Utility Climate Resiliency Study

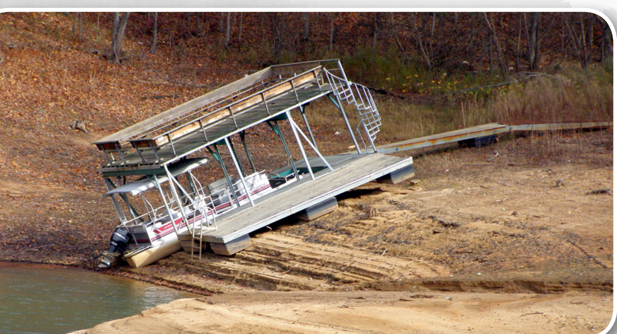
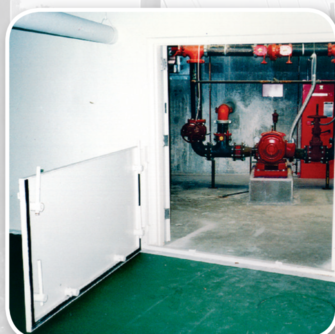
Submitted to:

Metropolitan North Georgia Water Planning District

December 2015







CDM Smith

Preface

This study was based on the fundamental premise that the future climate conditions in North Georgia are uncertain, and cannot be forecast with specificity. From this premise arose three questions: (1) What is the range of plausible climate conditions for the next fifty years, (2) What aspects of water and associated infrastructure are most vulnerable to this uncertainty, and (3) How can North Georgia effectively plan to address and mitigate these risks?

To address these questions, plausible future climate scenarios were defined based on the current state of climate science, and were intended to effectively bracket the possible range of temperature and precipitation variations over the next fifty years. These scenarios were informed by the collection of Global Circulation Models (GCMs) commonly employed, but did not rely specifically on any one projection. Each scenario was considered equally plausible, and the study was not in any way aimed at predicting which future climate trends are most likely. Rather, simulation tests were conducted to determine if any or all potential trends could create new risks for water supply, water demand, water quality, flood potential, and nonpoint source pollution levels. On a relative basis, then, the potential risks were compared to help characterize their significance and help the District prioritize future planning efforts or more detailed studies.

Once these vulnerabilities were understood, the facilities and infrastructure used to manage water throughout the District were evaluated to better understand their vulnerability to changes in water quality and quantity. Many water resources and facilities exhibited risks regardless of the future climate trends, suggesting that preemptive measures would be broadly, and almost certainly, beneficial in planning. Other aspects of the water environment exhibited risks only for specific future trends, and as such, measures are recommended on an adaptive basis, to be implemented in response to specific climate trends as (and if) they may develop.

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Acknowledgements

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- Metro North Georgia Water Planning District
  - Andy Cornwell
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- Clayton County Water Authority
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Once these vulnerabilities were understood, the facilities and infrastructure used to manage water throughout the District were evaluated to better understand their vulnerability to changes in water quality and quantity. Many water resources and facilities exhibited risks regardless of the future climate trends, suggesting that preemptive measures would be broadly, and almost certainly, beneficial in planning. Other aspects of the water environment exhibited risks only for specific future trends, and as such, measures are recommended on an adaptive basis, to be implemented in response to specific climate trends as (and if) they may develop.

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Executive Summary

ES.1 Introduction and Objectives

The Metropolitan North Georgia Water Planning District (Metro Water District) has undertaken a utility climate resiliency study to assess the potential impacts of climate variability on the region's water resources and infrastructure. The goal is to identify and characterize potential climate variability impacts so appropriate adaptation measures can be considered during the 2016 District Water Management Planning effort and beyond.

Over the past 15 years, north Georgia has experienced three multi-year droughts followed by years of significant and record rainfall requiring local governments and utilities to shift between drought protection and flood management strategies. The recent frequency of these weather swings demonstrates the need to incorporate climate resiliency in the Metro Water District's future water management and planning.

This study is NOT intended to be predictive. In other words, no attempts are made at predicting future climate conditions for the Metro Water District. Rather, the study focuses on identifying resources and infrastructure that are most vulnerable to uncertainty in future climate conditions so that planning and readiness efforts can focus on the most critical issues.

Specific objectives of the study are listed below:

- **Plausible Future Climate:** Develop a set of potential future climate scenarios centered on a 2050 planning horizon that effectively bound the conditions suggested by climate models and historically available data.
- **Impacts to Water Resources:**
    - **Water Demand:** Determine how future climate conditions could affect water demand, when controlling for other factors that impact water use.
    - **Water Supply:** Determine how future climate conditions could affect the firm yield or reliability of water supply reservoirs, and how drought severity might change.
    - **Water Quality:** Determine how future climate conditions could affect river water temperatures and dissolved oxygen levels.
    - **Watersheds:** Determine how the future climate scenarios may impact a variety of watershed issues including: the frequency and intensity of storm events, peak streamflow levels, and pollutant loading.
- **Risks to Water Infrastructure:** Translate the potential climate impacts identified above into a qualitative assessment of the risks these impacts present to water infrastructure including wastewater treatment plants, water treatment plants, stormwater conveyance systems, wastewater collection systems, and dams and levees.

- **Adaptive Strategies:** Recommend a suite of relevant, proven measures that could help address or reduce the specific risks identified to water resources and infrastructure:
  - Near-term "no regret" recommendations that could enhance ongoing activities or provide multiple benefits beyond reducing sensitivity to climate conditions,
  - Specific suggestions to help reduce water and wastewater facilities vulnerability to specific climate trends if they develop.

ES.2 Climate Scenarios

Future climate scenarios were developed utilizing a combination of state-of-the-art climate models and historically available climate data. All scenarios are intended to represent discrete *plausible* climate futures centered on a 2050 planning horizon. No attempt is made to assess the likelihood that these potential climate futures will occur, but rather they are presented in order to determine the range of possible impacts to the region's water resources if they should occur. The climate scenarios are defined below, with percentiles referring to the suite of over 100 Global Circulation Models (GCMs) whose results were distilled down to the following scenarios that bounded the evaluation in this report:

1. **Central Tendency**: interquartile range: 25th to 75th percentiles temperature and precipitation
2. **Hot/Dry**: 75th to 100th percentile temperature, 0 to 25th percentile precipitation
3. **Hot/Wet**: 75th to 100th percentiles temperature and precipitation
4. **Warm/Wet**: 0 to 25th percentile temperature, 75th to 100th percentile precipitation
5. **Warm/Dry**: 0 to 25th percentile temperature and precipitation
6. **Historic Trend:** This scenario was independent of the climate models, and simply extrapolated observed climate trends from the historical record out through 2050.

ES.3 Vulnerability of Water Resources

Table ES.1 summarizes the estimated range of potential impacts of the future climate scenarios on key aspects of the District's water resources through 2050. Each impact is discussed briefly in the sections that follow, and in more detail throughout the report.

Table ES.1: Summary of Water Resource Vulnerability to Uncertain Future Climate Conditions

Water Resource	Range of Potential Impacts (for the case studies evaluated)	Most Severe Climate Scenario
Water Demand	• Up to a ~4% increase	Hot/Dry
Water Supply and Drought	• Increased drought severity • Up to ~10% reduction in reservoir firm yield for small to midsize reservoirs (but potential increase in wetter scenarios)	Hot/Dry
Water Quality	• Decreasing values of extreme low flow • Up to ~3 deg. F. increase in water temperature • Up to 1.4 mg/l decrease in dissolved oxygen	Hot/Dry
Watershed Impacts	• Up to a ~12% increase in rainfall depth • Up to ~11% increase in peak streamflow • Corresponding increase in nonpoint source pollution	Hot/Wet

ES.3.1 Vulnerability of Water Demand

Many factors influence water demands, such as economy, water use efficiency, water rates and rate structures, presence of drought-related mandatory restrictions, and weather. In order to isolate the impacts that future climate can have on water use, a multivariate statistical water demand model was developed. Future climate scenarios were input into the statistical model in order to determine the net impact on water demand. **Figure ES.1** shows the potential impacts that the climate scenarios have on water demands, all other factors remaining the same. **The potential impacts from climate on water use range from 1.3 percent (historical trend climate) to 3.8 percent (hot/dry climate scenario) by 2050**. This means that if nothing else changed except for climate, water demand is projected to be between 1.3 and 3.8 percent higher in 2050.

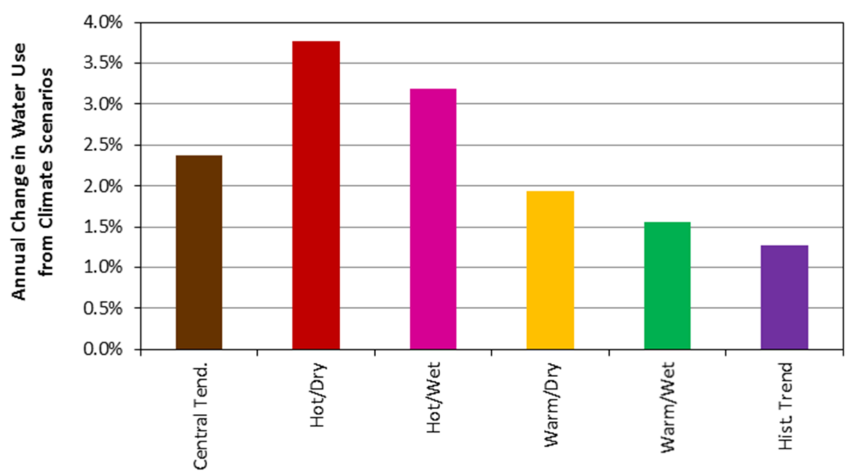

Figure ES.1 Potential Impacts on Water Demand from Climate Scenarios in 2050

ES.3.2 Future Drought Severity and Vulnerability of Water Supply

Estimates of potential future drought severity were developed by using precipitation and temperature estimates for the climate scenarios listed in Section ES.2 in the equation for the Palmer Drought Severity Index (PDSI). The PDSI is a well-known metric for characterizing drought conditions and is based on a simplified soil moisture water balance model that takes into account time series information on both precipitation (source of soil moisture) and temperature (loss of soil moisture via evapotranspiration). Historical climate conditions have generally resulted in "near normal" conditions on average, but many of the potential future climate scenarios used in this study suggest increasing drought severity through the next century, as indicated in **Figure ES.2**:

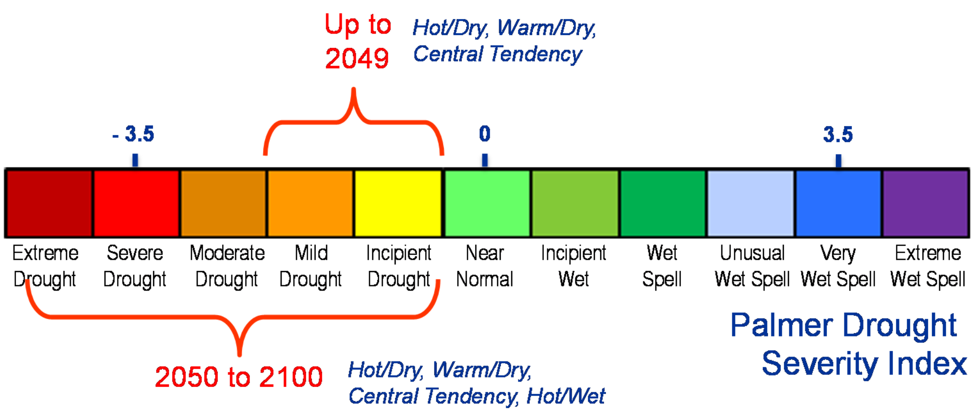

Figure ES.2 Potential Impacts of Future Climate on Drought Severity

Five small to mid-size single purpose water supply reservoirs within the Metro Water District were also evaluated as case studies, and results suggested that the firm yield of these reservoirs could either increase or decrease as a direct consequence of future climate trends, as illustrated in **Figure ES.3**. **Drier conditions could decrease the firm yield in these reservoir between 5 and 10 percent, approximately, while wetter conditions could increase the firm yield up to 30 percent, though this result was isolated – most increases were near or less than 10 percent.** The reservoirs studied were less susceptible to surface evaporation than to changes in runoff, and the results suggest that storage can provide some buffering against changes in extreme low flows. However, because of the variation in these results, and the fact that no strong correlation was identified between the results and the physical features of the reservoirs or their watersheds, these results should not be extended to other reservoirs within the Metro Water District. Each reservoir should be analyzed for its own unique vulnerability and resilience.

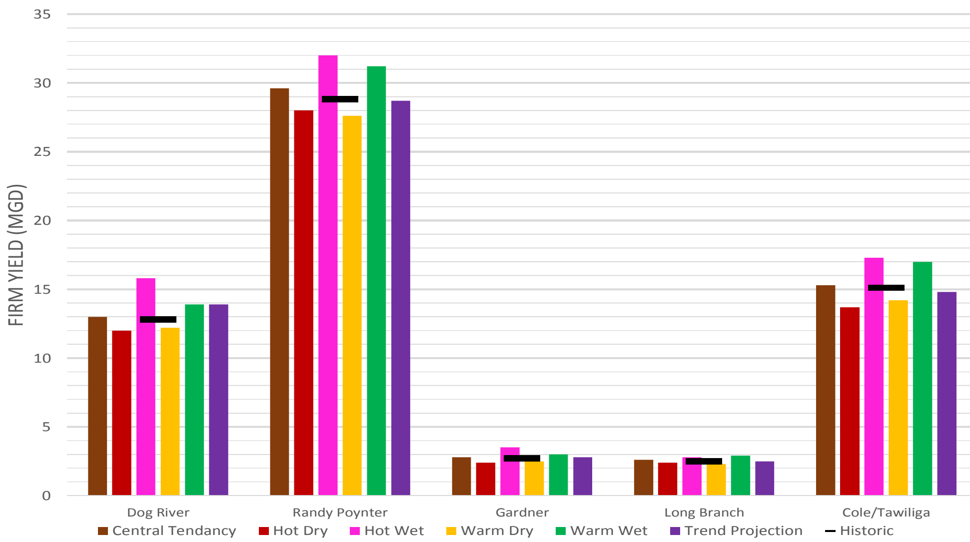

Figure ES.3 Potential Impacts of Future Climate on Reservoir Firm Yield*

**Historic firm yield values are presented for comparison, and represent estimate developed with the same models and assumptions as used for future conditions - they do not necessarily reflect permitted or other published values.*

ES.3.3 Vulnerability of Water Quality

It is well established that the quality of streams and lakes is highly sensitive to both temperature increases and changes in flow regime. Higher water temperatures can be lethal to key freshwater biota. Higher temperatures also lead to increased pollutant oxidation rates and lower dissolved oxygen (DO) saturation levels, both of which result in decreased DO concentrations. Increased nuisance algal growth rates are also a concern with higher water temperatures. These problems are all exacerbated by lowered flow rates, which increase reach residence times and decrease dilution and assimilative capacities.

All climate conditions evaluated in this study suggest that water temperature could increase on average over a range of less than 0.5 degrees F to almost 3 degrees F. Combining these increased temperatures with corresponding reduction in extreme low flow conditions could result in reductions in DO of up to 1.4 mg/l (for reference, the state water quality standards for DO are 4 to 5 mg/l, depending on the type of fishery the water body supports). **Figure ES.4** illustrates these findings for four case study watersheds within the District. Reductions of this level could impair aquatic habitat and the ability of receiving waters to assimilate contaminates. This, in turn, could create a need for stricter pollution control standards, both for point source and nonpoint source pollution.

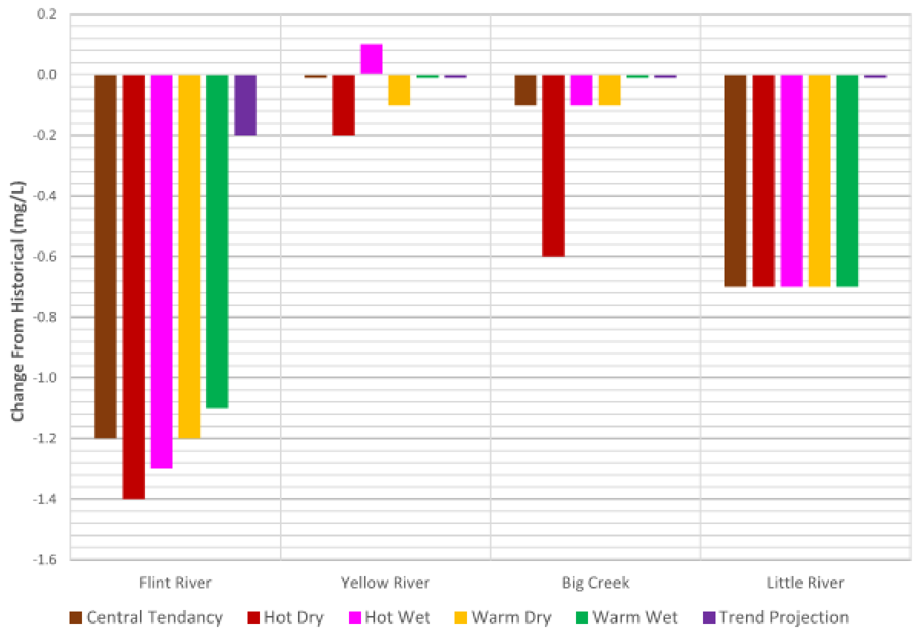

Figure ES.4 Potential Relative Changes in Reach Average Dissolved Oxygen

ES.3.4 Watershed Impacts

For the purposes of this study, climate variability impacts that affect watershed issues include storm intensity, peak streamflows, and nonpoint source pollutant loads. **By 2050, one-day extreme rainfall depths could be up to 5 to 10 percent higher relative to 20th century conditions, according to estimates presented in EPA's Climate Resilience Evaluation and Awareness Tool (CREAT).** **Figure ES.5** illustrates the potential changes in storm depth for significant storms (5-year, 10-year, and 25-year recurrence). **Figure ES.6** illustrates the corresponding changes in peak streamflow that could also result. These increases could result in increased flooding, erosion, and nonpoint source pollution.

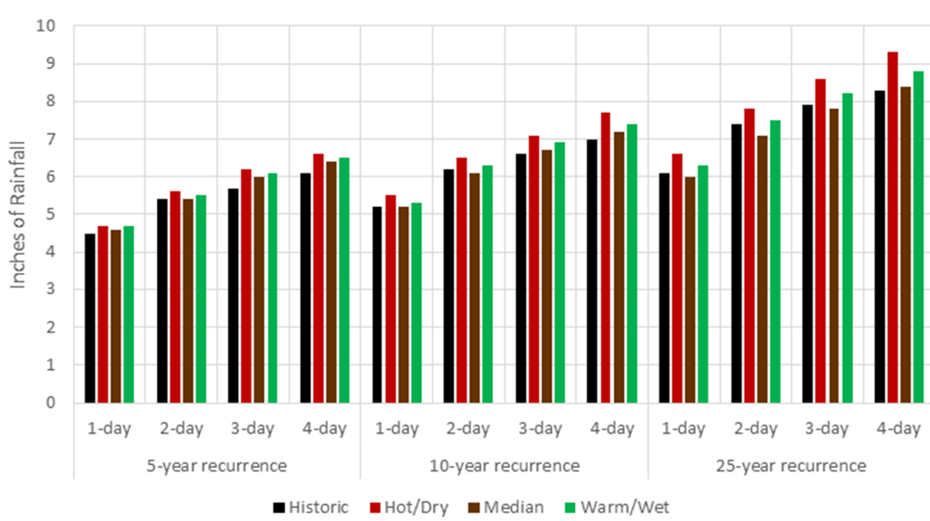

Figure ES.5 Potential 2050 Storm Depths for Various Recurrence Intervals and Durations

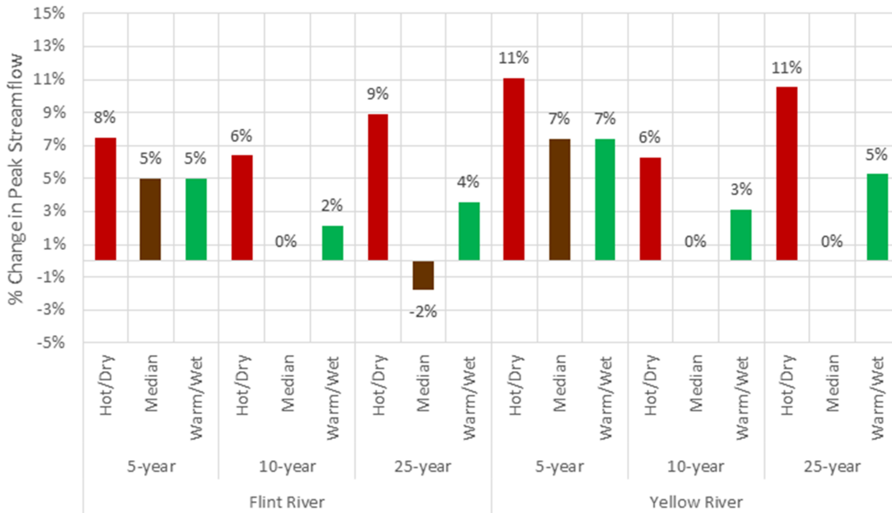

Figure ES.6 Potential Change in Peak Streamflows for Various Intensity and Duration Storms Due to Climate Variability

ES.4 Vulnerability of Water-Related Infrastructure

The infrastructure types that are considered most vulnerable are those that are highly sensitive to changes in water sector impact and have minimal capacity to adapt to climate scenarios. The facilities and the associated water sector impact are listed in **Table ES.2**. The report includes scorecards for each type of facility in the table paired with specific risks of climate uncertainty.

