/2GC | -87.85384 | 42.99858 | FC |
| SG | -87.87986 | 43.01004 | CO, FC |
| MG | -87.88352 | 43.02671 | FC |
| HB | -87.85308 | 42.98994 | CO, FC |
| SSB | -87.88107 | 42.99536 | FC |

Comparison of model predictions with fecal coliform measured at stations MG, SG, NG and HB in June and July 2008 showed that the model reproduced well the timing and range of measured values. The effects of light attenuation and decay terms were hard to observe. Under real flow conditions a change in settling velocity, light-dependent inactivation rate, and base mortality within feasible ranges reported in the literature produced no observable effect on fecal coliform concentrations. This means that the transport is fairly rapid and over a short time frame where the aforementioned variables do not have a major influence.

## Model predictions for 1990

As explained in the Methods section, the whole-lake model and the nested model were run for 1990 using concurrent meteorological forcing over the watershed and the lake, and the watershed loads estimated by SEWRPC/ Tetra Tech. No climate-change projection for meteorological forcing over the lake was developed for that year.

TetraTech developed baseline and projected flow and loads for 1990. The hydrodynamic and transport model was run using 1990 lake meteorological forcing and both the baseline and projected loads for the Milwaukee River and Oak Creek. The purpose of those runs was to test the effect of different loads under the same lake hydrodynamics.

**Figures 5a and 5b** shows calculated fecal coliform concentrations (CFU/100 mL) during March-May 1990 at the Milwaukee River mouth, the main gap MG, south gap SG, north gap NG, Bradford Beach BB, South Shore Beach SSB, and the Linnwood LI and Howard Avenue HA intakes, for baseline and projected loads, respectively.

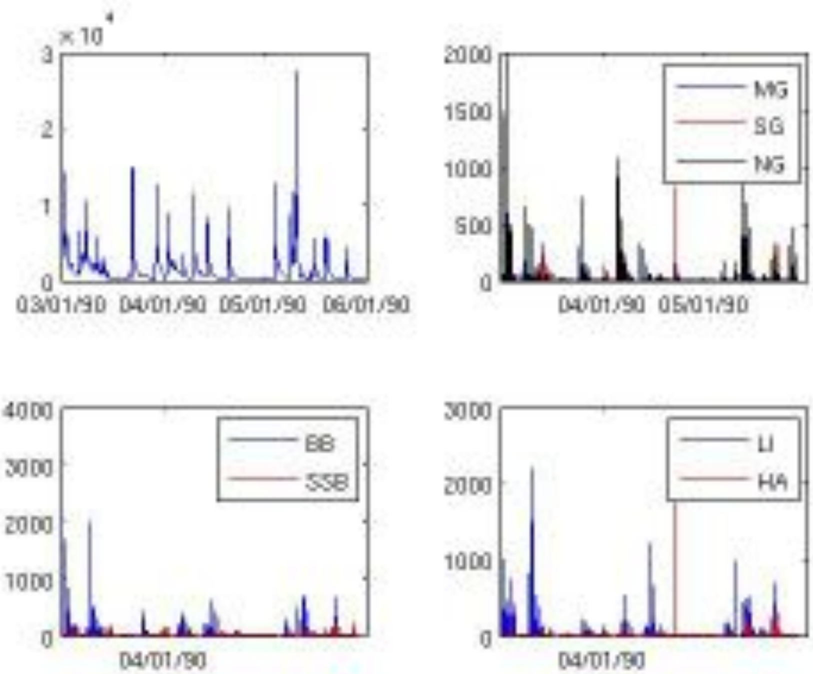
A comparison of model runs showed negligible difference between the results illustrated in **Figures 5a and 5b**. The transport of baseline and projected fecal coliform at relevant sites showed negligible effect of using those two different loads for the same lake hydrodynamics.