Table ES.2 High Sensitivity, Low Adaptive Capacity Infrastructure Types

Infrastructure Type	Greatest Risk
Wastewater Treatment Plants	Increase in 24-hour Storm Depths
	Increase in Nonpoint Source Pollutant Loads
Water Treatment Plants	Increase in Water Demand and/or Droughts
Stormwater Conveyance Systems	Increase in 24-hour Storm Depths
Wastewater Collection Systems	Increase in 24-hour Storm Depths
Dams and Levees	Increase in 24-hour Storm Depths

ES.5 Adaptation Strategies

Numerous objectives guided the formulation of adaptation strategies for the Metro Water District. The fundamental objective was to recommend a suite of relevant, proven measures that could help address or reduce the specific risks identified in this study. Secondarily, it is important for the District as it moves into its next phase of planning to distinguish between projects and policies that could offer universal benefits regardless of future climate conditions from those that would be targeted at mitigating the impacts of just one or two future climate trends. Hence, another objective of the study was to recommend a suite of “preemptive” adaptation measures that could be implemented immediately with no regrets, and also a group of measures that would only be implemented if triggered by specific future climate trends once they are clearly evident. **Table ES.3** lists the recommended preemptive adaptation measures that could be adopted in the near term with very low risk and broad benefits.

Table ES.3 Recommended Preemptive Climate Adaptation Measures

Preemptive Measures	Relevant Climate Conditions	Specific Risks	Benefits of the Measure
Implement climate tracking protocols	All	- Future climate trends are uncertain	- Specific response measures can be triggered by the onset of actual, recognizable trends
Green Infrastructure	All	- Increased Storm Depth/frequency/Intensity - Increased nonpoint source pollution - Reduced reservoir yields	- Mitigate storm depth and volume - Reduce nonpoint pollution loads - Increased local water supply
Drought Management Plans that specifically identify risks to individual reservoirs	All	- Increased tendency toward more severe/frequent drought conditions from all scenarios - Potential reduction of reservoir yield - Uncertainty about the type of drought that is riskiest for each reservoir (long and gradual vs. short and sudden)	- Specific drought triggers for each utility and supply system - Unified guidance from the District on drought conditions/response - Correlation with Demand Management (below) - Potential for supply side management
Demand Management	All	- Increase in water demand	- Help conserve water by lowering demand
Integrate Reclaimed Water into Supply Planning (possibly through policy incentives that do not yet exist)	All conditions could increase demand and drought risk. Dry scenarios also reduce reservoir yield.	- Increase in water demand - Reduction in reservoir yield - Increased drought frequency and/or severity	- Utilizes an available resource to offset demand without new hydrologic stresses - Policies and incentives could foster regional collaboration
Extreme Precipitation Analysis	Central, Hot Dry, Warm Wet	- Increased Storm Depth/frequency/Intensity	- Prioritize specific facilities at the greatest risk (conveyance, treatment, retention, etc.) that would benefit from climate-triggered enhancements
Conveyance system inspection and maintenance	All	- Increased flows during storm events - Damage due to lowering water table and tree root migration	- Prioritize upgrades to conveyance systems.

Other measures aimed at minimizing the impacts of specific risks to resources or facilities are also included at the end of the report, with the recommendation that active climate trend tracking be used through future decades to trigger such responses.

Table of Contents

List of Figures

List of Tables

Appendices

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Section 1

Introduction and Objectives

1.1 Project Objectives

The Metropolitan North Georgia Water Planning District (Metro Water District) has undertaken a utility climate resiliency study to assess the potential impacts of climate variability on the region's water resources and infrastructure. The goal is to identify and characterize potential climate variability impacts so appropriate adaptation measures can be considered during the 2016 District Water Management Planning effort.

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Specific objectives of the study are listed below:

- **Plausible Future Climate:** Develop a set of potential future climate scenarios centered on a 2050 planning horizon, utilizing a combination of climate models and historically available data.
- **Impacts to Water Demand:** Determine how future climate scenarios affect water demand, when controlling for other factors that impact water use.
- **Impacts to Water Supply:** Determine how future climate scenarios affect the firm yield or reliability of water supply reservoirs and how much of the current yield of the reservoirs may be at risk.
- **Impact to Water Quality:** Determine how future climate scenarios affect river water temperatures and dissolved oxygen levels and what hydro-climate conditions and watershed physical characteristics are these water quality parameters most sensitive too.
- **Impact to Watersheds:** Determine how the future climate scenarios may impact a variety of watershed issues including: the frequency and intensity of storm events, peak streamflow levels, and pollutant loading.
- **Risks to Water Infrastructure:** Translate the climate impacts identified in the categories above into a qualitative assessment of the risks these impacts present to water infrastructure including wastewater treatment plants, water treatment plants, stormwater conveyance systems, wastewater collection systems, and dams and levees.
- **Adaptive Strategies:** Recommend a suite of relevant, proven measures that could help address or reduce the specific risks identified to water infrastructure.

1.2 Report Outline

The following sections are included within this report:

- **Section 2 Future Climate Scenarios:** A total of six plausible future climate scenarios of both temperature and precipitation are developed based on climate models and a trend analysis of historical data. Paleo data and impacts of future climate on drought are also discussed.
- **Section 3 Climate Vulnerability Methodology:** This section describes how the future climate scenarios and other data were utilized to perform a vulnerability analysis on the Metro Water District's water resources in terms of water demand impacts, water supply impacts, water quality impacts, watershed impacts, and infrastructure considerations.
- **Section 4 Climate Vulnerability Analysis:** This section presents the results of the vulnerability analysis for the Metro Water District's water resources, including water demand impacts, water supply impacts, water quality impacts, watershed impacts, and infrastructure considerations.
- **Section 5 Adaptive Strategies:** This section presents various adaptation strategies for climate resiliency that the Metro Water District should consider in its development of water resource management plans, working closely with utilities in the region.
- **Section 6 Recommendations for Future Work:** This section identifies near term activities recommended for implementation by the District.
- **Section 7 References:** This section provides a list of references used throughout the report as well as some additional resources on recommendation areas.

Section 2

Future Climate Scenarios

Future climate scenarios were developed utilizing a combination of climate models and historically available climate data. All scenarios are intended to represent discrete *plausible* climate futures centered on a 2050 planning horizon. No attempt is made to assess the likelihood that these potential climate futures will occur, but rather they are presented in order to determine possible impacts to the region's water resources if they should occur.

2.1 Global Climate Models

Future climate projections for the Metro Water District have been summarized under this task using a range of available global climate model (GCM) projection data sets. These include both monthly and daily projections of future air temperature and precipitation. Published climate model projections for north Georgia, downscaled to a 1/8 degree latitude/longitude grid, were obtained from the U.S. Bureau of Reclamation (Reclamation) data portal.[1]

A total of 108 different climate model projections were downloaded for the period 2000 to 2100. A modeling "overlap" period of projections and a historical observed dataset (gridded to same 1/8th degree grid) were also obtained for the years 1950 to 1999. All projections represent the latest in scientific research and were developed under the World Climate Research Programme Coupled Model Intercomparison Project, Phase 5 (CMIP5). The CMIP5 data set includes 35 different climate models developed at top research institutions around the world and applied across a range of model input assumptions. No attempt was made to assess the likelihood of these models being correct or not. Rather they were used to test plausible future climate scenarios for this study.

Climate model projections were averaged across four 1/8th degree grid cells centered on the City of Atlanta (**Figure 2.1.1**). Each grid cell was equally weighted in the calculation. The captured region is considered representative of the larger Metro Water District study area, with respect to climate variability, for the vulnerability assessment performed here. Although many of the specific vulnerability study sites lie just outside of this central region, spatial variations in climate across this general region are not believed to be significant to warrant the use of more site specific climate data. This assumption is supported by the fact that only relative changes (modeled future vs. modeled past) in planning variables, as impacted by relative changes in climate, were analyzed in subsequent tasks.

[1] The U.S. Bureau of Reclamation data portal can be accessed at: http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/dcpInterface.html

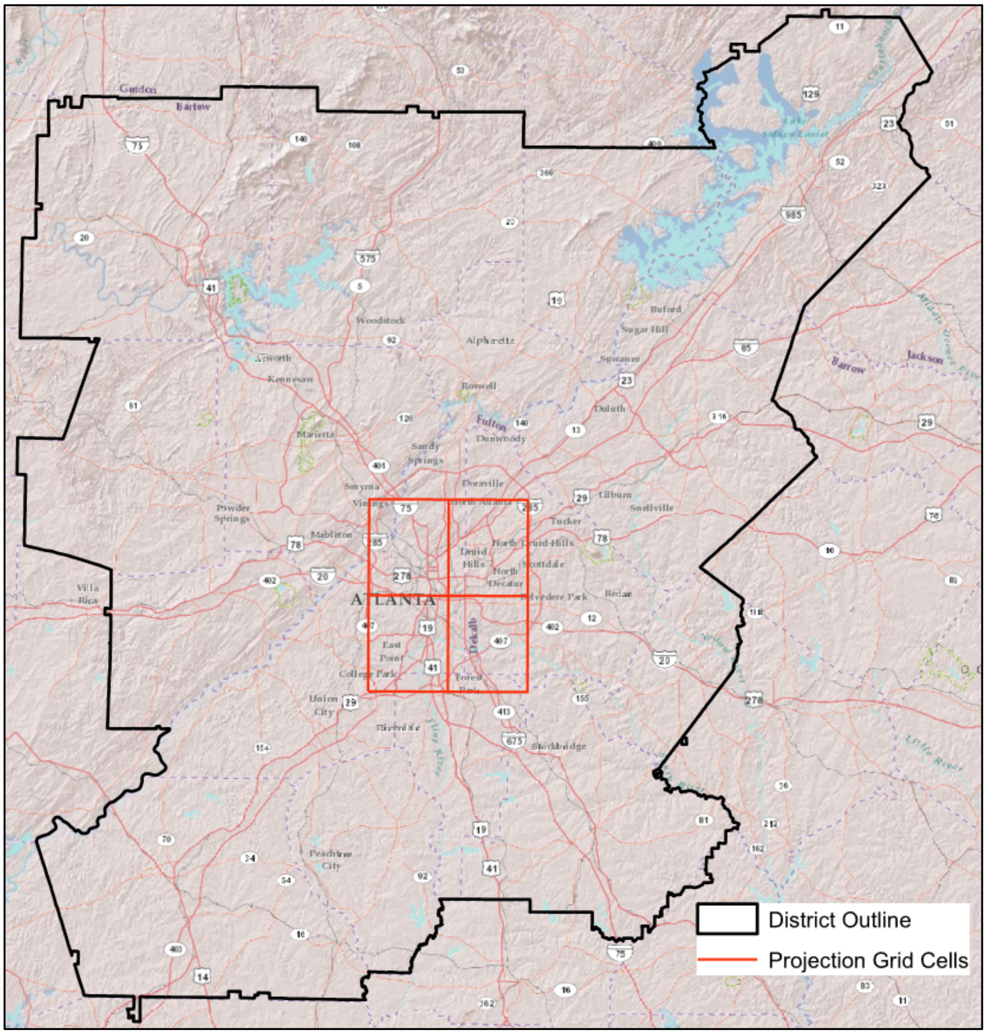

Figure 2.1.1 Representative Climate Model Projection Grid Cells

A 2050 planning horizon was selected for this work after consultation with the Metro Water District and the District's Technical Coordinating Committee (TCC). This planning horizon is in line with the anticipated planning horizon associated with the 2016 water plan update. A sampling band of ± 15 years, centered on 2050, was used to capture "natural" year to year variability in the climate data, while still being representative of climate trend projections associated with the middle of the 21st century.

Climate model data were pooled into five different "ensembles", each of which is used to develop different future climate scenarios for use in subsequent analyses. The scenarios are intended to be viewed as equally plausible and representative of the range of inherent variability and uncertainty in the climate model projections. The ensembling process was guided by annual anomaly plots that display the changes in mean annual temperature (ºF) and precipitation (as a percentage) predicted by each projection for the 2050 planning horizon, compared to the recent past (1950 – 1999) (**Figure 2.1.2**). All 108 GCM projections, downscaled to the Metro Water District, are represented on this plot as discrete points. Five (5) different climate data ensembles were constructed using this plot representing the five boxed quantile ranges shown:

1. **Central Tendency**: interquartile range: 25th to 75th percentiles Temp and Precip
2. **Hot/Dry**: 75th to 100th percentile Temp, 0 to 25th percentile Precip
3. **Hot/Wet**: 75th to 100th percentiles Temp and Precip
4. **Warm/Wet**: 0 to 25th percentile Temp, 75th to 100th percentile Precip
5. **Warm/Dry**: 0 to 25th percentile Temp and Precip

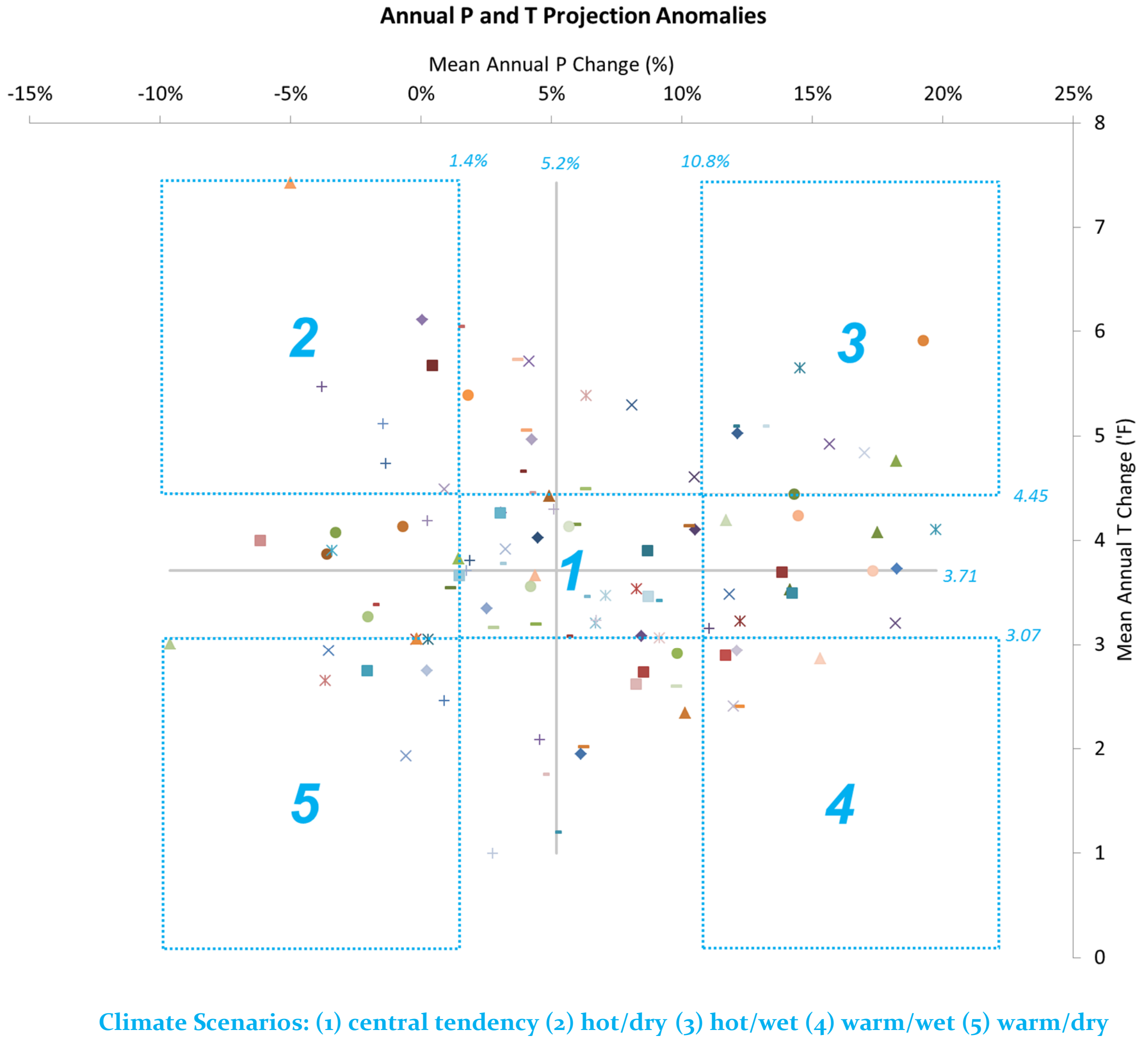

Figure 2.1.2 Annual Anomalies (2050 vs. historical) of GCM Temperature and Precipitation Projections, with Designated Scenario Ensembles (each symbol represents a different climate model projection set)

Data from all of the model projections residing within a given quantile box were pooled to create the five ensembles. In this way, not all of the available climate projections were used and no projection was used in more than one ensemble. Advantages of this approach, as advocated by Reclamation (Reclamation 2010), are that it allows for easy visualization of the range and uncertainty in climate projections and does not require subjective selection of model projections; while at the same time still providing a practical number of pooled scenarios for use in subsequent analyses.

Another goal of this approach was to avoid overdependence on any particular GCM or GCM subset, and rather, to bound the GCM predictions with the quadrants chosen as they are located at the extreme corners of the results. Some GCM results are not included in the quadrants, but because this is not a predictive or probabilistic exercise, they would only tend to "soften" the 5 scenarios by drawing them back toward the center. By definition in this study, all scenarios are considered equally probable. By extension, then, the goal to bound the GCM predictions with the scenarios is somewhat independent of how many GCM results fall within each quadrant. As long as the quadrants capture the extremes, the scenarios effectively bound the range of plausible future conditions without overemphasizing or underemphasizing and potential trend.

For each of the five ensembles, a series of summary plots and tables were produced to characterize future climate conditions, as projected by the GCMs for specific planning horizons. These summaries, for both temperature and precipitation, include annual time-series plots, mean monthly seasonal plots, and percentile plots. Recurrence intervals associated with 24 hour storm events will be calculated for specific planning horizons. Annual and monthly mean, min, max, and standard deviation values have also been tabulated for each ensemble. These plots and tables can be found in **Appendix A**.

For each climate model ensemble, a method referred to as the "hybrid delta ensemble" (HDe) method (Reclamation, 2010) was applied to adjust historical climate records to reflect the five future climate projection data sets. In this method, statistical adjustments are made to the historical observed data set (1950 – 1999) based on relative changes predicted by the pooled GCM projections. In this way, this method preserves the month-to-month pattern of variability and many of the core statistics of the observed historical record in its projection of future conditions. The method has been used extensively by the U.S. Bureau of Reclamation, and others, as a means of incorporating climate model projections into water resources planning studies.

The "delta" in the HDe name refers to the difference between GCM projections of the future vs. GCM hindcasts of the past. The "hybrid" term refers to the fact that the method uses a range of delta values to adjust the historical record based on relative climate conditions. For example, during wet observed periods calculated deltas associated with wet modeled periods are used. Similarly during observed dry periods, dry modeled period deltas are used to adjust the record. The same principle is applied in adjusting the temperature record. The advantages of this approach are that it is often more palatable to stakeholders because it is so strongly tied to actual observed climate data (rather than using model projections by themselves) and it eliminates any overriding bias in the GCMs by using delta values (modeled vs. modeled) rather than the projection data themselves. The reader is referred to Reclamation (2010) for further details of this method.

The 1950 to 1999 period was selected as the historical climate baseline period for this study for a number of reasons. First of all, we desired to follow, as closely as possible, well established and published methods for developing climate scenarios for water resources planning. The 1950 to 1999 period is standard in Reclamation's HDe approach. There are seemingly multiple reasons for this. Firstly, historical climate observations projected onto the same 1/8 degree spatial grid as the climate model projections, and critical to the approach, are only available for this limited historical period (Maurer et al. 2002). Secondly, all of the climate models used in this study have been "trained" (calibrated) to the 1950 to 1999 period as part of the model downscaling task. Model output beyond 1999 are pure projection and are not directly linked to observed data. There are therefore numerical advantages and increased defensibility in using this period as a baseline for calculating climate "delta" values (modeled future minus modeled baseline). Lastly, the past ten years globally have been among the hottest on record. Including this decade in the historical baseline, intended to represent a stationary past, would therefore be somewhat inappropriate and potentially make the approach less defensible. This was undoubtedly a consideration in Reclamation's original methodology development. More specific to our study, we also recognize that while the drought of the late 2000's in Atlanta is not explicitly included in the record, we do include droughts of similar scale and duration from the mid 1950's and late 1980's. In particular, the lowest precipitation year on record (1954) is included in our historical baseline. We therefore are confident that we have captured an adequate representation of climate variability in the Metro Water District in our selected baseline period. Lastly, it should be noted that since the focus of this study is on quantifying *relative* changes in water resources as a function of a variable and changing climate, the baseline period serves only as a reference in the analysis and, it can be argued, the specific climate characteristic of the period are less critical.

The result of the HDe method is a set of five different 50 year climate data sets that are reflective of 2050 conditions, as projected by climate model, but maintain the same pattern of variability observed in the recent historical record (1950 – 1999). Monthly time series and percentile plots of each are shown in **Appendix B**. These data sets were used in the subsequent vulnerability analyses as discrete scenarios. A summary of the average monthly precipitation and average monthly temperature for each of the climate scenarios is shown in **Figure 2.1.3** and **2.1.4.**

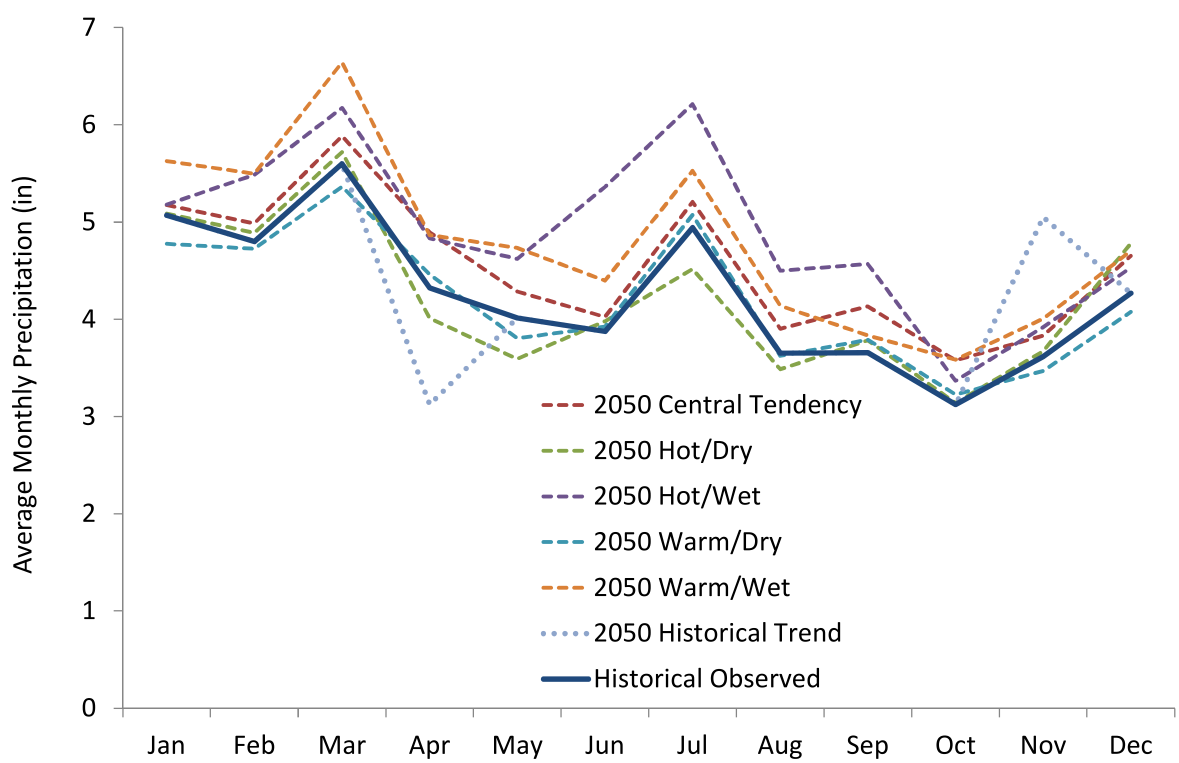

Figure 2.1.3 Average Monthly Precipitation per Climate Scenario

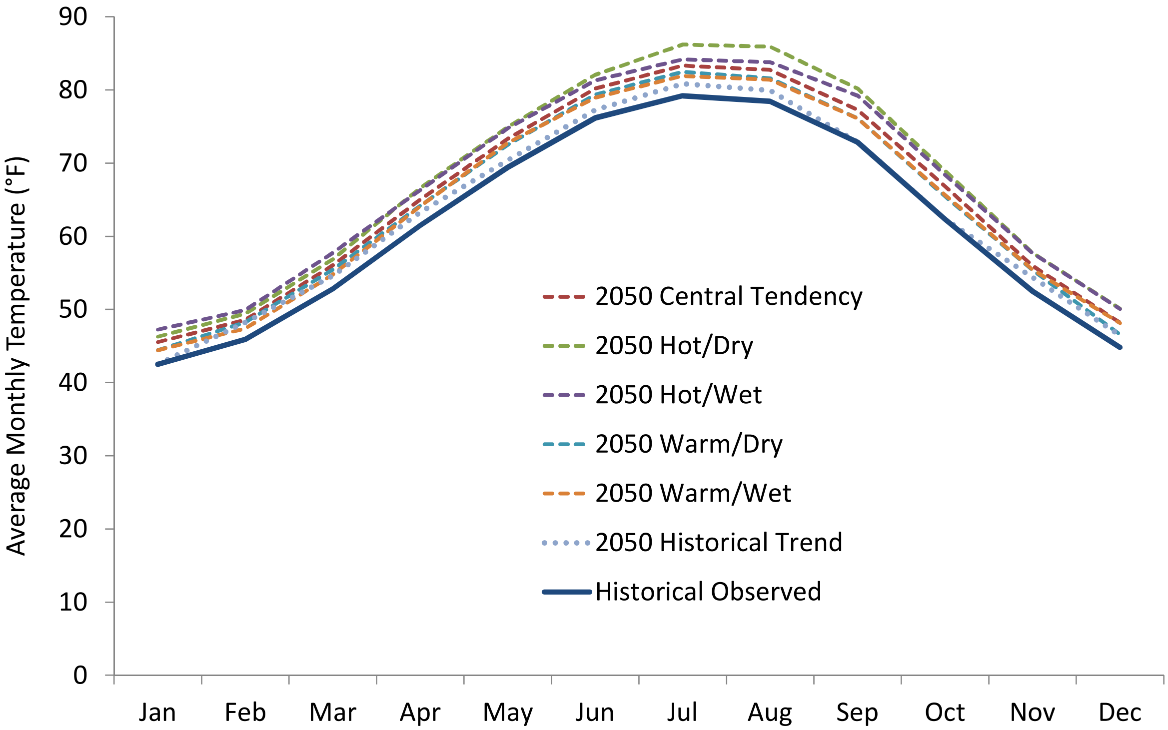

Figure 2.1.4 Average Monthly Temperature per Climate Scenario

2.2 Historical Trend Analysis

A sixth scenario was developed based on historical weather data. The overarching assumption in developing this scenario is that observations of the recent past can be used to generate a plausible potential future climate condition. In other words, the past is a good predictor of the future. For this scenario, trend analyses were performed on a continuous monthly historical climate record (Hartsfield-Jackson Atlanta International Airport) for each calendar month. The periods 1930 to 2013 for precipitation, and 1900 to 2013 for temperature, were used for this exercise. Any potential urban heat island impacts associated with historical data were ignored for this study since the overall trends in the data used for subsequent analyses are unlikely to change.

Mann-Kendall non-parametric statistical trend tests were used to identify statistically significant ($p \leq 0.1$) trends in both temperature and precipitation. For months with statistically significant trends (e.g. January), the following transformations were applied to adjust historical observations to reflect future (2050) conditions as predicted by the identified historical trends:

$$T_{Jan}^{t,2050} = T_{Jan}^{t} + S_{Jan} * (2050 - t)$$

$$P_{Jan}^{t,2050} = P_{Jan}^{t} + S_{Jan} * (2050 - t)\ ,$$

Where: T^{t}_{Jan} and P^{t}_{Jan} = monthly observed January (as an example) temperature and precipitation at year t in the historical record, respectively; $T^{t,2050}_{Jan}$ and $P^{t,2050}_{Jan}$ = adjusted climate records, from year t, that reflect 2050 projections; and S = the slope of the statistically significant trend line for the given calendar month (e.g. January) and climate variable. For calendar months without statistically significant trends, the untransformed historical data were used to represent future conditions. Results of the trend analysis are provided in **Table 2.2.1.**

Table 2.2.1 Mann-Kendall Trend Analysis for Metro Water District Historical Climate Data

Parameter	Period of Record	p value	Significant? (p,=0.1)	slope	Units
Temperature					
All Monthly Temperatures	1900 - 2013	0.07	YES	0.0014	°F per year
Jan Temperature	1900 - 2013	0.99	NO	0	°F per year
Feb Temperature	1900 - 2013	0.02	YES	0.031	°F per year
Mar Temperature	1900 - 2013	0.06	YES	0.023	°F per year
Apr Temperature	1900 - 2013	0.006	YES	0.023	°F per year
May Temperature	1900 - 2013	0.09	YES	0.013	°F per year
Jun Temperature	1900 - 2013	0.03	YES	0.014	°F per year
Jul Temperature	1900 - 2013	0.0002	YES	0.022	°F per year
Aug Temperature	1900 - 2013	0.0002	YES	0.020	°F per year
Sep Temperature	1900 - 2013	0.6	NO	0.004	°F per year
Oct Temperature	1900 - 2013	0.5	NO	0.004	°F per year
Nov Temperature	1900 - 2013	0.007	YES	0.025	°F per year
Dec Temperature	1900 - 2013	0.099	YES	0.022	°F per year
Precipitation					
All Monthly Precip	1930 - 2013	0.4	NO	0.00019	in. per year
Jan Precip	1930 - 2013	0.9	NO	0.0006	in. per year
Feb Precip	1930 - 2013	0.5	NO	-0.0005	in. per year
Mar Precip	1930 - 2013	0.5	NO	-0.006	in. per year
Apr Precip	1930 - 2013	0.09	YES	-0.016	in. per year
May Precip	1930 - 2013	0.4	NO	0.007	in. per year
Jun Precip	1930 - 2013	0.5	NO	-0.006	in. per year
Jul Precip	1930 - 2013	0.9	NO	-0.001	in. per year
Aug Precip	1930 - 2013	0.5	NO	0.006	in. per year
Sep Precip	1930 - 2013	0.4	NO	0.008	in. per year
Oct Precip	1930 - 2013	0.2	NO	0.01	in. per year
Nov Precip	1930 - 2013	0.02	YES	0.019	in. per year
Dec Precip	1930 - 2013	0.8	NO	-0.002	in. per year
Other Parameters					
Annual Max 24 hr Precip	1930 - 2013	0.7	NO	0.002	in. per year
Monthly PDSI	1900 - 2013	0.4	NO	0.0001	PDSI per year

2.3 Additional Analysis

2.3.1 Paleo-Climate Analysis

Paleo-climate data for the region were investigated to determine if the far past displayed any trends not captured by the more recent historical data. Often through the use of tree-ring reconstructions, paleo data provide a record on the order of hundreds to thousands of years as compared to instrumental records which typically only cover a century or so in duration.

Tree-ring reconstruction is able to estimate climate parameters by developing a statistical model that captures the relationship between tree growth and the parameter of interest during the period of instrumental overlap. The model can then be applied to tree-ring data before instrumental records were available. Two reconstructed datasets were found for the Metro Water District area: the first estimates spring rainfall amounts for March through June back to 933, the other dataset contains the summer Palmer Drought Severity Index (PDSI) back to 365. Two main studies were also found that analyzed long term drought in the Southeastern United States through similar PDSI reconstructions.[2]

The main findings from these datasets and studies were that the recent period of instrumental data is wetter than the longer paleo record and that more frequent droughts can be seen in the paleo record as compared to the instrumental record. **Figure 2.3.1** shows the 20-year rolling average from both datasets along with the average over the full period of record. Within this record the existence of extended droughts, in some cases on the order of 20-years duration, can be seen to have previously existed.

A specific future climate scenario was not able to be developed based on the paleo data due to the low resolution (one data point per year) and absence of temperature information. However, qualitatively the paleo record adds credibility that future droughts might be more severe and frequent than what has been seen in the recent past.

[2] These studies and datasets include:

Cook E.R. *et al* 1999 Drought reconstructions for the continental United States *J. Clim.* **12** 1145-1162

Pederson N *et al* 2012 A long-term perspective on a modern drought in the American Southeast *Environ. Res. Lett.* **7** 014034

Seager R *et al* 2009 Drought in the southeastern United States: causes, variability over the last millennium, and the potential for future hydroclimate change *J. Clim.* **22** 5021-45

Stahle D.W. and Cleaveland M.K. 1992 Reconstruction and analysis of rainfall over the southeastern U.S. for the past 1000 years *Bulletin of the American Meterorological Society* 73(12): 1947-1961

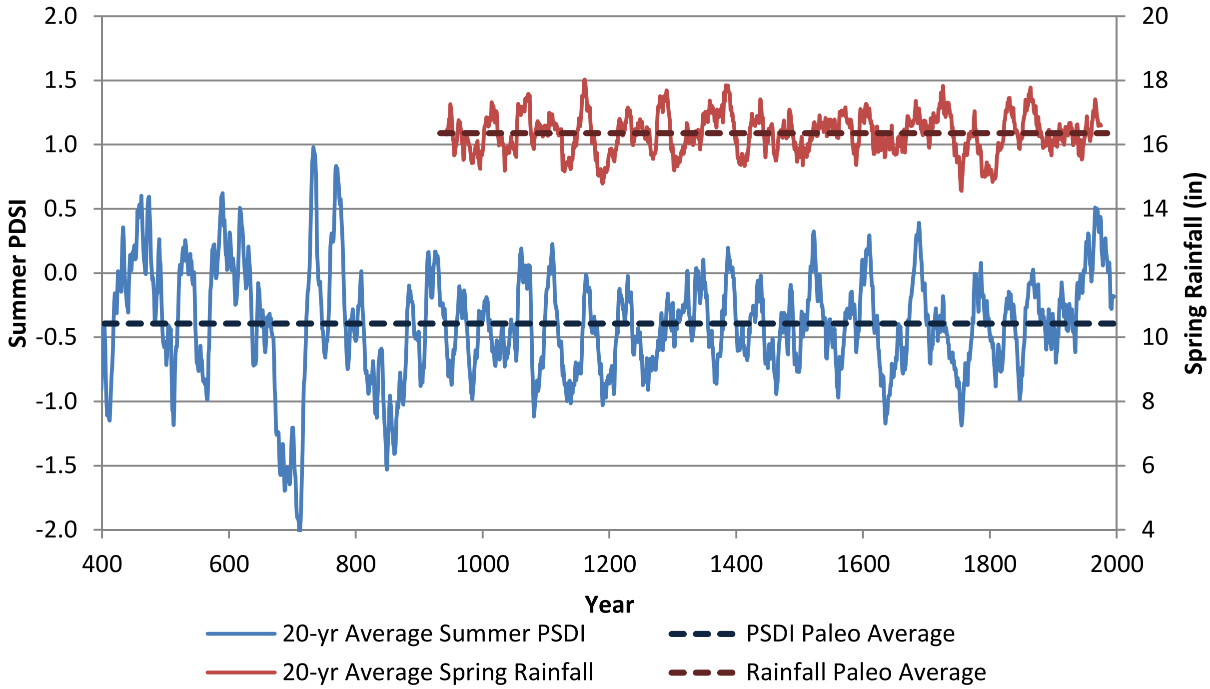

Figure 2.3.1 Metro Water District Paleo Data Summary

2.3.2 Palmer Drought Index Analysis

To assess potential changes in drought conditions reflected by the climate data sets, the PDSI was calculated for each timestep in the monthly climate data sets. PDSI is a well-known metric for characterizing drought conditions and is based on a simplified soil moisture water balance model that takes into account time series information on both precipitation (source of soil moisture) and temperature (loss of soil moisture via evapotranspiration) [Palmer, 1965]. Positive PDSI values indicate a soil moisture surplus while negative values indicate a moisture deficit. The more negative the PDSI value, the worse the drought conditions, with various drought threshold PDSI values defined in the literature. A customized version of NOAA's NCDC PDSI calculator (FORTRAN) was used for these calculations. PDSI values were calculated for both the historical data set (e.g. 1930 – 2000) and each of the GCM projection traces (2000 – 2100) that constitute the five climate scenarios presented above. Additionally, Mann-Kendall trend analysis was performed on the calculated historical PDSI data set, as summarized in Table 2.2.1.

Figure 2.3.2 shows the historical average PDSI based on observed weather from 1900-2014, and the PDSI that could change over time based on the GCM projections included in the five climate scenarios. The average PDSI based on historical, observed weather is -0.20, or near-normal conditions. Looking out from now until 2050, the average PDSI could range from 0.24 (near-normal) to -1.81 (mild drought)—depending on the future climate scenario. Looking out from 2050 to 2100, the average PDSI could range from 0.21 (near-normal) to -4.49 (extreme drought).

Summary of Drought Analysis: Atlanta, 2000 - 2100				
Projection	**Avg PDSI**	**Avg Drought Condition**	**Avg PDSI**	**Avg Drought Condition**
Historical Observed (1900-2014)	-0.20	near normal		
	2000-2049		**2050-2100**	
Central Tendency	-0.73	incipient dry	-1.72	mild drought
Hot/Dry	-1.81	mild drought	-4.49	extreme drought
Warm/Dry	-0.81	incipient dry	-1.34	mild drought
Hot/Wet	-0.1	near normal	-0.99	incipient dry
Warm/Wet	0.24	near normal	0.21	near normal

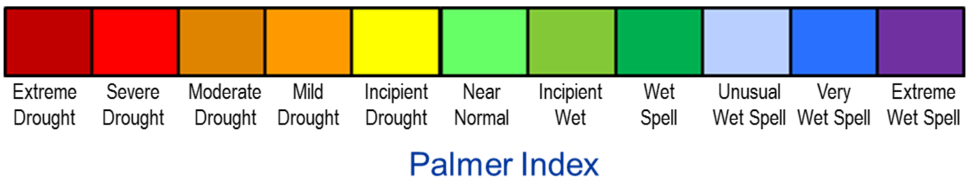

Figure 2.3.2 Potential Changes in Palmer Drought Severity Index from Future Climate Scenarios

2.3.3 General Understanding of Future Drought and Flood Frequency

Literature reviews were conducted to better inform the reader on the potential climate trends for the region. Many literature sources reference global climate models (GCMs). Although significant uncertainties are inherent in these model projections, the GCMs are widely accepted as representing the best available science on the subject, and have proven highly useful in planning as a supplement to historical data. A wealth of literature now exists on the use of GCMs across the globe.

The National Climate Assessment (NCA) provides information on climate trends such as temperature and precipitation for the southeastern United States and also highlights water availability. The NCA suggests a recent trend towards increased heavy precipitation events will continue. The study shows the increase in frequency of extreme daily precipitation events (a daily amount that now occurs once in 20 years) by the later part of this century (2081-2100) compared to the later part of last century (1981-2000). For the Metro Water District area, these events could occur four times as often. Although extreme rainfall events are projected to increase, the trends in general precipitation are less certain. Nevertheless, a reduction in water availability for the southeast region is projected by the NCA due to increased evaporative losses resulting from rising temperatures alone. This is partially corroborated by this study. Some of the scenarios evaluated suggest that the region could experience lower rainfall in future years, while others suggest that rainfall might increase. Nonetheless, all of the scenarios evaluated suggest that temperatures will be higher, and this could lead to additional loss of water due to evaporation. Not addressed in this study are trends in the distribution of annual rainfall, which, coupled with higher temperatures and potentially lower annual rainfall volumes, could produce increased drought frequency and severity.

In addition, the US Army Corps of Engineers recently published the Regional Climate Change and Hydrology Literature Synthesis for the South-Atlantic Gulf Water Resources Region (HUC3), inclusive of the Metro Water District's area. This report is a compilation of peer reviewed historic and projected climate literature. Information from several peer-reviewed reports is summarized in **Figure 2.3.3** below. The observed column included studies focused on an analysis of historic data while the projected column includes studies where models were used to project forward in time typically through 2100. It can be seen that there is much more consensus around trends in temperature than precipitation and hydrology.