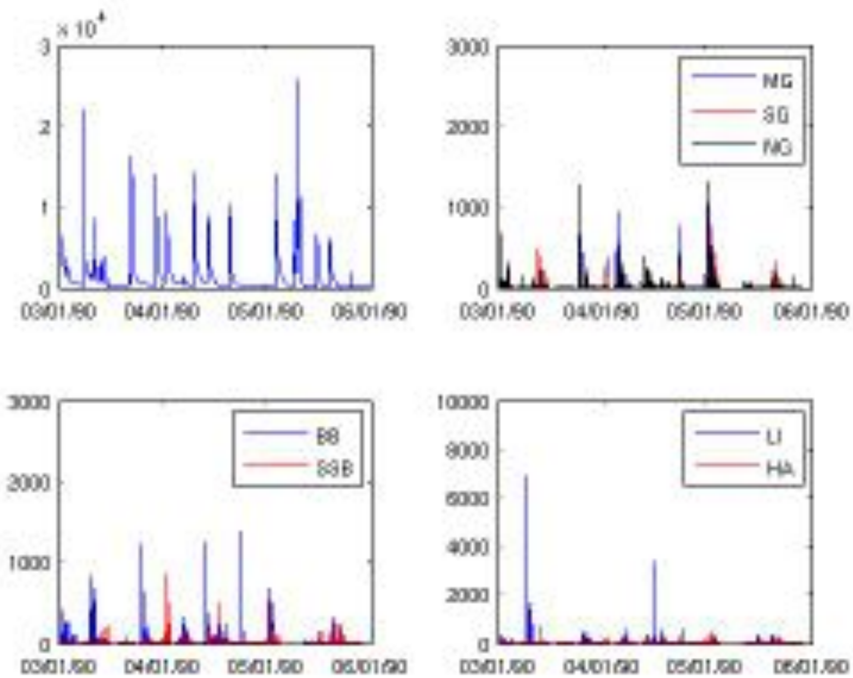
The spreadsheets con_1990_base.xlsx and con_1990_proj.xlsx contains calculated fecal coliform concentrations for the 1990 baseline and projected scenarios, respectively.

## Model predictions for baseline and climate change scenarios

The computer model was used to predict hydrodynamic conditions and fecal coliform concentrations for the baseline and climate change conditions summarized in **Table 5** Calculated concentrations for all scenarios are provided in the spreadsheet format illustrated in **Table 7**.

**a**




**b**

**Figure 5. Calculated fecal coliform concentrations (CFU/100 mL) during March-May 1990 at the Milwaukee River mouth (top left), sites MG, SG and NG (top right), BB and SSB (bottom left), and LI and HA (bottom right). a) Baseline loads and b) Projected loads.**

**Table 7. Illustration of spreadsheets that contain calculated fecal concentrations at the relevant locations shown in Figure 2 and Table 3. Concentrations were calculated also at the Linnwood (LI) and Howard Avenue (HA) water intakes, not shown in Figure 2 and Table 6.**

| Date and time | SG | HB | GC | NG | LI | 1/2 GC | MG | SSB | BB | HA |
|---|---|---|---|---|---|---|---|---|---|---|
| 4/1/05 0:00 | 3.3 | 0.7 | 0 | 9454.5 | 0.5 | 0.3 | 843.6 | 4.6 | 3088.9 | 0.1 |
| 4/1/05 1:00 | 3.3 | 0.7 | 0 | 9367.9 | 0.1 | 0.3 | 695.8 | 4.5 | 3234.4 | 0.1 |
| 4/1/05 2:00 | 3.4 | 0.6 | 0 | 8978.4 | 0 | 0.4 | 233.7 | 4.4 | 3364.9 | 0.1 |
| 4/1/05 3:00 | 3.5 | 0.6 | 0 | 8198.7 | 0 | 0.3 | 155.4 | 4.1 | 3411.1 | 0.1 |
| 4/1/05 4:00 | 3.6 | 0.6 | 0 | 7443.9 | 1.4 | 0.3 | 285.8 | 3.9 | 3335.5 | 0.1 |
| 4/1/05 5:00 | 3.7 | 0.6 | 0 | 6833.3 | 8.2 | 0.3 | 336.8 | 3.5 | 3262.3 | 0.1 |
| 4/1/05 6:00 | 3.7 | 0.6 | 0 | 6449.6 | 184.7 | 0.3 | 149.1 | 3.2 | 3244.4 | 0.1 |
| 4/1/05 7:00 | 3.9 | 0.5 | 0 | 6320.8 | 115.5 | 0.2 | 56.6 | 2.9 | 3184.6 | 0.1 |
| 4/1/05 8:00 | 4.1 | 0.5 | 0 | 6379.9 | 74.7 | 0.2 | 355 | 2.6 | 3048.3 | 0 |
| 4/1/05 9:00 | 2.1 | 0.4 | 0 | 6411.8 | 57.8 | 0.1 | 795 | 2.4 | 2899.7 | 0 |

**Figure 6** shows calculated fecal coliform concentrations at relevant locations for the Spring 2005 baseline and the corresponding worst-case scenario. For the worst case scenario, defined by higher wind speed predicted by model cccma_cgcm3_1, more hours with concentration larger than a threshold of 1,000 CFU/100 mL are predicted at the main gap MG and locations north of the Milwaukee River mouth (NG and BB), and fewer hours at locations south of the Milwaukee River mouth (SG and SSB).