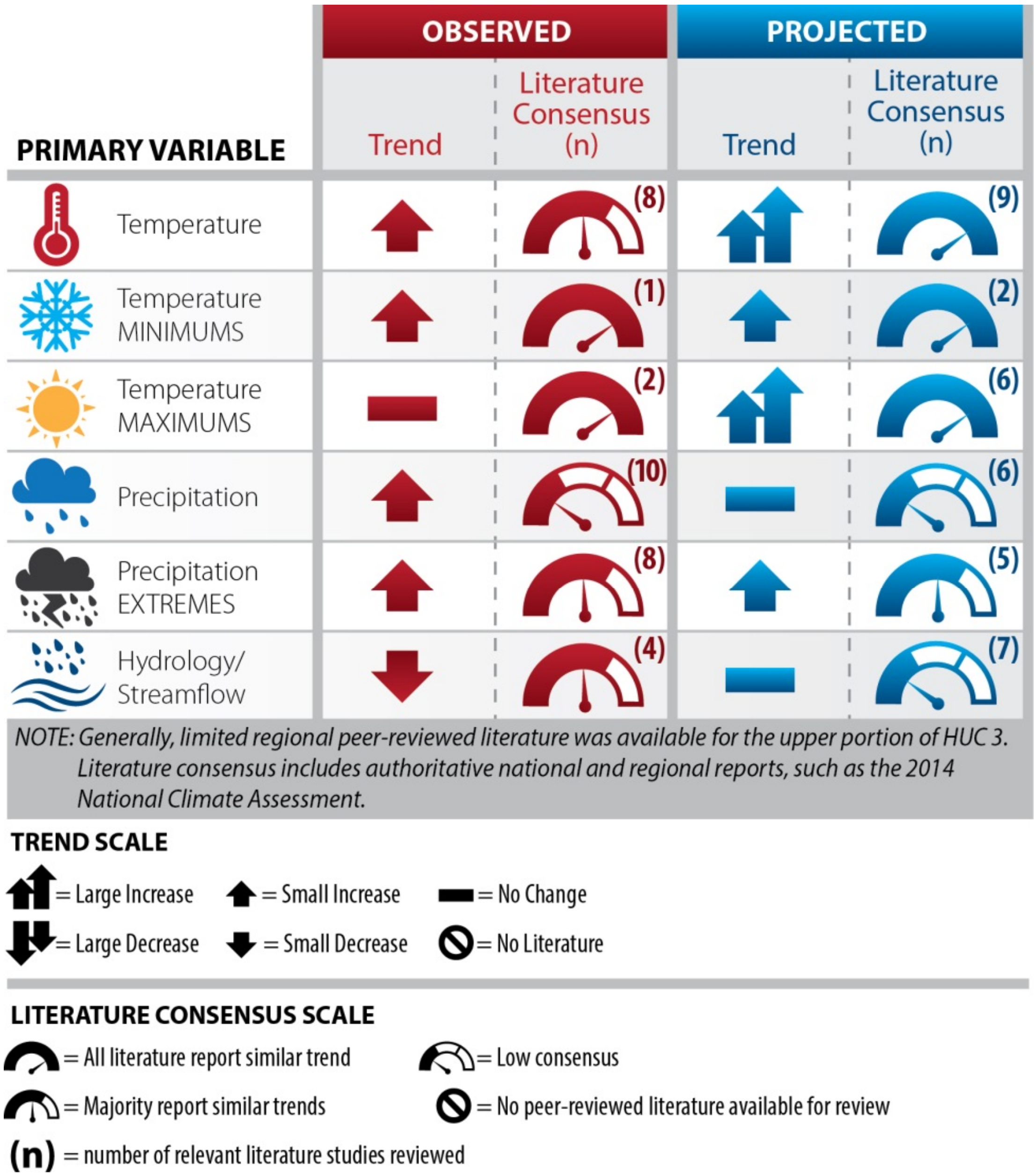

Figure 2.3.3 Summary of Observed and Projected Climate Trends and Literary Consensus (USACE, 2015)

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Section 3

Climate Vulnerability Methodology

Utilizing the climate scenarios presented in **Section 2**, as well as other key data, detailed climate vulnerability methodologies were developed in order to assess the climate impacts on the Metro Water District's water resources, including:

- Water demand
- Water supply
- Water quality
- Watershed characteristics (flood statistics and pollutant loading)

"Climate vulnerability" is defined as "*the susceptibility of a system to damage or stress from a climate-induced impact.*" This section provides detailed descriptions of the methodologies, assumptions, data sets and statistical analyses used to determine the climate vulnerability described in **Section 4**.

3.1 Water Demand Impacts Methodology

Water demand is a function of many factors, including growth, economy, price of water, water conservation, and weather. To determine the impact of climate variability on water demands, a multivariate statistical regression model was used to isolate the impacts that weather has on water demands.

3.1.1 Data Used

To develop the statistical regression model, the period of 1995 to 2013 was utilized. To normalize for growth, per capita water use was selected as the dependent variable. Monthly per capita water use (gallons/person/day) for the region was calculated by dividing all surface water withdrawals from DeKalb, Fulton, and Gwinnett Counties by population in those same three counties. The surface withdrawals included reservoirs and direct diversions from the Chattahoochee River. Surface withdrawals and population were provided by the Metro Water District.

The independent variables in the statistical regression model were selected based on their ability to predict monthly per capita water use. These variables included: (1) unemployment rate, as a measurement of the region's economy; (2) time periods in which mandatory drought water restrictions were in place; (3) price of water; (4) plumbing efficiency, representing both plumbing codes and utility rebates; (5) Georgia Water Stewardship Act requirements; and (6) temperature and precipitation.

<u>Unemployment</u>
A weighted average regional unemployment rate was calculated by taking annual unemployed persons per population for DeKalb, Fulton, and Gwinnett Counties from 1995 to 2014. This information was provided by the Atlanta Regional Commission. Unemployment averaged about 4 percent during the mid-1990's to the mid-2000s. The great economic recession began in 2007, with the region's peak unemployment rate of 10 percent occurring in 2010. Every year since 2010, the

unemployment rate has been slowly decreasing as the economy for Georgia improved. By 2013, the region's unemployment rate was 8 percent. As the unemployment rate increases (due to economic recessions), water use is expected to decrease as there is less economic activity, less discretionary income, and home foreclosures.

Periods of Mandatory Drought Water Restrictions

Periods in which mandatory drought-related water restrictions were in place were provided by the District. Equivalent stages of restrictions were derived from the type of restrictions in place. In years 2000, 2001, 2005, and 2006 a level 1 restriction was in place, calling for some reductions in outdoor water use. By 2007, greater restrictions in outdoor water use were imposed with an equivalent restriction level 2. And by 2008, the greatest restriction level was in place, level 4. The greater the drought restriction level, the less water use is expected.

Price of Water

An average residential monthly water bill was constructed for Gwinnett County to represent the relative change in water price over time for the Metro Water District region. Water rate data from the UNC/GEFA annual water utility survey was utilized to construct this average monthly water bill. The data set reflects fixed and variable charges, as well as changes in tiered water rates over time for a sample of water utilities in the county for an assumed single-family water usage. The nominal (current year dollars) water bill was then converted into year 2000 constant dollars in order to remove impacts of inflation using the consumer price index (CPI) for Atlanta (see **Appendix C** for more detail). This price of water indicator shows that from 1995 to 2007, the average monthly residential water bill increased in real terms by about $6. As greater utilities imposed tiered water rates (meaning the greater the water consumption, the greater the rate paid), a distinct jump in the average water bill at the marginal water use level occurred in 2009. By 2013, the average monthly water bill in real terms was almost double what it was in 1995.

Plumbing Code Efficiency

To reflect changes in plumbing efficiency due to increasing plumbing code requirements and utility rebates for high efficiency toilets, an average toilet flush volume was calculated by using the ratio of post-plumbing code homes to pre-plumbing code homes. Added to this ratio of post-code to pre-code homes, was the estimate of high efficiency toilets that were installed in the region due to utility rebate programs. Since 2007, Metro Water District estimates roughly 100,000 high efficiency toilets have been rebated. Based on this information, the average toilet flush volume was estimated to be 3.7 gallons per flush in 1995. By 2005, the average flush volume was 3.2 gallons per flush, while the average flush volume in 2013 was estimated to be 2.7 gallons per flush (see **Appendix C** for more detail). The lower the flush volume, the lower the expected water use.

Georgia Water Stewardship Act

In light of recent severe water resource management challenges in Georgia, including rapid growth and droughts, the General Assembly enacted the **Georgia Water Stewardship Act** during the 2010 legislative session. Key provisions of the Act include:

- Required Actions by Local Governments
  - By **January 1, 2011**, adopt or amend local ordinances to uniformly restrict outdoor water use for landscapes between 10 a.m. and 4 p.m. daily.
  - After **July 1, 2012**, enforcement of updated plumbing code specifying:

- o High-efficiency flow specification for plumbing fixtures, including toilets, urinals and showerheads.
- o Sub-meters installed in new multi-unit buildings, including residential, commercial and light industrial facilities.
- o High-efficiency cooling towers in new construction.

- Required Actions by Public Water Systems
  - Completion of annual water loss audits by systems serving 10,000 or more people by **January 1, 2012**, and by systems serving 3,000 or more people by **January 1, 2013**.
  - Submission of annual water loss audits to the GAEPD within 60 days of audit.

This information was converted into a scaled variable that increased from level 1 to level 3, based on the relative amount of conservation required by the law.

Temperature and Precipitation

Monthly average maximum temperature and monthly total precipitation from 1995 to 2013 was obtained from the Hartsfield-Jackson Atlanta International Airport weather station. This station was deemed representative for the region after examining the relative monthly changes in weather from 1950 to 2013. **Figure 3.1.1** summarizes the annual precipitation from 1995 to 2013, clearly showing the periods of extended lower rainfall in years 2000-2001 and 2007-2008, and 2011 and 2012.

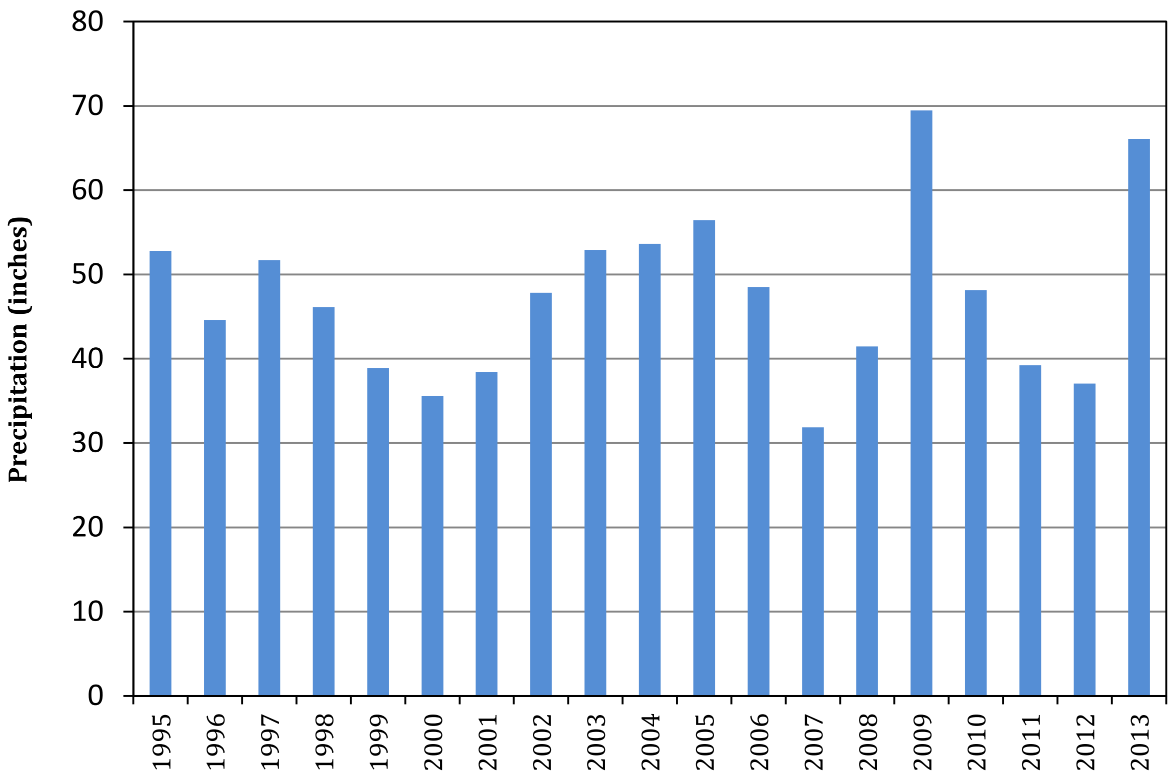

Figure 3.1.1 Annual Precipitation
(Source: Hartsfield-Jackson Atlanta International Airport Weather Station)

3.1.2 Statistical Regression Model and Validation

Using multivariate statistical regression, a natural log model was constructed by converting all variables to natural log values. Multiple regression analysis is a statistical procedure that is able to assess the strength of correlations of multiple factors on the "dependent" variable (i.e., per capita water use). One underlying premise of multiple regression analysis is that the values of the dependent variable and the "explanatory" variables should follow a normal distribution. If the data are not normally distributed, then it is common to convert the data into the natural log form which then becomes normally distributed without changing the relationship between variables. From dozens of empirical studies on water demands since the 1980s, it is shown that water use and many of the explanatory variables often used in multiple regression (e.g., income, price of water) are indeed not normally distributed. Thus the statistical analysis of water demands are often developed with the data in natural log form. The regression equation is shown below:

$$Q_t = I_t^a + UE_t^b + D_t^c + MP_t^d + PE_t^e + WSA_t^f + T_t^g + P_t^h + MB_t^i$$

where:

t = monthly time index
Q = log of monthly per capita water use (gal/person/day)
I = log of model intercept
UE = log of unemployment rate (%)
D = scaled variable indicating level of drought-related water restrictions (1-4)
MP = log of marginal price for water, as indicated by a construct of monthly water bill ($/month)
PE = log of plumbing efficiency, as indicated by an average toilet flush volume (gal/flush)
WSA = scaled variable (1-3) indicating Georgia Water Stewardship Act's levels of conservation
T = log of average maximum monthly temperature (^{o}F)
P = log of monthly precipitation (inches)
MB = select monthly binary variables to account for seasonality (0 or 1)
a-i = model coefficients (elasticities)

The regression model output is summarized below (see **Appendix C** for more details):

R Square	0.916
Adjusted R Square	0.909
Standard Error	0.056
Significance F	<0.0001
Observations	228

The adjusted R^2 value indicates overall correlation of all independent variables to the dependent variable. Most econometricians and statisticians believe models with an R^2 greater than 0.70 have good overall correlation. The Metro Water District's model has an R^2 of 0.91. The standard error indicates the amount of forecast error the model has in predicting the dependent variable; and usually models with standard errors of less than 10 percent are considered good predictors. The Metro Water District's model has a 5.6 percent standard error. The significance F value is the overall significance that the dependent variable can be predicted. Usually statisticians believe that models are statistically valid with F values 0.05 or less. The Metro Water District's model has an F value less than 0.0001. In summary, the Metro Water District's demand model is very robust and excellent in explaining the factors that influence per capita water use. **Figure 3.1.2** shows the model verification, with the blue line representing actual per capita water use and the dashed black line representing the regression model's prediction of per capita water use. As seen on the graph, the statistical model replicates actual monthly water use well.

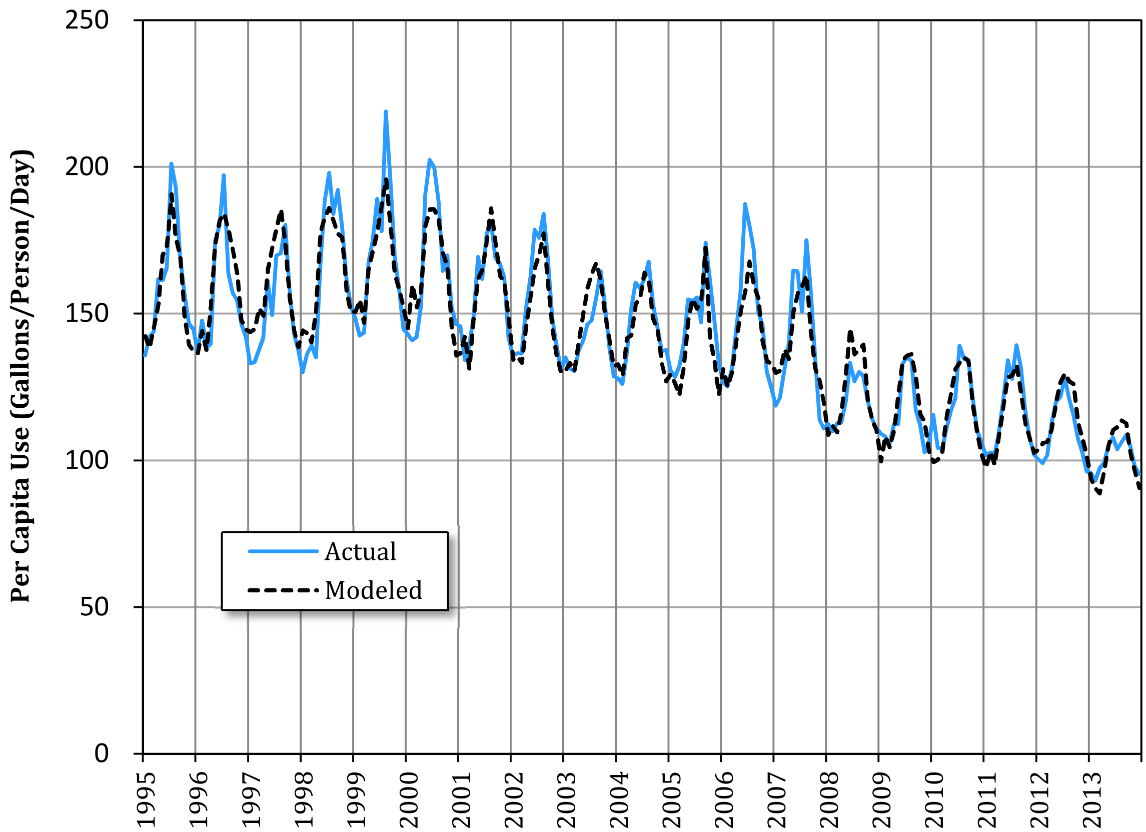

Figure 3.1.2 Statistical Water Demand Model Verification

3.2 Water Supply Impacts Methodology

A total of five representative water supply reservoirs were identified for use within the analysis. These reservoirs were chosen to be geographically dispersed as well as to represent a diversity of volumes, residence times, drainage areas, and supply utilizations. The five reservoirs represent small to mid-size reservoirs in lieu of very large reservoirs for the following three reasons:

a) Small reservoirs may be vulnerable to both short-term (several months) and long-term (several years) climate trends, while larger reservoirs may be less susceptible to the shorter term trends. Focusing on smaller reservoirs is more likely to capture a full range of vulnerabilities.

b) This aspect of the study focuses on water supply only, and single-purpose utility-managed reservoirs were desired to help isolate this water use for analytical purposes.

c) The selected reservoirs afforded the opportunity for individual utilities within the District to participate directly in the study.

The goal for the analysis was to identify changes to firm yield and reliability for the potential future climate scenarios through use of reservoir storage modeling. The predicted precipitation for each climate scenario was converted into runoff patterns while the predicted temperature changes affected the modeled evaporation rates. The results of this analysis are not intended for permitting, but rather, to better understand the potential vulnerability of water storage and yield to future climate uncertainty.

3.2.1 Purpose

The fundamental goal of modeling the selected water supply reservoirs was to determine if possible future climate conditions could affect the firm yield or reliability of these reservoirs. More specifically, these models helped determine how much of the current yield of the reservoirs may be at risk, and what indicators could alert planners of any potential increases or decreases in future yield.

Because the output is not intended for permitting purposes but rather for a relative study of current and future conditions, it is not essential that firm yield estimates exactly match other published values, or carry an inherent precision on the order of 0.1 mgd as is often inferred from firm yield studies. Rather, it is important that estimates of current yield be reasonably close to published values in order to establish a credible baseline from which to evaluate potential relative changes due to possible future climate conditions.

3.2.2 Selected Reservoirs

Water supply reservoirs were selected with broad physical and hydrologic characteristics in order to help identify key relationships between climate patterns and the risks of changing yield. **Table 3.2.1** lists the five reservoirs selected for simulation study, with the support of the local utilities that utilize them, while **Figure 3.1** illustrates their drainage areas.

Table 3.2.1 Selected Reservoirs and Key Features

Reservoir	County	Storage Volume (BG)	Drainage Area (sq. mi.)	Percent watershed developed	Percent Impervious	Estimated Average Flow (cfs)
Dog River Reservoir	Douglas	1.9 (el. 760)	78.3	15.4	2.8	117
Randy Poynter Reservoir	Rockdale	5.4 (el. 735)	47.0	38.5	9.9	78
Long Branch Reservoir	Henry	1.5	4.3	8.3	1.5	5
Gardner Reservoir	Henry	0.7	16.9	35.9	10.5	21
Upper Towiliga/Cole Reservoir	Henry	6.0	29.4	13.1	2.1	40

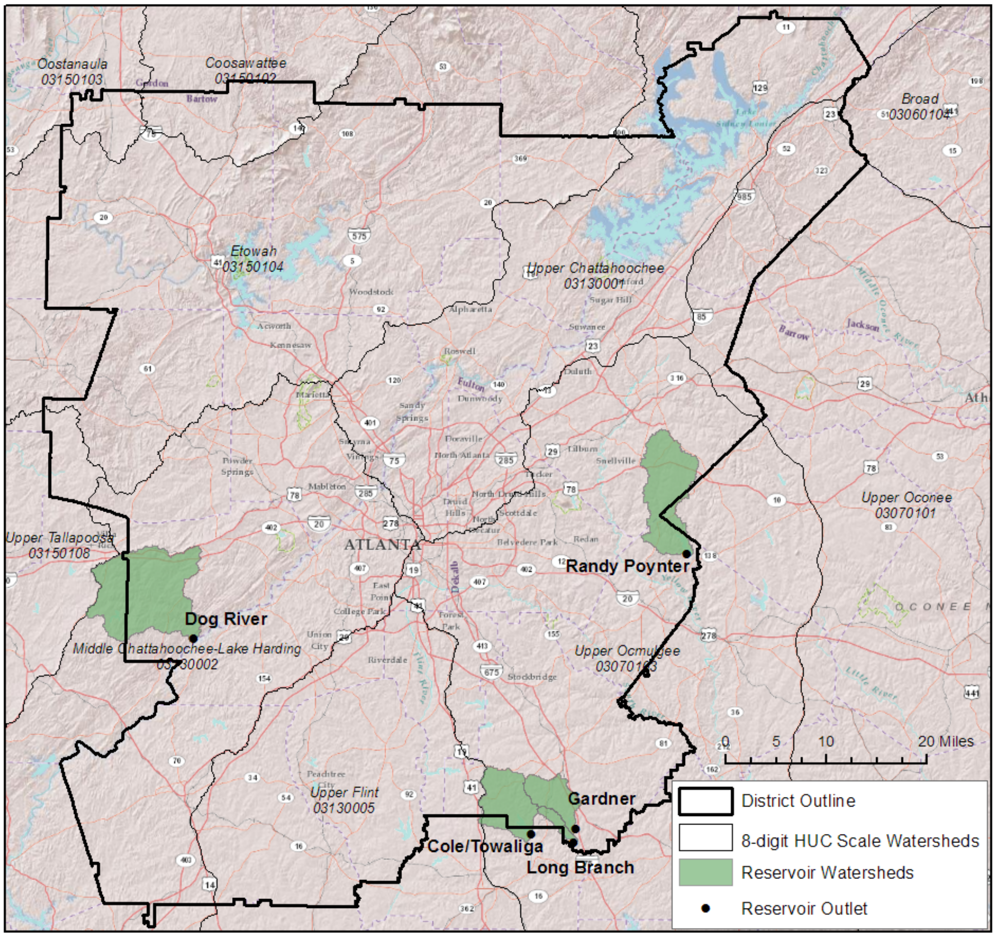

Figure 3.2.1 Reservoir Drainage Basins

3.2.3 Baseline Climate Data

The historic monthly precipitation and temperature dataset developed as part of building the future climate scenarios will be used as the baseline climate data in this analysis. The historical dataset covers 1950-1999 and was created using multiple long-term continuous weather stations and gridded spatially for the study area. Additionally daily evaporation was collected from the National Climate Data Center (NCDC) at two locations in the vicinity of the study area:

- NCDC COOP Station 90432: University of Georgia, Athens. (June 1953 – May 1971)
- NCDC COOP Station 98950: University of Georgia Plant Science Farm. (June 1971-December 1999)

While there are other evaporation records collected at other nearby stations that are closer to the study area, the Athens gages consistently provided the most days per year of measurements through the study period of 1950-1999. Allatoona Dam is closer to Atlanta but as can be seen in **Figure 3.2.2** below, its record is primarily 1952-1978 and 1988-1994, with just a few days per year after that. Merging the gages in Rome and Calhoun also yields a long record. However, only Athens consistently has 300 days a year across much of its period of record. The median days per year of data available are

310 for Athens, 220 for Allatoona, and 237 for Rome/Calhoun. Hence, the Athens data were used to minimize the need to fill data gaps synthetically.

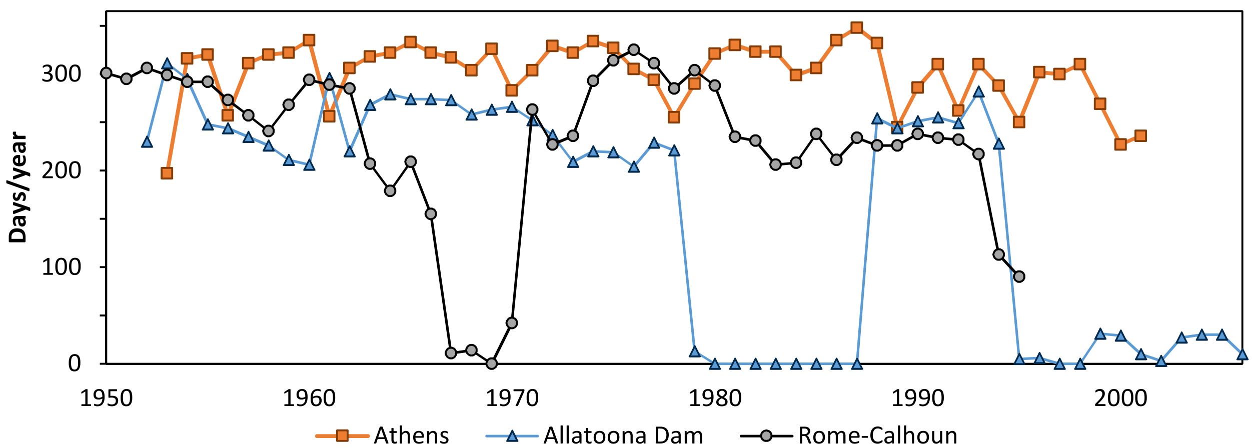

Figure 3.2.2 Extent of Nearby Evaporation Records

Missing pan evaporation data were filled in with Hargreaves theoretical temperature-based values and converted to monthly totals for use in the model. Pan evaporation values were multiplied by a pan evaporation correction coefficient of 0.76.

3.2.4 Streamflow Estimation

Historic inflows were needed from 1950-1999 to match the baseline climate data. None of the five reservoir basins have long-term continuous streamflow gages before the year 2000. Hence, synthetic streamflow records were generated using one of two techniques in each basin:

1. Dog River Reservoir and Randy Poynter Reservoir (Summary): Both of these basins have USGS gages with multi-year continuous records beyond the year 2000. These records were found to be highly correlated (on a monthly basis) with other USGS records with overlapping time periods, and which also extended back to 1950. Regression equations were developed to extend the inflow records for the reservoirs (**see below for details**).

2. Henry County Reservoirs (Gardner, Long Branch, and Cole - Summary): None of these reservoirs have gaged inflow from the USGS. However, flow records were available for a period of approximately ten years and the Henry County Water Authority Long Range Water Supply Plan presents regression equations for each of these three reservoirs using a nearby long-term gage that extended back before 1950. These regression equations were applied in this study (**see below for details**).

In lieu of the statistical methods above, rainfall-runoff modeling was also considered as an estimation technique for streamflow. However, because three of the basins are ungagged, there would be no flow records to which such models could be calibrated, and it was determined that rainfall-runoff modeling would result in more uncertainty that what we can expect with the statistical record extension/development techniques described above. It was also deemed to be more data-intensive and costly than the statistical methods. Results below indicate that the statistical methods reproduce the dynamics of high and low flow in the respective rivers, and while not perfect, will provide a reasonable basis for comparative analysis.

Dog River Reservoir: The Dog River Basin has a USGS gage with a continuous record a short distance upstream of the reservoir from 2007-2013 (USGS Gage 02337410). These records were found to be highly correlated (on a monthly basis) with records on the Flint River and Alcovy River (USGS Gages 02344500 and 02208450, respectively) with overlapping time periods. The Alcovy correlation was better, but the Alcovy records only extended back through 1972, so the Flint correlation was used to synthesize flows from 1950-1971, and the Alcovy correlation was used from 1972-1999. Comparison of the regression models against the historic measured flow is illustrated in **Figure 3.2.3**. The extended flow record at the gage, representing a drainage area of 66.5 square miles was then increased by drainage area ratio to the full drainage area into the reservoir (78.3 square miles).

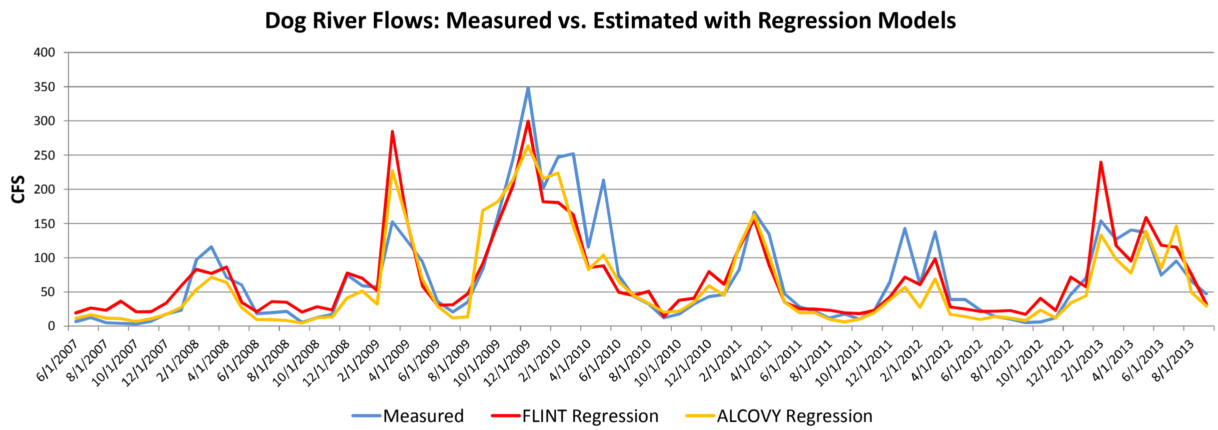

Figure 3.2.3 Dog River Regression Models for Extending Historic Inflow into the Dog River Reservoir

Randy Poynter Reservoir: The Randy Poynter Basin has two USGS gages with continuous records upstream of the reservoir from 2001-2013 (USGS Gage 02207400 on Brushy Fork Creek, and USGS Gage 02207385 on Big Haynes Creek). These records were also found to be highly correlated (on a monthly basis) with records on the Flint River and Alcovy River (USGS Gages 02344500 and 02208450, respectively) with overlapping time periods. The Alcovy correlation was better, but the Alcovy records only extended back through 1972, so the Flint correlation was used to synthesize flows from 1950-1971, and the Alcovy correlation was used from 1972-1999. Comparison of the regression models against the historic measured flow is illustrated in **Figures 3.2.4 and 3.2.5**. To help preserve low flow accuracy for Big Haynes Creek, a nonlinear regression equation was developed for Flint River flows less than 170 cfs, and a linear equation was used for flows above 170 cfs. The extended flow record at these gages, representing a combined drainage area of 25.8 square miles was then increased by drainage area ratio to the full drainage area into the reservoir (47 square miles).

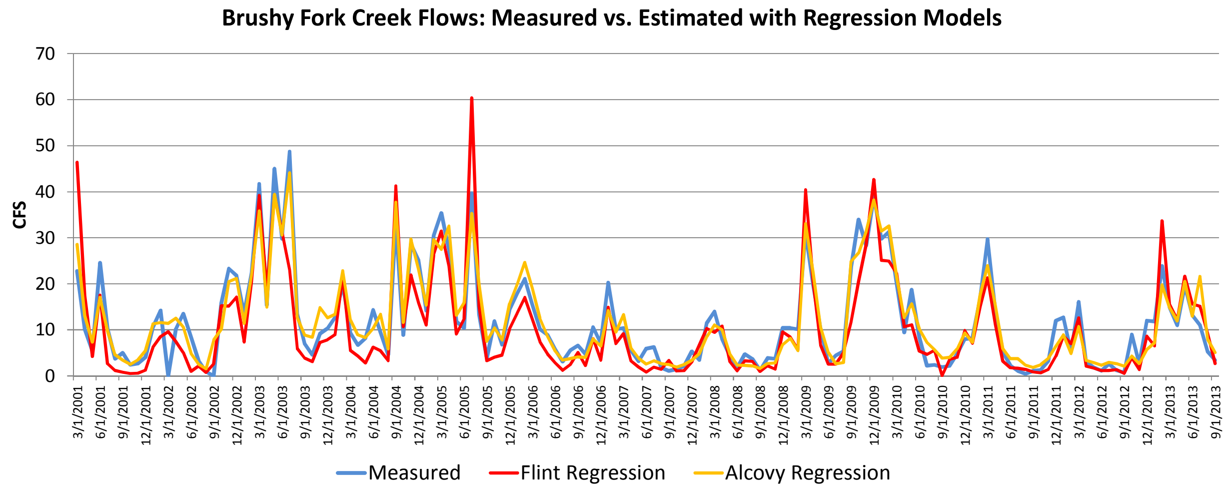

Figure 3.2.4 Brushy Fork Creek Regression Models for Extending Historic Inflow into Randy Poynter Reservoir

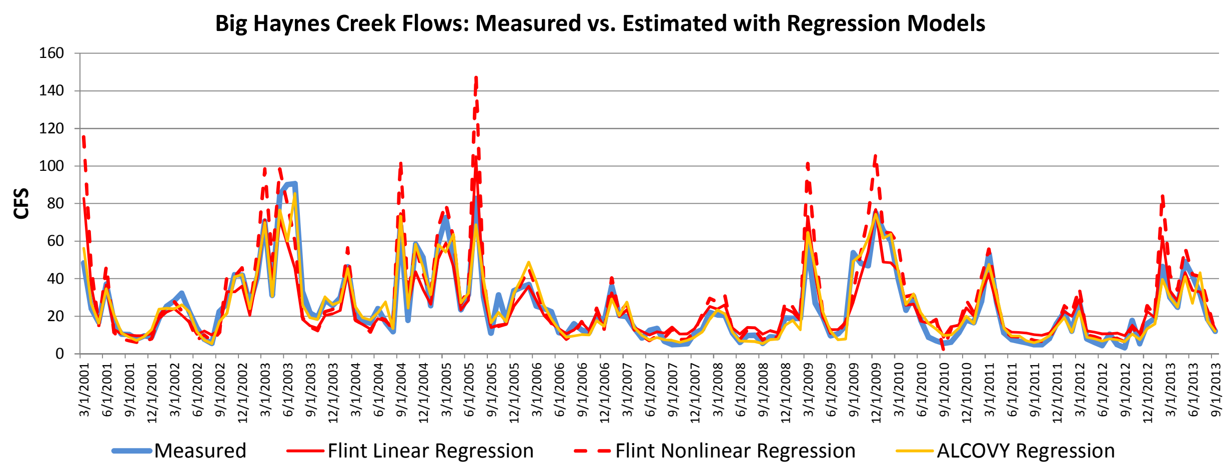

Figure 3.2.5 Big Haynes Creek Regression Models for Extending Historic Inflow into Randy Poynter Reservoir

Henry County Reservoirs (Gardner, Long Branch, and Cole): None of the river basins flowing into these reservoirs have gaged inflow from the USGS. However, flow records were available from 1961-1971 for a short-term gage located on the Towaliga River near Jackson, GA (USGS Gage 02211300), and these records are reported as correlated with flows in the Tobesofkee Creek near Macon, GA (USGS Gage 02213500) according to the Henry County Water Authority Long Range Water Supply Plan Update. Table 3-1 in that report presents regression equations for each of these three reservoirs. These previously-developed regression equations were applied in this study.

In lieu of the statistical methods above, rainfall-runoff modeling was also considered as an estimation technique for streamflow. However, because the basins are not well gaged over the simulation period, there would be few, if any, flow records to which such models could be calibrated, and it was determined that rainfall-runoff modeling would result in more uncertainty than what we can expect with the statistical record extension/development techniques described above. Rainfall-runoff modeling was also deemed to be much more data-intensive than the statistical methods.

Figure 3.2.6 below illustrates the synthesized long-term inflow records for each of the five reservoirs, and demonstrates on a logarithmic scale the range of hydrologic conditions, as average flows vary over an order of magnitude.

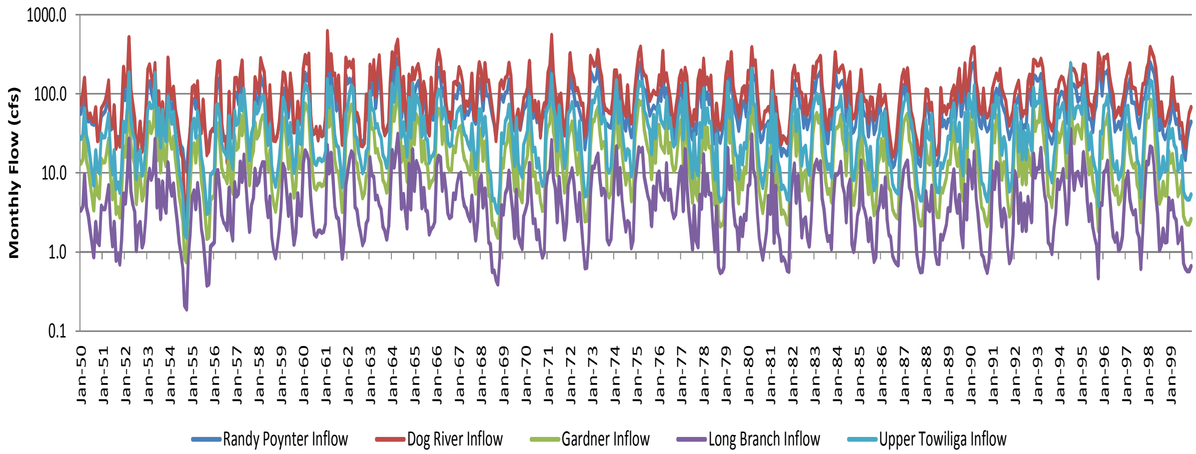

Figure 3.2.6 Synthesized Long Term Historic Inflow for the Five Reservoirs

3.2.5 Model Development

The reservoir yield models were developed in the transferrable platform of Microsoft Excel. The models employed a monthly time step that matches the resolution of the synthesized inflow data. The models included the following components:

- Reservoir bathymetry (relationships between stage, storage, and surface area)
- Monthly hydrologic inflows (from the procedure outlined above)
- Direct precipitation
- Surface evaporation
- Spills and downstream releases
- Consumptive withdrawals
- Operating requirements such as minimum drawdown level, downstream flow requirements, etc.

These are simple mass balance models, tracking inflow, outflow, and change in storage. Inflows (as described above) and the model functionality were validated by comparing the calculated historical firm yield from these new models to previously published values, as available.

Examples of model input and output are illustrated below (**Figure 3.2.7 and 3.2.8**). Firm yield was calculated by adjusting the average monthly withdrawal over the historical period of 1950-1999 until the withdrawal rate depletes the available storage at least once. The models report the percentage of time that demand cannot be satisfied, so that both the firm yield and yield values with reliability 95 percent (for example) can be reported and compared.