**Table 8** summarizes the worst-case scenario results; the predicted number of hours with concentration larger than 1,000 CFU/100 mL at the water intakes LI and HA are negligible for both baseline and worst-case scenario.

**Figure 7** shows calculated fecal coliform concentrations at relevant locations for the Spring 2011 baseline and the corresponding best-case scenario. For the best case scenario, defined by lower wind speed predicted by model mri_cgcm2_3_2a, changes in transport of fecal coliform are smaller than for the worst-case scenario, and have opposite sign. More hours with concentration larger than a threshold of 1,000 CFU/100 mL are predicted at locations south of the Milwaukee River mouth (SG and HA). Fewer hours are predicted at the main gap MG, at location NG north of the Milwaukee River mouth, and at location SSB. **Table 9** summarizes those results; the predicted number of hours with concentration larger than 1,000 CFU/100 mL at the water intakes LI and HA are negligible for both baseline and best-case scenario.

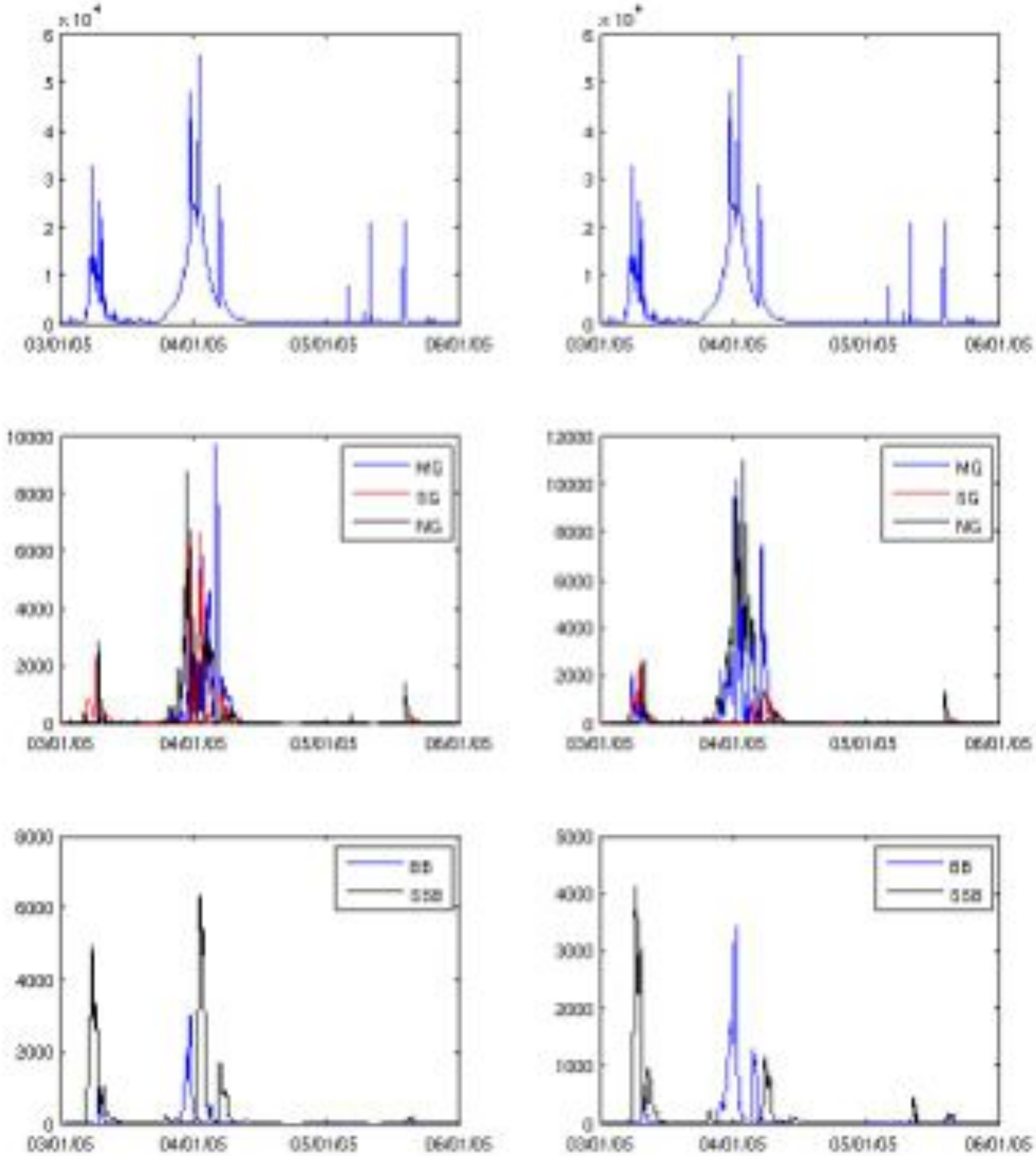



**Figure 6. Predicted fecal coliform concentrations at relevant locations for the 2005 baseline condition (left column) and the corresponding worst-case scenario (right column). The top row shows that the fecal coliform concentration input at the mouth of the Milwaukee River is the same for both cases.**

**Table 8. Predicted number of hours with fecal coliform concentration larger than 1,000 CFU/100 mL at relevant locations, for baseline and worst-case scenario.**

| Station | Baseline condition | Worst-case scenario |
|---|---|---|
| MG | 121 | 201 |
| NG | 156 | 223 |
| SG | 86 | 43 |
| SSB | 129 | 58 |
| BB | 35 | 74 |
| LI | 0 | 0 |
| HA | 0 | 0 |

**Table 9. Predicted number of hours with fecal coliform concentration larger than 1,000 CFU/100 mL at relevant locations, for baseline and best-case scenario.**

| Station | Baseline condition | Best-case scenario |
|---|---|---|
| MG | 334 | 321 |
| NG | 111 | 98 |
| SG | 206 | 227 |
| SSB | 164 | 142 |
| BB | 0 | 0 |
| LI | 0 | 0 |
| HA | 0 | 3 |