	RESERVOIR INFLOWS							RESERVOIR OUTFLOWS										VOLUME				
Date	Streamflow In (cfs)	Streamflow In (mgd)	Streamflow IN (MG)	Precip (IN/MO)	Reservoir Area (AC)	Direct Precip (AF)	Direct Precip (MG)	Evap (IN/MO)	Surface Evap (AF)	Surface Evap (MG)	Desired WD (MGD)	Withdrawal (MGD)	Withdrawal (MG)	Desired DS Rel. (MGD)	Downstream Rel (MGD)	Downstream Release (MG)	Spill (MG)	Total IN (MG)	Total OUT (MG)	Reservoir Vol (MG)	Reservoir Elevation	Min Elev
1/1/1950	73.4	47.4	1442.3	2.40	255.6	51.2	16.7		0	0	12.80	12.80	389.12	6.46	6.46	196.4	873.5	1459.0	1459.0	1881.0	760	723.5
2/1/1950	105.5	68.2	2072.7	3.30	255.6	70.3	22.9		0	0	12.80	12.80	389.12	6.46	6.46	196.4	1510.1	2095.6	2095.6	1881.0	760	723.5
3/1/1950	158.0	102.0	3102.3	4.13	255.6	87.9	28.6		0	0	12.80	12.80	389.12	6.46	6.46	196.4	2545.4	3130.9	3130.9	1881.0	760	723.5
4/1/1950	62.1	40.1	1220.2	1.56	255.6	33.3	10.8		0	0	12.80	12.80	389.12	6.46	6.46	196.4	645.6	1231.1	1231.1	1881.0	760	723.5
5/1/1950	50.1	32.4	984.7	4.43	255.6	94.3	30.7		0	0	12.80	12.80	389.12	6.46	6.46	196.4	429.9	1015.4	1015.4	1881.0	760	723.5
6/1/1950	55.8	36.0	1095.7	3.75	255.6	79.8	26.0		0	0	12.80	12.80	389.12	6.46	6.46	196.4	536.2	1121.7	1121.7	1881.0	760	723.5
7/1/1950	46.1	29.8	904.4	7.06	255.6	150.4	49.0		0	0	12.80	12.80	389.12	6.46	6.46	196.4	367.9	953.4	953.4	1881.0	760	723.5
8/1/1950	44.5	28.7	873.6	5.43	255.6	115.7	37.7		0	0	12.80	12.80	389.12	6.46	6.46	196.4	325.8	911.3	911.3	1881.0	760	723.5
9/1/1950	66.7	43.1	1309.5	3.73	255.6	79.6	25.9		0	0	12.80	12.80	389.12	6.46	6.46	196.4	749.9	1335.4	1335.4	1881.0	760	723.5
10/1/1950	25.4	16.4	498.1	3.20	255.6	68.2	22.2		0	0	12.80	12.80	389.12	6.46	6.46	196.4	0.0	520.3	585.5	1815.8	759	723.5
11/1/1950	30.8	19.9	604.0	0.77	249.1	16.1	5.2		0	0	12.80	12.80	389.12	6.46	6.46	196.4	0.0	609.3	585.5	1839.6	759.5	723.5
12/1/1950	65.4	42.3	1285.1	3.24	252.4	68.2	22.2		0	0	12.80	12.80	389.12	6.46	6.46	196.4	680.4	1307.3	1265.9	1881.0	760	723.5
1/1/1951	71.9	46.5	1412.8	2.43	255.6	51.7	16.8		0	0	12.80	12.80	389.12	6.46	6.46	196.4	844.1	1429.7	1429.7	1881.0	760	723.5
2/1/1951	80.3	51.9	1577.8	3.15	255.6	67.1	21.9		0	0	12.80	12.80	389.12	6.46	6.46	196.4	1014.1	1599.6	1599.6	1881.0	760	723.5
3/1/1951	100.8	65.1	1980.3	5.09	255.6	108.4	35.3		0	0	12.80	12.80	389.12	6.46	6.46	196.4	1430.1	2015.6	2015.6	1881.0	760	723.5
4/1/1951	146.0	94.3	2868.0	5.18	255.6	110.3	35.9		0	0	12.80	12.80	389.12	6.46	6.46	196.4	2318.4	2903.9	2903.9	1881.0	760	723.5
5/1/1951	36.7	23.7	720.9	0.52	255.6	11.1	3.6		0	0	12.80	12.80	389.12	6.46	6.46	196.4	139.0	724.5	724.5	1881.0	760	723.5
6/1/1951	39.1	25.3	767.7	5.03	255.6	107.2	34.9		0	0	12.80	12.80	389.12	6.46	6.46	196.4	217.1	802.6	802.6	1881.0	760	723.5
7/1/1951	71.0	45.8	1393.6	6.78	255.6	144.4	47.0		0	0	12.80	12.80	389.12	6.46	6.46	196.4	855.1	1440.6	1440.6	1881.0	760	723.5
8/1/1951	20.4	13.2	400.5	1.14	255.6	24.2	7.9		0	0	12.80	12.80	389.12	6.46	6.46	196.4	0.0	408.4	585.5	1703.9	757.5	723.5
9/1/1951	26.8	17.3	527.0	4.96	239.4	98.9	32.2		0	0	12.80	12.80	389.12	6.46	6.46	196.4	0.0	559.2	585.5	1677.7	757.5	723.5
10/1/1951	21.7	14.0	426.2	3.32	239.4	66.3	21.6		0	0	12.80	12.80	389.12	6.46	6.46	196.4	0.0	447.8	585.5	1540.0	755.5	723.5
11/1/1951	55.9	36.1	1098.3	2.19	226.5	41.4	13.5		0	0	12.80	12.80	389.12	6.46	6.46	196.4	185.2	1111.8	770.7	1881.0	760	723.5
12/1/1951	217.6	140.6	4273.8	8.66	255.6	184.4	60.1		0	0	12.80	12.80	389.12	6.46	6.46	196.4	3748.3	4333.8	4333.8	1881.0	760	723.5
1/1/1952	125.0	80.7	2454.0	3.71	255.6	78.9	25.7		0	0	12.80	12.80	389.12	6.46	6.46	196.4	1894.2	2479.7	2479.7	1881.0	760	723.5
2/1/1952	148.2	95.7	2910.4	3.99	255.6	85.1	27.7		0	0	12.80	12.80	389.12	6.46	6.46	196.4	2352.6	2938.1	2938.1	1881.0	760	723.5
3/1/1952	513.5	331.7	10084.2	9.63	255.6	205.2	66.9		0	0	12.80	12.80	389.12	6.46	6.46	196.4	9565.6	10151.1	10151.1	1881.0	760	723.5
4/1/1952	114.5	74.0	2248.6	2.54	255.6	54.2	17.7		0	0	12.80	12.80	389.12	6.46	6.46	196.4	1680.7	2266.2	2266.2	1881.0	760	723.5
5/1/1952	73.4	47.4	1441.7	3.51	255.6	74.9	24.4		0	0	12.80	12.80	389.12	6.46	6.46	196.4	880.6	1466.1	1466.1	1881.0	760	723.5
6/1/1952	47.8	30.8	937.8	2.84	255.6	60.5	19.7		0	0	12.80	12.80	389.12	6.46	6.46	196.4	372.0	957.5	957.5	1881.0	760	723.5
7/1/1952	15.2	9.8	299.1	1.08	255.6	23.0	7.5		0	0	12.80	12.80	389.12	6.46	6.46	196.4	0.0	306.6	585.5	1602.1	756.5	723.5
8/1/1952	25.1	16.2	493.6	6.10	233.2	118.5	38.6		0	0	12.80	12.80	389.12	6.46	6.46	196.4	0.0	532.2	585.5	1548.8	755.5	723.5

Figure 3.2.7 Example Reservoir Model Mass Balance Input and Calculation Worksheet
(Partial data shown only)

Yield Estimation Model
Metro North Georgia Water Planning District
Reservoir Yield Estimation Model

Reservoir Name: Dog River Reservoir

Full Volume (MG): 1881 — Target WD (mgd): 12.8
Min Volume (MG): 60 — Target DS Release (cfs): 10

Number of Months with shortage: 0
Percent of Months with shortage: 0.0%

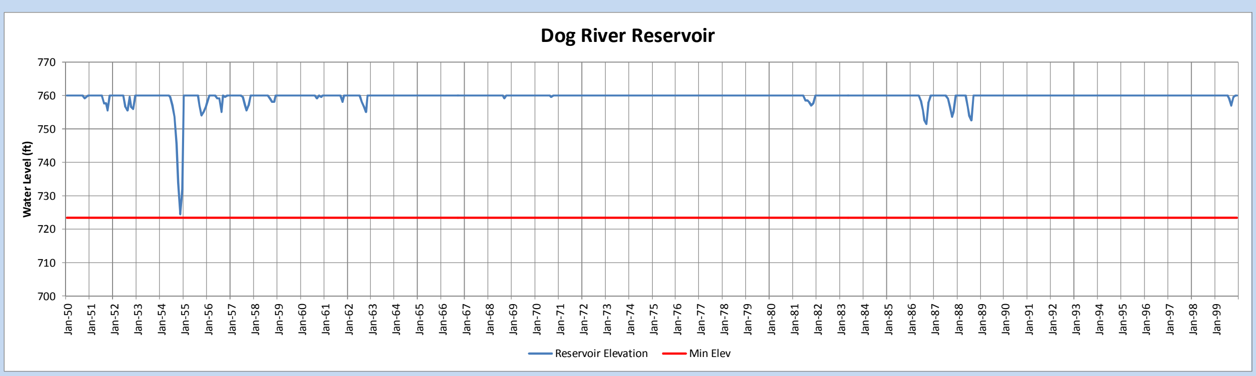

Figure 3.2.8 Example Reservoir Model Output
(Sample results only)

Simplifying assumptions were made regarding downstream flow requirements (which were given priority over supply withdrawals in the yield models), and the volume that is considered fully available for water supply in each reservoir. These assumptions were taken from published reports to the greatest extent possible, and the values used in the analysis are listed in **Tables 3.2.2 and 3.2.3** below, along with citations for their sources. Storage-Area-Elevation curves were available from the utilities operating the reservoir, and were not adjusted for this study.

Table 3.2.2 Downstream Flow Requirements

Reservoir	Downstream Flow Requirement (cfs)	Source of Information
Dog River	9	Douglasville-Douglas County Water & Sewer Authority fact sheet
Randy Poynter	1.9	Jack Turner Dam Operations and Maintenance Manual, Section 2 (June 2002)
Gardner	2.8	Henry County Water Authority website: http://www.hcwsa.com/reservoirs-as-water-supply
Long Branch	0.4	
Cole/U. Tawiliga	2.6*	

*Approximated as 50% of the total required release from Lower Towiliga Reservoir, which is fed by Upper Tawiliga Reservoir.

Table 3.2.3 Usable Storage Volume

Reservoir	Usable Storage Volume (MG)	Notes	Sources of Information
Dog River	1,731	1,881 Max, 150 Min	Storage-Area-Elevation curves and documentation from respective utilities
Randy Poynter	5,280	5,400 Max, 120 Min	
Gardner	587	Assumed to be 80% of total storage, per Henry County Water Authority Long Range Water Supply Plan Update, Section 3	
Long Branch	1,238		
Cole/U. Tawiliga	4,643		

Additionally, it was assumed that Upper Tawiliga Reservoir (also referred to as "Cole Reservoir" provides the majority of yield for the Tawiliga System (Upper and Lower Tawiliga reservoir). Lower Tawiliga Reservoir, and its contributing drainage area downstream of Upper Tawiliga Reservoir were not included in this analysis.

A further simplification is that demand is assumed to be constant in each month of the year, with the exception of the Dog River Reservoir. **Table 3.2.4** lists the monthly factors applied to average annual demand for Dog River, and these were applied because they were previously published as Table 6 of the report: *Hydraulic Budget Models: Dog River Reservoir & Bear Creek Reservoir, Black and Veatch Project No. 179756 (July 2013).*

Table 3.2.4 Dog River Reservoir Monthly Demand Factors

Month	Percent of Annual Average Demand
Jan	91%
Feb	90%
Mar	93%
Apr	100%
May	110%
Jun	111%
Jul	111%
Aug	110%
Sep	107%
Oct	98%
Nov	92%
Dec	87%

3.2.6 Climate Adjusted Hydrology

Once the baseline yield values were determined for each reservoir, the precipitation, streamflow, and evaporation time series were modified to determine if the yield rates are sensitive to possible future climate conditions. The adjusted monthly precipitation time series associated with the future climate scenarios as presented in **Appendix B** were used directly to estimate changes in surface precipitation. Potential climate-induced changes to streamflow and evaporation were estimated as described in the following sections. Once these time series were adjusted, they were input into the reservoir yield models and the yield and reliability values were recomputed and compared with the historic yield estimates.

3.2.6.1 Climate Regression Models for Potential Future Streamflow

Once historical streamflow into the reservoirs was synthesized, it was then necessary to determine how these inflow records could change if subject to the future climate scenarios. Changes in streamflow were estimated using multivariate regression of historic precipitation and temperature (one, two, and three month totals or averages as possible predictor variables). The regression equations were applied for historic climate conditions (P and T) and the potential future conditions (P and T) to estimate a percentage change in streamflow. Note that to maintain a consistent comparative basis and direction of change, the percentage change was computed without the actual historic streamflow, but the climate conditions that created it. The percentage change was then added to or subtracted from the historic streamflow measurements to establish climate-adjusted inflow estimates, and to avoid the introduction of exaggerated uncertainty by using absolute values of future flow predictions generated only from precipitation and temperature, which alone cannot explain all of the variability in monthly streamflow.

The goal was not to recreate perfect hydrologic prediction models, because precipitation and temperature alone are not the only causal mechanisms that affect streamflow. Rather, the goal was to isolate the impacts of these climate variables on streamflow, and use these relationships to investigate how changes in these variables could alter future streamflow patterns, and thus affect reservoir yield.

To estimate any given monthly flow, the precipitation and temperature statistics for the current and prior two months were considered. Generally the best correlations between precipitation and streamflow were found by using the current month precipitation and the total precipitation over the current and prior month. The best correlation between temperature and streamflow was found using the average temperature over the three months leading up to the current month (inclusive). Examples are shown below in **Figure 3.2.9** for the Dog River inflow, and these are reasonably typical of results for the other four reservoirs

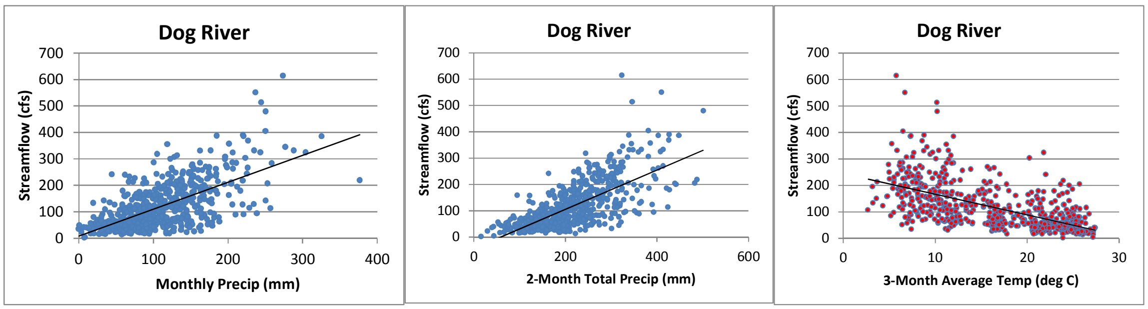

Figure 3.2.9 Correlation Between Monthly Precipitation, Temperature, and Streamflow (Dog River*)
*Results are similar in other reservoirs.

Individually, the precipitation variables can explain approximately 42 to 48 percent of the monthly variability in streamflow for the Dog River (28 to 49 percent across all five reservoirs), while the temperature can only explain approximately 35 percent of the variability in the Dog River flow (consistent across all five reservoirs). This was the first indication that monthly streamflow is probably more highly correlated to precipitation than to temperature. The next step was to combine them into multivariate regression models to examine how well they could describe streamflow variations collectively. Regression equations of the following form were developed by using optimization algorithms to minimize the sum of squared errors between regression predictions and synthesized values:

$$Q_t = aP_t^d + b(P_t + P_{t-1})^e + c(\{T_t + T_{t-1} + T_{t-2}\}/3)^f \qquad \textit{(eqn. 3.2.1)}$$

where:

t = monthly time index
Q = average monthly flow in cfs
P = monthly precipitation in mm
T = average monthly temperature in °C
a-c = calibrated coefficients
d-f = calibrated exponents

Each equation, therefore, is the sum of three factors and their associated calibration parameters: monthly precipitation, total precipitation over the past two months, and average temperature over the past three months.

Table 3.2.5 lists the calibrated coefficients for this equation for each of the five reservoirs, all of which are based on the same monthly precipitation and temperature values, which were not varied geographically. We can see that the calibrated parameters for the two precipitation terms carry much more influence in the equations for each reservoir than do the parameters for temperature. Either the coefficient or the exponent for the three-month average temperature is close to zero, which reinforces the earlier conclusion that precipitation is much more a driver of streamflow variability than is temperature, though temperature can have observable impacts at extreme statistical low flow conditions, such as the 7Q10, by increasing soil evaporation. However, because of the buffering effect of storage in the reservoirs, yield is generally not sensitive to extreme low flow conditions of short duration, but rather long-term hydrologic trends that affect the depletion and replenishment of storage, and these are much more dependent on rainfall than on temperature.

Table 3.2.5 Calibrated Multivariate Regression Parameters for Streamflow*

Parameter Function	Parameter Name	Dog River	Randy Poynter	Gardner	Long Branch	Upper Tawiliga
Coefficient, Current Precip	a	0.1410	0.0528	0.0014	0.0011	0.0247
Coefficient, Total 2-month Precip	b	0.0175	0.0130	0.0123	0.0024	0.0102
Coefficient, 3-month avg. Temp	c	0.0003	8.9734	0.0003	0.0007	0.0001
Exponent, Current Precip	d	1.2122	1.2894	1.7651	1.5563	1.3405
Exponent, Total 2-month Precip	e	1.5446	1.5089	1.3165	1.3566	1.4504
Exponent, 3-month avg. Temp	f	0.2619	0.000002	0.2289	0.0038	0.1561

*See equation 3.2.1 above

Figure 3.2.10 illustrates the regression models for the effects of precipitation and temperature on flow into the five reservoirs. The two climate variables were found to explain between 36 and 54 percent of the total monthly variability in streamflow for the five reservoirs. Of note is that the models do not predict extreme high flow very well, but this was deemed to be inconsequential to firm yield estimates, which are more dependent on sustained low-flow conditions. All of the simulated reservoirs recover from steep drawdown quickly, so underestimating peak flows did not impact firm yield results.

Figure 3.2.10 Multivariate Climate Regression Models for the Five Reservoirs*
**Each model based only on monthly precipitation and temperature in order to isolate the* influence *of climate on streamflow.*

As illustrated in the figure, the regression equations are able to predict the occurrence and magnitude of low flow reasonably well, if not always the duration. However, inaccuracies in these models are expected, because we are isolating the predictive variables to just the climate impacts, and not the impacts of local geography, geology, land use, etc. Because climate can only predict a portion of the streamflow variability, it was necessary to use *relative* changes in flow rather than absolute flow values predicted with the regression models.

The regression models were applied first to the historic monthly precipitation and temperature values, and then to the precipitation and temperature values associated with the future climate scenarios, and the ratio between the two predictions was applied to the historic flow, as shown in the following equation:

$$Q_{future} = \frac{Regression\ Flow\ (Future\ P,T)}{Regression\ Flow\ (Historic\ P,T)} \times Q_{historic} \qquad \textit{(eqn. 3.2.2)}$$

In this way, the regression models were useful by predicting the direction and relative magnitude of streamflow changes, but large uncertainties in any specific streamflow value were prevented from propagating through the yield analysis.

3.2.6.2 Climate Regression Model for Potential Future Evaporation

Applying similar principles to water surface evaporation as those applied to streamflow, a climate regression model was developed for free-surface evaporation throughout the Metro Water District. Site-specific variations in evaporation were not considered, as evaporation is a more geographically homogenous phenomena than runoff, which must be estimated locally. Also, intuitively, evaporation from lake surfaces would be physically correlated with air temperature, and not with precipitation. Hence, historical monthly evaporation was only correlated with air temperature.

Figure 3.2.11 illustrates the correlation between historic air temperature and lake surface evaporation. Monthly air temperature predicts approximately 76 percent of the recorded evaporative losses from lake surfaces.

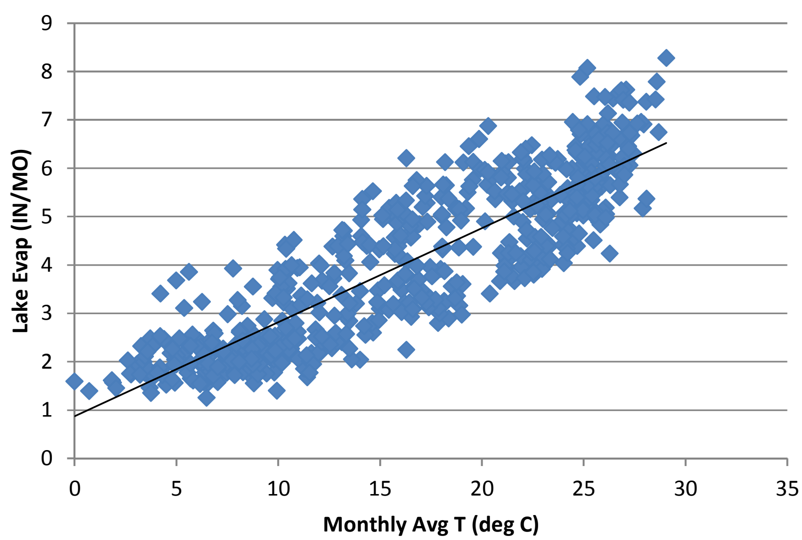

Figure 3.2.11 Correlation Between Temperature and Measured Lake Evaporation

From this relationship, the following linear regression equation was developed:

$$E_t = aT_t + b \qquad \textit{(eqn. 3.2.3)}$$

where:

t = monthly time index
E = monthly lake surface evaporation (inches)
T = average monthly temperature in ^oC
a = calibrated coefficient
b = calibrated y-intercept

The calibrated value of *a* was 0.1946, and the calibrated value of *b* was 0.8687. The application of this regression relationship was applied to the historical temperature and compared against measured lake surface evaporation. This comparison is shown in **Figure 3.2.12**. Again, most of the monthly variability in evaporation is described well by temperature. Some of the higher values of evaporation are underpredicted, but these generally occur in periods later in the record that did not usually create the highest hydrologic stress that defines firm yield (which was usually observed in the 1950s). Additionally, an error of 1-inch in lake surface evaporation for a period of one month would have a negligible impact on reservoir drawdown and firm yield. Again, the precipitation and corresponding runoff is much more a driver of firm yield than is evaporation from the lake surface. As an experimental example, free surface evaporation was increased by 20 percent for the Dog River Reservoir, and the firm yield was reduced by less than 1 percent.

Also, as was done with the streamflow estimates, the absolute values of predicted evaporation were not used directly. Rather, the relative difference between the regression model applied to historic temperature and possible future temperature was applied as a ratio to the historic evaporation, so that it increased or decreased with an appropriate direction and relative magnitude, but did not, for example, double simply because of model uncertainty.

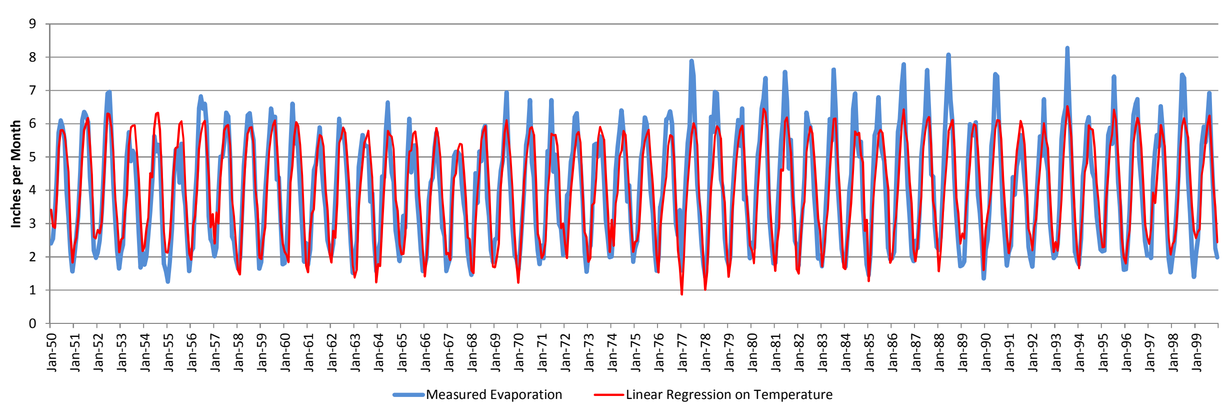

Figure 3.2.12 Regression Model for Evaporation as a Function of Temperature

3.3 Water Quality Impacts

Four stream reaches (**Figure 3.3.1**) were evaluated with respect to potential water quality impacts and vulnerabilities associated with climate variability. The selected study streams are: Flint River, Yellow River, Big Creek, and Little River. Reach watersheds vary in size and land use, from 37 to 268 square miles and from 48 to 81 percent developed. **Table 3.3.1** and **Figure 3.3.2** show the watershed statistics and land cover information for each of the chosen stream reaches.

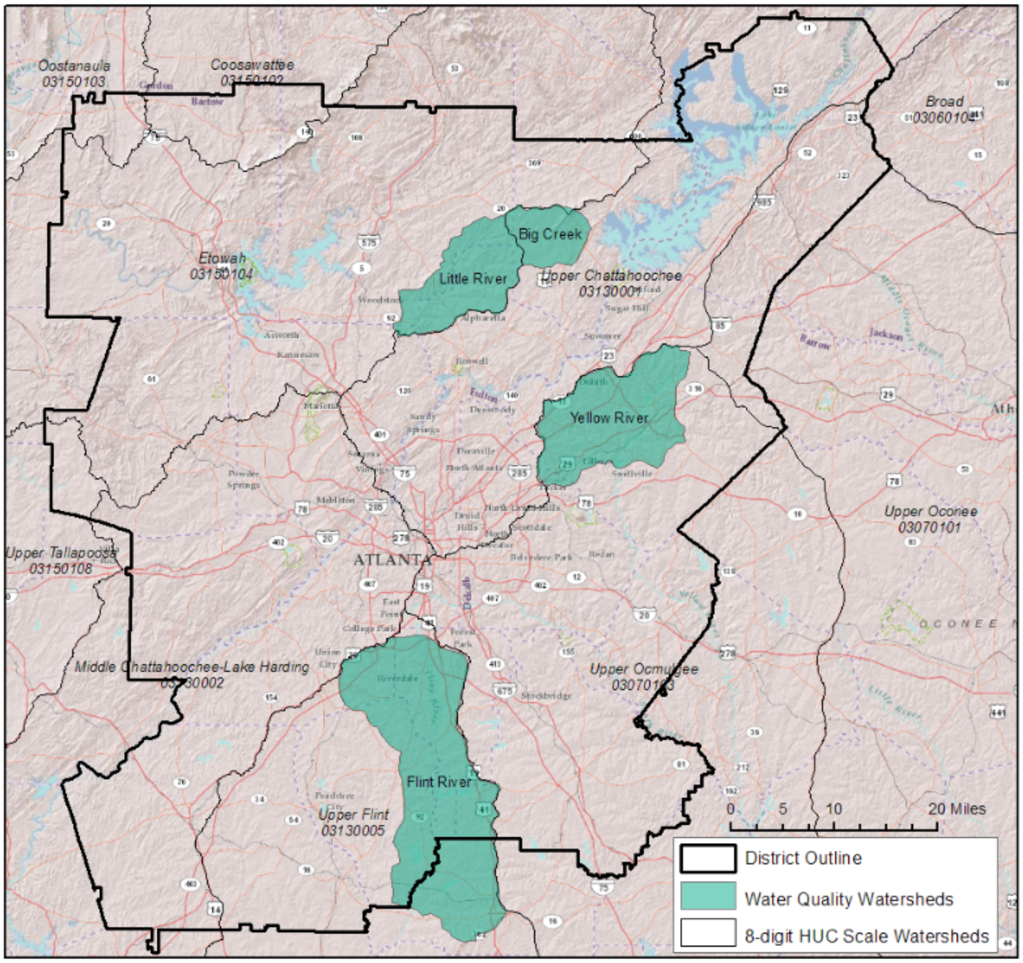

Figure 3.3.1 Water Quality Case Study Reach and Drainage Basin Locations

Table 3.3.1 Water Quality Study Watershed Characteristics

Study Reach	Drainage Area (square miles)	Percent Impervious	Modeled Reach Length (mi)
Big Creek	37.4	9.88	9
Little River	80.6	6.29	1
Yellow River	126.9	25.59	9
Flint River	267.5	13.31	28

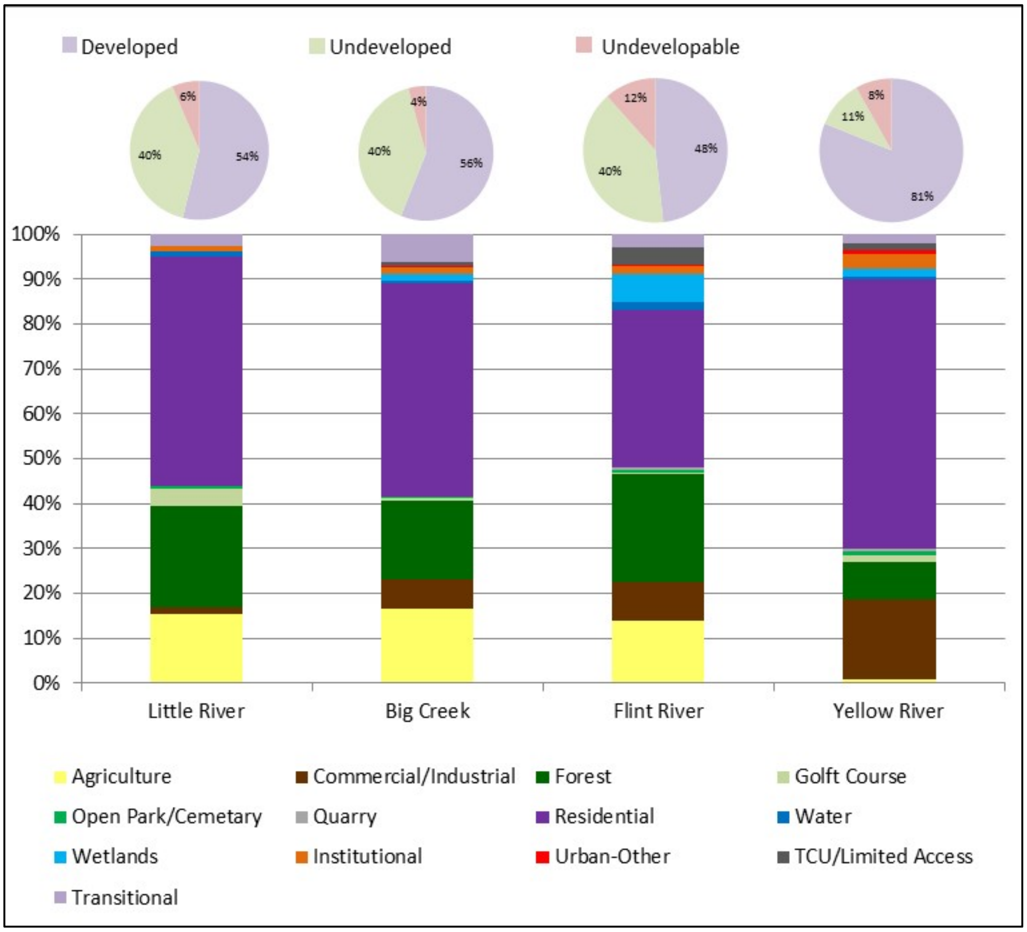

Figure 3.3.2 Land Cover of Water Quality Study Reaches
(National Land Cover Database, 2011)

The process of evaluating each reach for water quality impacts from climate variability followed four steps:

1. Develop empirical hydrologic regression models which predict stream flow changes as a function of temperature and precipitation variability.

2. Use newly developed QUAL2K water quality models to translate projected air temperature and low flow changes into changes in river water temperature;

3. Use existing Georgia Dosag water quality models to translate projected low flow and water temperature changes into changes in river dissolved oxygen.

4. Evaluate climate impacts on each study reach and explore the potential implications for existing wastewater discharges.

3.3.1 Empirical Hydrologic Regression Models

The hydrologic regression models, developed using site specific historical flow and climate data for each case study basin, predict annual 7 day low flow as a function of the combination of two climate variables: an extended cumulative precipitation total and a near-term average air temperature. Intuitively, we interpret the former as a driver of perennial baseflow and the latter as reflective of summer evapotranspiration (ET) losses in the basin. For three of the four basins, the best predictor variables were total water year precipitation and 2 month average temperature. For the Flint River, 8 month total precipitation and 1 month average temperature were found to be slightly better predictors of stream low flow and are used in the regression models. These differences across sites are not surprising and reflect differences in basin hydrogeology. Streamflow data used in the analysis were obtained from US Geological Survey (USGS) flow gages, where available (**Table 3.3.2**). For locations with insufficient data, a nearby gage was used to supplement the time series of streamflows to complete the 1950-1999 historical baseline period. This was done by developing a regression equation relating the study reach streamflow to streamflow from a nearby river with adequate data availability. Final hydrologic empirical regression models are summarized in **Table 3.3.3**.

Table 3.3.2 Water Quality Study Streamflow Gages

<table>
<tr><th rowspan="2">Study Reach</th><th colspan="2">Primary USGS Gage</th><th colspan="2">Secondary USGS Gage</th></tr>
<tr><th>Gage Name & Number</th><th>Available Years</th><th>Gage Name & Number</th><th>Years Used to Supplement Primary Gage</th></tr>
<tr><td>Big Creek</td><td>02335700
Big Creek near Alpharetta</td><td>1960-1999</td><td>02392500
Little River near Roswell</td><td>1950-1959</td></tr>
<tr><td>Little River</td><td>02392500
Little River near Roswell</td><td>1950-1974</td><td>02335700
Big Creek near Alpharetta</td><td>1975-1999</td></tr>
<tr><td rowspan="2">Yellow River*</td><td rowspan="2">02206500
Yellow River near Snellville</td><td rowspan="2">1950-1970 and 1988-1999</td><td>02207500
Yellow River near Covington</td><td>1976-1982</td></tr>
<tr><td>02208450
Alcovy River near Covington</td><td>1972-1975</td></tr>
<tr><td>Flint River</td><td>2344500
Flint River near Griffin</td><td>1950-1999</td><td colspan="2">not necessary</td></tr>
</table>

*Note: No data were available at any suitable gages for 1972

Table 3.3.3 Results from Hydrologic Regression Analysis

Stream	Independent Variables	Regression Equation	R-Squared Value
Flint River	X_1: Minimum annual 8-month total precipitation X_2: Maximum annual 1-month average temperature	$269 + 0.089X_1 - 10.9X_2$	0.55
Yellow River	X_1: Total water year precipitation X_2: Maximum annual 2-month average temperature	$-49.0 + 0.075X_1 - 0.34X_2$	0.37
Big Creek	X_1: Total water year precipitation X_2: Maximum annual 2-month average temperature	$18.7 + 0.017X_1 - 1.20X_2$	0.71
Little River	X_1: Total water year precipitation X_2: Maximum annual 2-month average temperature	$87.4 + 0.028X_1 - 4.06X_2$	0.72

The predictive abilities of our simplified hydrologic regression models in terms of capturing variability in annual low flow varies across sites, as evidenced by the range in R-squared values. For two of the sites (Big Creek and Little River) the regression models do an excellent job of capturing the majority of the inter-annual variability in 7 day low flow (R^2 = 0.71 and 0.72, respectively). For the other two sites (Flint River and Yellow River), the model regressions are weaker (R^2 = 0.55 and 0.37, respectively) indicating that our simple two parameter models are not sufficient for explaining all (or even a majority) of the variability in extreme low flow. There are clearly other factors at play here, including possible land use changes over time or additional climate dynamics not represented in the two parameter model. However, for this study we are interested in isolating only the response of stream low flow to the climate changes we are able to quantify (monthly air temperature and precipitation). These climate elasticities are well-represented, to the extent possible given available data and project constraints, by all four regression models, regardless of overall R^2 values.

3.3.2 QUAL2K Water Quality Models

The QUAL2K models apply well-established heat and radiation balance algorithms to estimate reach average, steady state water temperature as a function of reach hydraulics, ambient air temperature, and incident solar radiation conditions (the latter parameterized according to model default values). Cloud cover and shade were assumed to be minimal, and held constant, for the study reaches and simulated late summer critical conditions. Model reaches were constructed for each model to replicate those represented in existing State GADosag models (described below). Baseline model reach lengths, flow rates, tributary and point source inputs, and headwater conditions were all set to replicate the modeled GADosag systems. Reach hydraulics (velocity and depth) are calculated in QUAL2K as a function of flow according to power equations, also obtained from the GADosag models. For future scenario simulations, only air temperatures and headwater and tributary flow rates were modified according to climate projections. Point source temperatures and flow rates were maintained at baseline levels.

3.3.3 Georgia Dosag Water Quality Models

Water quality models, for each case study reach, have been previously developed, calibrated, and published by the State of Georgia, in support of discharge permitting. These models were developed using a tool called GADosag. GADosag is a steady-state, branching, one-dimensional, freshwater dissolved oxygen model for TMDLs, NPDES permit development, and dissolved oxygen standards review (Georgia EPD). They apply classic Streeter-Phelps type equations to simulate dissolved oxygen dynamics in a river as a function of reaeration and pollutant oxidation. Simulated pollutants in the model include nitrogenous and carbonaceous bio-chemical oxygen demand (NBOD and CBOD). No aquatic plant or algae dynamics (photosynthesis and respiration) were included in the models used here. Inputs to the model include flow and water temperature. The model does not calculate water temperature as a function of environmental conditions, thus the need for separate models, described above, to quantify water temperature impacts. The projected water temperatures from the QUAL2K models serve as inputs to the GADosag models. Only flow and water temperature parameters were changed in the models to simulate future scenarios in this study. Flows were modified, in line with the "delta" method applied elsewhere, using modeled adjustment factors. These adjustment factors were calculated using the hydrologic regression models, described above, as: modeled future low flow / modeled historical low flow. Adjustment factors were applied to existing GADosag model headwater and tributary flows. All other parameters were held at previously established values. This includes wastewater and industrial discharge flows and quality, which were significant components of reach flow and mass balances for all sites. In other words, effluent discharge flows and loads were assumed to remain constant in the future, un-impacted by climate variability.

For all models, late summer (September) conditions were simulated. September was identified, in a separate analysis of flow gage data, as the month with the lowest average flow in the calendar year. It was thus deemed to be best representative of critical conditions, with respect to water quality, and presumably serves as the critical period for State permitting analysis. A total of seven (7) climate scenarios were simulated, including a historical baseline, for each of four (4) study sites. Separate QUAL2K and GADosag models were developed for each. As described previously, the historical baseline scenario corresponds to the 1950 to 1999 period. Future climate scenarios were developed by adjusting this historical period to reflect climate model projections of the 2050 (± 15 years) planning horizon.

3.4 Watershed Impacts Methodology

The impacts of climate variability on watershed issues were evaluated using the following steps:

1. List potential watershed impacts relevant to Metro Water District planning.
2. Quantify potential changes in frequency and intensity of storm events due to climate variability
3. Develop simple hydrologic models to relate the changes in storm frequency and intensity to peak streamflows.
4. Estimate potential impacts of precipitation patterns on watershed pollutant loads.

3.4.1 Potential Watershed Impacts

A draft list of potential watershed impacts from climate variability was developed based on scoping discussions with the Metro Water District, preliminary research into other watershed-based climate variability impact studies, and general watershed planning guidance documentation. The US Environmental Protection Agency's (EPA) Global Change Research Program has released several studies in recent years exploring the impact of climate variability on watershed systems[3,4]. EPA also provides a handbook for developing watershed plans, which provides watershed issues to consider when planning to protect and restore local surface water resources[5]. Future watershed planning may include studies to assess the impact of climate variability on these same traditional watershed planning objectives.

List of Potential Watershed Impacts from Climate Variability

- Pollutant loading
- Habitat quality and biodiversity
- Sedimentation
- Erosion
- Stream morphology
- Flooding
- Public access and recreation

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[3] US EPA, 2012. Climate and Land-Use Change Effects on Ecological Resources in Three Watersheds: A Synthesis Report.

[4] US EPA, 2013. Watershed modeling to assess the sensitivity of streamflow, nutrient and sediment loads to potential climate change and urban development in 20 U.S. watersheds.

[5] water.epa.gov/polwaste/nps/handbook_index.cfm

- Floodplain connectivity
- Base flow
- Wetlands
- Hydraulic connectivity
- Riparian buffer and shading
- Fisheries

3.4.2 Storm Frequency and Intensity

To quantify changes in frequency and intensity of storm events, trend analysis of daily climate projection models as well as historical weather data was performed. This analysis results in identification of statistically significant changes in 24-hour storm event frequency and intensity for the 2050 planning horizon relative to the recent past. Additional metrics for characterizing changes in extreme flow and precipitation were also considered. To determine the effect of the future climate scenario on projected river high flows, a method similar to that used for regulatory low flows was followed.