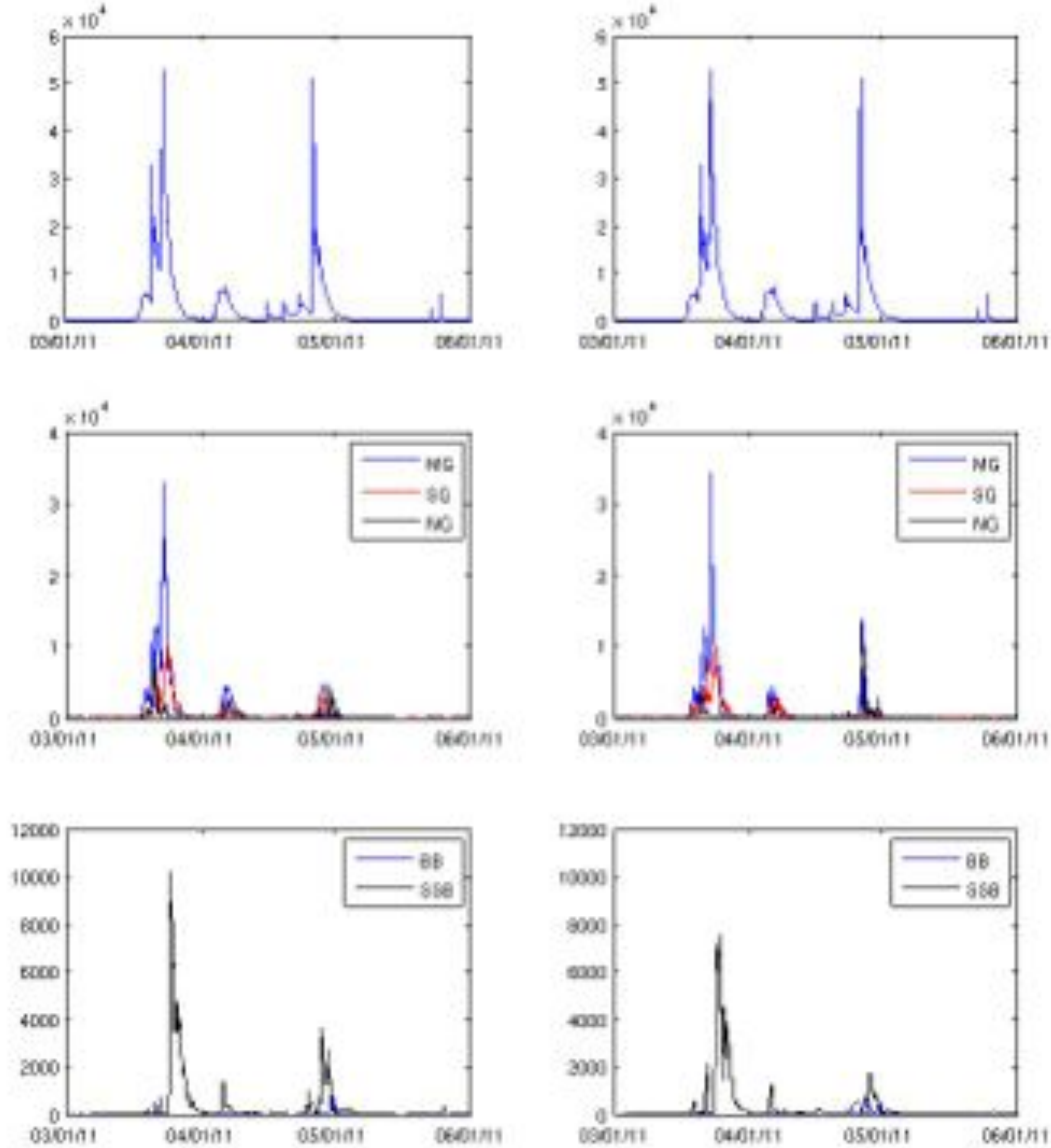


**Figure 7. Predicted fecal coliform concentrations at relevant locations for the 2011 baseline condition (left column) and the corresponding best-case scenario (right column). The top row shows that the fecal coliform concentration at the mouth of the Milwaukee River is the same for both cases.**

The changes in fecal coliform transport are explained by changes in current directions under climate change conditions. We calculated average currents during periods of high tributary concentration for baseline and climate change conditions, and the time-averaged change in currents during those periods. Model-predicted currents for baseline and worst-case scenario showed that the change in average currents is mostly to the south, so the predictions indicate more days with concentration higher than the threshold at locations south of the mouth of the Milwaukee River. Model-predicted currents for baseline and best-case scenario showed that the change in average currents is mostly to the north, so the predictions indicate more days with concentration higher than the threshold at locations north of the mouth of the Milwaukee River.

### 4.4 LAKE MODELING CONCLUSIONS

Predictions were made for hydrodynamics and fecal coliform transport under climate change conditions in coastal waters around Milwaukee. The predictions were made by combining a) downscaled climate change data for meteorological stations around Milwaukee and Lake Michigan made by the Center for Climatic Research at UW Madison, b) predictions of flows and bacteria loads for the watersheds and rivers that contribute to Lake Michigan around Milwaukee made by the Southeastern Wisconsin Regional Planning Commission (SEWRPC) and Tetra Tech, and c) a hydrodynamic and bacteria transport model for Lake Michigan around Milwaukee implemented for this study. To the best of the authors' knowledge, this is the first study that incorporates downscaled climate change data to study flows, bacteria loads and transport in Lake Michigan coastal waters.

Climate change scenarios were developed using the arguments that bacteria loads to Lake Michigan are larger during the spring season, and transport in coastal waters is most sensitive to changes in wind speed and direction.

Uncertainty in climate change predictions was dealt with by using the climate projections that yielded the $10^{th}$ and $90^{th}$ percentile changes in spring-season wind speed at the Milwaukee Airport station to define the worst-case and best-case climate change scenarios, respectively. Sets of downscaled climate change data for 11 ASOS stations around Lake Michigan were interpolated over Lake Michigan and used as meteorological forcing for baseline and climate change scenarios.

The patterns of bacteria transport showed significant changes under climate change conditions. Climate change predictions showed significant changes in the number of violations of concentration at relevant locations in the Lake Michigan coast around Milwaukee.

The worst-case scenario was defined by higher wind speed and developed using model cccma_cgcm3_1 predictions. The best-case scenario was defined by lower wind speed and developed using model mri_cgcm2_3_2a predictions. For the best-case scenario the changes in transport of fecal coliform are smaller than for the worst-case scenario, and have opposite sign.

The changes in fecal coliform transport are explained by changes in current directions under climate change conditions. For worst-case scenario the change in average currents is mostly to the south, and the predictions indicate more days with concentration higher than the 1,000 CFU/100 mL threshold at locations south of the mouth of the Milwaukee River. For best-case scenario the change in average currents is mostly to the north, and the predictions indicate more days with concentration higher that the threshold at locations north of the mouth of the Milwaukee River.

The hydrodynamic and transport model was run using 1990 lake meteorological forcing and both the baseline and projected loads for the Milwaukee River and Oak Creek. The purpose of those runs was to test the effect of different loads under the same lake hydrodynamics. The transport of baseline and projected fecal coliform at relevant sites showed negligible effect of using those two different loads for the same lake hydrodynamics.

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# 5 Major Conclusions and Recommendations for Future Studies

Weather phenomena already drive water quality, so changes in these patterns (i.e. climate change) only modify the existing effects. Modeling allows us to make predictions of the direction (increased or decreased) and the magnitude of these changes. Since climate predictions are on the order of a percentage change (i.e. 10-20% increase in spring rain volumes, etc.), we could expect that changes in the water resource impact will be within a similar order of magnitude. The modeling performed here serves as a decision support tool to call out important changes that may be out of proportion to the change in precipitation or other variable, or exacerbated by several factors working in concert. Decision support tools, such as the modeling described here, identifies adverse impacts that could be either prevented or prepared for in facility planning and water resource management. The modeling also helps identify particular sensitive or vulnerable effects, such as more days of poor water quality at a particular beach caused by shifting wind fields.

- Significant decreases in annual flow are predicted for both the "best" and "worst" case climate scenarios for 2050. This occurs because PET is predicted to increase at a much faster rate than precipitation. This in turn reduced loads of several of the pollutants (with a few exceptions, see Section 2.4 and below);
- The best and worst case climate scenarios were chosen based on spring rain. The watershed modeling results showed less total storm runoff but more high runoff events. As a result, increased sediment washoff from the land surface and, for some events, instream scour/resuspension in the Menomonee and Kinnickinnic watersheds produced annual TSS loads under climate change conditions that are greater than under baseline conditions. Annual average TSS concentrations were also projected to increase under climate change in those two watersheds. In the Milwaukee and Root River watersheds, TSS loads and instream concentrations were projected to decrease under climate change, while in the Oak Creek watershed, TSS loads were projected to decrease, but instream concentrations were projected to increase. Annual streamflow volume was projected to decrease under climate change in all five watersheds. These results point out the complexity of the relationships between annual and event changes in load and streamflow, which ultimately produce changes in pollutant concentrations.
- Overall stream water quality was not greatly impacted by climate change scenarios used in this study. This was unexpected and largely driven by the effect of higher air temperatures producing increasing PET. There are no table differences on how this interaction might occur between a rural watershed and a urban one (see section 3.3)

- The effects of increases in PET due to higher air temperatures were greater than the effects of slightly more total annual rainfall and more intense individual storms under both climate scenarios, resulting in a decrease in annual storm runoff volume. Detailed examination of how PET is predicted to change with increased stomatal closure was specifically examined (see section 3 and Appendix B). Generally, an approximately 10% offset set of the reduced runoff was predicted for the Menomonee watershed. Section 5, "Discussion," of Appendix B compares approaches to representing stomatal closure in the U.S. Environmental Protection Agency HSPF continuous simulation watershed model used for this study with other studies using the U.S. Department of Agriculture Agriculture Research Service/Texas A&M University AgriLife Research Soil and Water Assessment Tool (SWAT) model. The variables used in the models and the sophistication of the models are important considerations. The effect of plant physiological responses are estimated by soil moisture changes in the HSPF model, which captures the complex interplay between soil moisture and runoff. In contrast, SWAT models directly consider vegetation, but use a courser estimation of runoff coefficients for different types of land use. Overall, this complex interplay needs further study as PET is a critical driver in runoff models. (See Appendix B, Discussion section)

- Wind was a primary driver in the hydrodynamic lake model and a significant change was seen in how bacteria was distributed in the nearshore. Under the worst case scenario, bacterial concentrations were elevated for 2.5 fold more hours than base line conditions. Minimal changes ere seen under the best case scenario.

Recommendations include a further examination of how PET is treated in models that are used for decision support. The differences between SWAT and HSPF treatment of effects of increased $C0_2$ are detailed in Appendix B (Discussion section, pages 13 and 14) highlight the large effect a single variable can have on model output. More empirical data for specific variables may improve model predictions under climate change conditions. Because it uses time series input data for numerous meteorlogical parameters, the HSPF watershed model applied for this study is well-suited to refinement to better simulate the effects of climate change using additional downscaled climate parameters, when such information becomes available.

Recommendations also include developing coupled models using synchronized time series. While we did not have the baseline time series available for the same periods, here we present an approach that allows us to link the modeling activities. The HSPF model could be revised to simulate a baseline meteorological time series record that is synchronized with the time periods for which the hydrodynamic model was developed.

# 6 Dissemination of Results

The McLellan lab maintains a page on their research lab website dedicated to various climate change projects, as well as a page dedicated to the NOAA/SARP project results. The final version of this report will be made available as a downloadable pdf. The number of downloads will be tracked.

McLellan lab climate page: http://home.freshwater.uwm.edu/mclellanlab/research-v2/wisconsin-initiative-on-climate-change-impacts-wicci-milwaukee-working-group-on-climate-change-impacts-and-the-urban-coastal-environment/

McLellan lab NOAA/SARP page: http://home.freshwater.uwm.edu/mclellanlab/climate-change-risks-and-impacts-on-urban-coastal-water-resources-in-the-great-lakes/

Sandra McLellan serves at the Milwaukee Working Group Chair for the Wisconsin Initiative on climate Change Impacts (WICCI) and Mike Hahn is a key member of the Milwaukee working group and also participates on the Stomwater Working Group. Expertise and findings from this project is disseminated to these groups through ongoing interactions. The final report will also be shared with these groups.

Scientific Presentations

Hahn, M. "Water quality modeling in the Greater Milwaukee watersheds and lake Michigan Nearshore"
Great Lakes Commission and US EPA Region 5 Lake Michigan Monitoring Coordinating Council
State of the Lakes Conference October 2013

Perry, D. Effect of Climate Change on Sewer Overflows in Milwaukee.
Date: October 1, 2012
Location: Water Environment Federation's Technical Exhibition and Conf. (WEFTEC), New Orleans, LA

McLellan, S.L.  Climate Change Impacts on the Great Lakes
Date:  Jun 8, 2011
Location:  Capitol Hill Oceans Weak, Washington, D.C.

McLellan, S.L.  Climate Change and Waterborne Pathogens in the Great Lakes.
Date:  March 3, 2011.
Weston Round table Series, Center of Sustainability and Global Environment, University of Wisconsin-Madison. Madison, WI

Invited Seminars and Talks

McLellan, S.L. Development of new indicators of fecal pollution
Date:  November 13, 2012
Location:  Medical College of Wisconsin-Department of Pediatrics

McLellan, S.L. Water Quality & Bacteria Contamination in Milwaukee's Lake Michigan Nearshore Area
Date:  November 7, 2012
Location:  Lake Michigan Stakeholders group, Milwaukee, WI

McLellan, S.L. Climate Change and Waterborne Pathogens in the Great Lakes
Date:  June 1, 2012
Location:  Milwaukee Riverkeeper Seniors, Milwaukee, WI

Presentations to watershed managers and agencies
McLellan, S.L. And Hahn, M. Impact of Climate Change on CSOs and SSOs in Milwaukee Watersheds
January 26, 2012
Milwaukee Metropolitan Sewerage District Commission Meeting
November 16, 2011
Technical Advisory Team at Milwaukee Municipal Sewerage District

McLellan, SL.  Update on Climate Research to the Sweetwater Trust Science Council
December 12, 2012

Interviews
Government Accountability Board (Hahn and McLellan)
May 1, 2012, (Ann Hobson and Joe Thompson)

Climate Adaptation Knowledge Exchange (CAKE) - March 2013
Case study found at http://www.cakex.org/case-studies/investigating-impact-climate-change-combined-and-separate-sewer-overflows-milwaukee-wat