By 2050, one-day extreme rainfall depths are projected to be five to ten percent higher relative to 20th century conditions, according to estimates presented in EPA's Climate Resilience Evaluation and Awareness Tool.[6] This increase concurs with the IPCC (2014), which indicates that "*Extreme precipitation events over most mid-latitude land masses and over wet tropical regions will very likely become more intense and more frequent as global mean surface temperature increases.*"[7]

Design storms for use in watershed modeling can be developed using synthetic hyetographs or historical data. For applications where an SCS (NRCS) Type II distribution is customarily used, this distribution can be applied using adjusted 24-hour rainfall depths as computed for the 2050 planning horizon. For conditions where use of realistic storm hyetographs is appropriate, observed hourly hyetographs from the Hartsfield-Jackson Atlanta International Airport can be scaled upwards according to the expected change in design storm magnitude. **Table 3.4.1** lists rainfall totals at various durations for major storms (defined as those events with 5-year or longer average recurrence interval depths at three or more of the durations shown) observed at the airport since 1948. These storms encompass a variety of hyetograph shapes, from short, intense events, such as those in July 1988, June 1991, and July 5, 2005, as well as less intense but high total rainfall multi-day storms such as in September 1989, and on July 10, 2005. Depending on the size of a watershed of interest, different hyetograph shapes may be appropriate as design events. These storms were used along with USGS streamflow gage records to develop a relationship between rainfall and peak daily streamflow for two study area streams. The peak streamflow analysis is discussed in the next section.

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[6] EPA, 2013. Climate Resilience Evaluation and Awareness Tool. http://water.epa.gov/infrastructure/watersecurity/climate/creat.cfm

[7] Intergovernmental Panel on Climate Change (IPCC), 2014. Fifth Assessment Synthesis Report. www.ipcc.ch/pdf/assessment-report/ar5/syr/SYR_AR5_LONGERREPORT.pdf

Table 3.4.1 Major Storm Depths (inches) at Hartsfield-Jackson Atlanta International Airport since 1948

Date	1-h	2-h	3-h	6-h	12-h	1-day	2-day	3-day	4-day
July 9, 1948	1.1	1.5	2.6	3.3	3.7	5.4	6.6	6.7	7.6
November 26, 1948	0.7	1.0	1.3	2.2	3.3	3.6	6.5	7.0	7.0
September 24, 1956	0.6	1.1	1.5	2.2	4.1	5.5	5.7	5.7	5.7
February 24, 1961	1.2	1.7	2.1	2.9	4.4	5.7	6.0	6.6	7.1
May 8, 1969	2.3	2.7	3.3	3.9	4.3	4.3	4.3	4.4	4.4
March 19, 1970	0.8	1.2	1.5	2.4	4.2	5.1	5.3	6.0	6.1
March 15, 1976	0.8	1.1	1.4	2.1	3.3	5.1	5.4	5.4	7.4
April 12, 1979	1.1	1.4	1.5	2.6	3.9	5.6	6.1	6.1	6.1
May 23, 1980	2.4	2.7	3.0	3.0	3.0	3.8	4.0	4.0	6.5
October 1, 1985	1.4	2.4	2.8	3.2	3.6	3.9	4.0	4.0	4.0
July 29, 1988	2.6	2.6	2.7	2.7	2.7	2.7	2.7	2.9	2.9
September 25, 1989	1.8	2.5	2.7	3.2	4.2	4.9	4.9	5.1	5.6
September 30, 1989	1.1	1.4	1.8	3.1	4.0	5.4	6.3	7.1	7.3
March 16, 1990	0.5	0.9	1.2	2.1	3.7	5.7	5.9	5.9	5.9
June 18, 1991	3.1	3.6	3.7	3.8	3.8	4.2	4.5	4.6	5.6
September 4, 1992	1.6	2.8	3.4	3.8	4.1	5.9	6.0	6.1	6.1
July 4, 1994	0.8	1.3	1.9	2.9	4.1	6.5	7.3	7.7	8.1
October 4, 1995	1.2	2.0	2.1	3.1	4.6	7.3	8.7	8.7	8.7
September 16, 2004	1.8	2.6	3.0	3.8	4.9	5.0	5.1	5.1	5.1
September 27, 2004	0.9	1.7	2.1	3.6	4.8	4.9	4.9	4.9	4.9
July 5, 2005	3.6	4.7	5.0	5.1	5.2	5.2	5.5	5.5	5.6
July 10, 2005	1.4	2.0	2.6	3.5	5.6	6.7	6.9	6.9	7.0
August 23, 2005	2.0	2.9	3.0	3.0	3.0	3.0	3.0	3.0	3.0
August 31, 2006	2.0	2.5	3.1	3.2	3.2	4.3	4.4	4.5	4.9
September 19, 2009	1.2	2.3	3.1	3.6	3.7	3.8	4.6	6.5	6.6
June 5, 2013	2.2	3.3	3.7	4.1	4.1	4.1	4.2	4.2	4.9
5-year	1.9	2.3	2.6	3.1	3.7	4.5	5.4	5.7	6.1
10-year	2.2	2.7	3.0	3.5	4.2	5.2	6.2	6.6	7.0
25-year	2.6	3.2	3.6	4.2	5.1	6.1	7.4	7.9	8.3

Note: Cell shading indicates the return period of the storm (yellow = 5-year, green = 10-year, red = 25-year). For example, on May 23, 1980 the 1-, 2-, and 3-hour rainfall totals were high enough to each be considered 10-year storms. The 4-day total for that event was high enough to be considered a 5-year storm. All other (unshaded) interval totals for that event were less than a 5-year storm.

3.4.3 Peak Streamflow Analysis

The peak streamflow analysis used hourly rainfall records to predict peak streamflow. The USGS maintains records of annual peak streamflow values that can be used to develop a regression relationship between known hourly rainfall, and other potential independent variables and peak streamflow. The regression relationship was then used to predict peak streamflows using the various future rainfall statistic predictions described in the previous subsection. A different relationship was developed for three different storm intensity/frequency pairs.

The peak streamflow analysis was conducted for two watersheds that have good peak streamflow data availability and are also being analyzed for wastewater/water quality impacts and pollutant loading impacts: Yellow River and Flint River watersheds. Peak streamflows are available for the Yellow River streamflow gage at Snellville (2206500) for 60 dates between 1943 and 2002 and for the Flint River gage near Griffin (0234450) for 78 dates between 1929 and 2013. **Table 3.4.2** lists the gages and available data. **Figure 3.4.1** shows the locations and delineations of the watersheds.

Table 3.4.2 USGS Streamflow Gages Used for Peak Streamflow Impacts Analysis

Stream	USGS ID	Available Daily Streamflow Data
Yellow River	02206500 near Snellville, 134 mi²	1942-1971 and 1988-2002
Flint River	02344500 near Griffin, 272 mi²	1937-present

The predicted changes in peak streamflows caused by potential changes in climate were used as a proxy for assessing the likely impact of changing precipitation patterns on flooding in the two study watersheds.

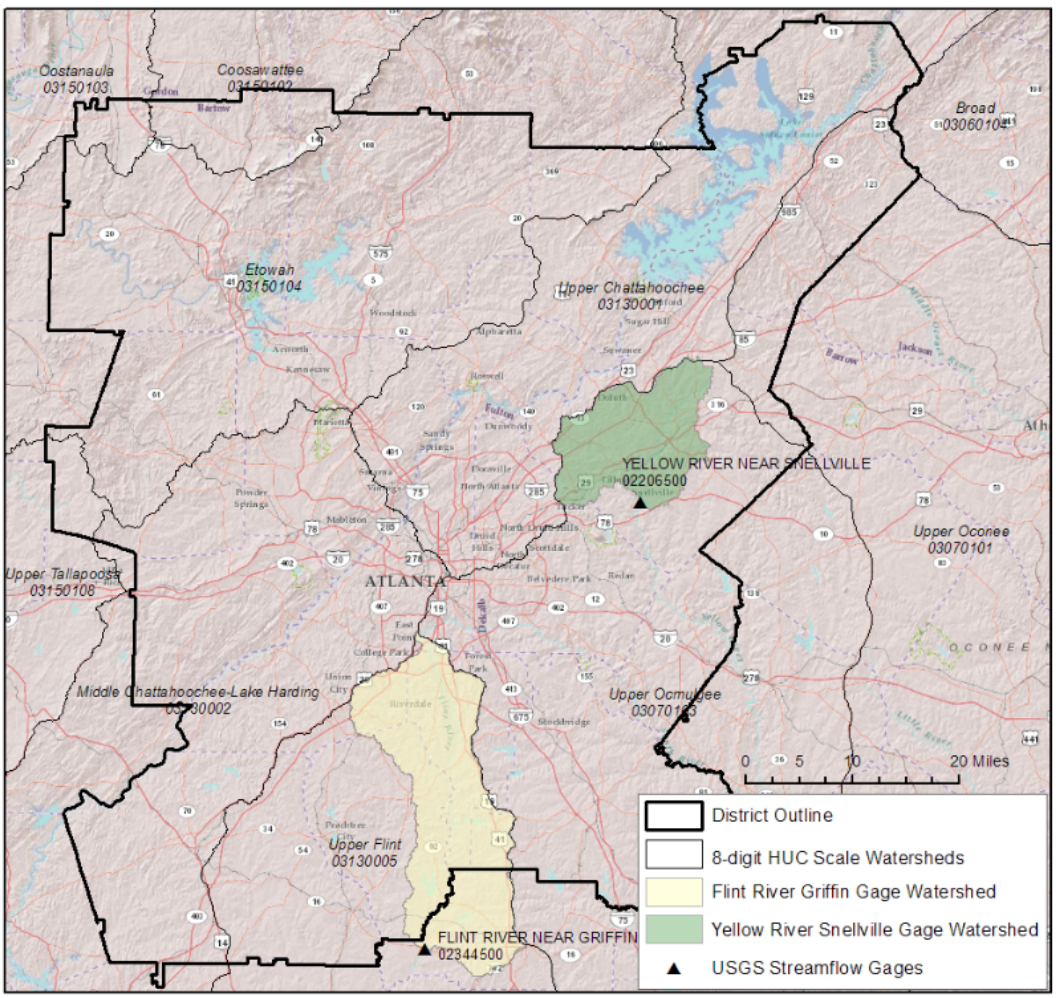


Figure 3.4.1 USGS Gages and Contributing Watersheds Used for Peak Streamflow Impact Analysis

Peak daily streamflow was extracted from the USGS gage records for unique rainfall events in Atlanta from June 1948 to August 2013. Streamflows were matched with 1,798 rainfall events for the Flint River gage and 1,051 rainfall events for the Yellow River gage. The maximum daily flow occurring during the four days during and after each storm was identified as the peak flow for that storm. Regression relationships were explored using a variety of independent rainfall variables, including the storm totals at different durations and rainfall totals representing antecedent conditions such as monthly or seasonal total rainfall. One through four day rainfall totals were the best predictors of peak daily streamflow, according to the following equations:

Flint River, R-squared = 0.27

$$Q_{peak\ daily} = -265.7 + 227.6P_{1\ day} + 121.6P_{2\ day} + 286.2P_{3\ day} + 156.3P_{4\ day} \quad \text{(Equation 3.4.1)}$$

Yellow River, R-squared = 0.34

$$Q_{peak\ daily} = -132.9 + 67.4P_{1\ day} + 52.0P_{2\ day} + 256.4P_{3\ day} + 136.3P_{4\ day} \quad \text{(Equation 3.4.2)}$$

Where:

$Q_{peak\ daily}$ = peak daily streamflow resulting from rain event, cfs

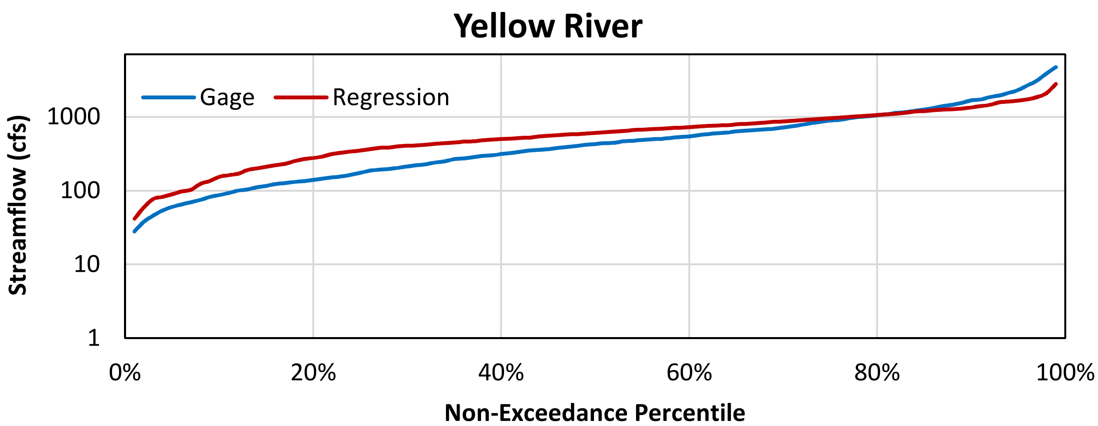
$P_{n\ day}$ = rainfall total for n days duration, inches

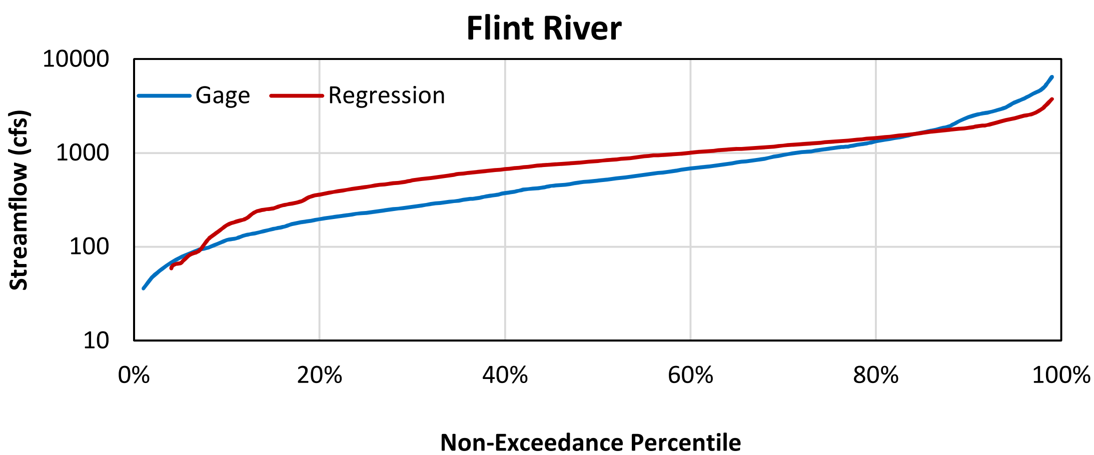
Many factors affect peak streamflow resulting from rainfall; the equations above do not consider all factors. The regression modeling does not necessarily offer a reasonable predictor for peak streamflow using independent variables, but offers an indication of the type of change that could be expected solely from climate factors. The R-squared values suggest that storm duration and intensity, as represented by the one to four day rainfall totals, comprise 30 percent of the factors driving peak streamflows in the Yellow and Flint Rivers. As such, the model results should not be viewed as estimates for planning purposes, but only as comparative indications of future risk.

EPA's CREAT tool projects changes in precipitation totals of various durations and recurrence intervals; the same cannot be done at this time and within the scope of this study for all factors that affect peak streamflow. **Figure 3.4.2** shows the frequency distribution for the observed and modeled peak streamflows over the dataset of available rainfall events used to generate the regression relationship.

These frequency distribution plots show that the regression model does not reproduce the highest peak flows resulting from storm events. Other factors besides one- to four-day total rainfall likely influence these extreme high flows. Other available recorded independent variables that may do well to represent these other factors, such as seasonal or previous month rainfall totals, did not correlate well with peak streamflows. Specifically, the monthly average recorded temperatures did not correlate well with the peak streamflow events used for this analysis. In the water supply and water quality impacts tasks, temperature was used as an independent variable in streamflow regression models and correlated fairly well. However, those models focused on low flows and average daily or monthly flows. Temperature and average/low streamflow trend well together because there tends to be less overall precipitation, and more evaporation, in warmer periods. The peak streamflow analysis for the Yellow and Flint Rivers has shown that storms in all seasons result in varying peak flows that are more related to the one through four day precipitation totals than the time of year that the storms occur.

Because the climate variables accessible in this study account for less than half of the contributing factors to peak streamflow, very little can be said with quantitative certainty about storm frequency, intensity, or peak streamflow trends without further study.





Note: Graphs are in log space, and actual deviations are larger than they appear visually.

Figure 3.4.2 Peak Streamflow Regression Models Showing Frequency Distribution of Gaged and Calculated Streamflow

3.4.4 Pollutant Loading

Annual average pollutant loading was modeled using land use data, projected rainfall totals, and event mean concentrations (EMCs). The pollutant loading assessment was conducted for the Flint River and Yellow River watersheds, which are also included in the wastewater and water quality impacts assessment. These two watersheds have considerably different land uses, as shown previously in **Figure 3.3.2** and below in **Table 3.4.3 and Figure 3.4.3**. The Flint River watershed has more agricultural and forested land than the Yellow River watershed. The Yellow River watershed, by comparison, is much more developed and mainly covered with residential and commercial/industrial uses. Conducting the pollutant loading assessment on these two watersheds will provide guidance as to how current land uses may affect a watershed's vulnerability to climate variability.

Table 3.4.3 Watershed Land Use for Pollutant Loading Comparison

Land Use	Flint River Watershed	Yellow River Watershed
Residential	35%	60%
Agriculture	14%	1%
Commercial/Industrial	8%	18%
Forest	24%	8%
Other	18%	13%

Source: 2011 National Land Cover Database (NLCD)

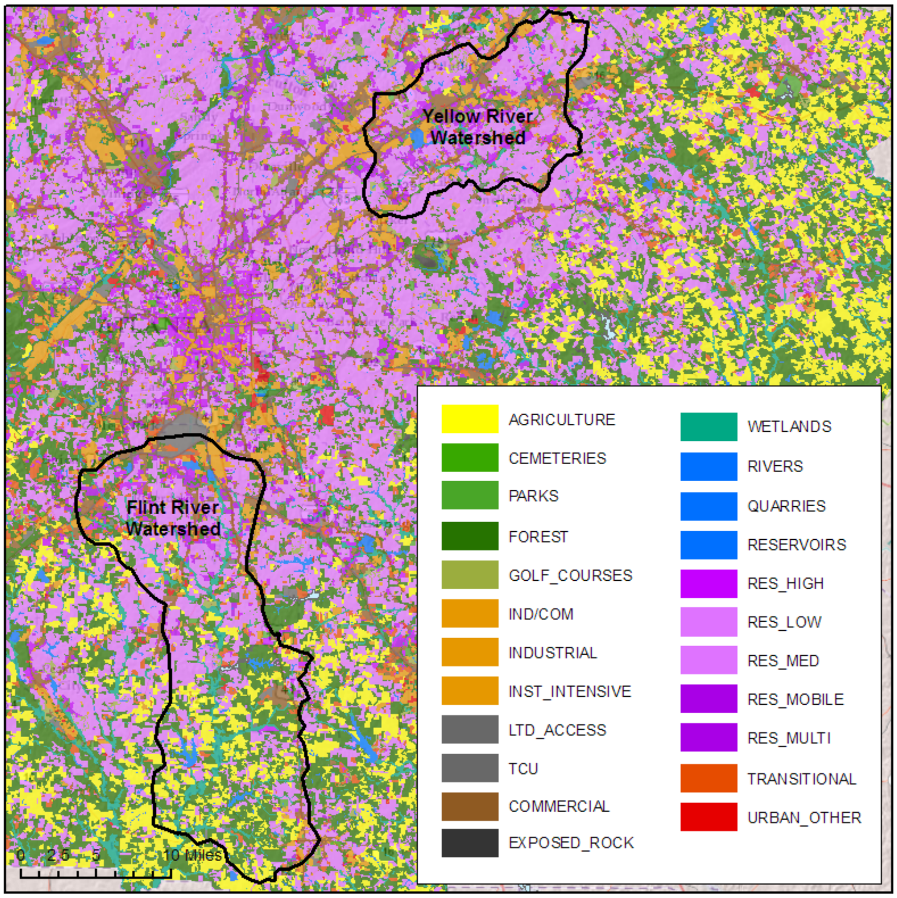


Figure 3.4.3 Land Use Map of Yellow and Flint River Watersheds
(National Land Cover Database, 2011)

The pollutant loading model relates land use to EMCs and directly connected impervious area, using the information shown in **Table 3.4.4**. These values have been published with CDM Smith's Watershed Management Model (WMM) and the sources listed with the table. The land use categories used in the data provided by the Atlanta Regional Commission were related to the land use categories listed below. Pollutants of interest were chosen based on watershed TMDLs and impairments. Total suspended solids loading were used to estimate changes in sediment loads. The NLCD and percent impervious land use classifications are slightly different and have been consolidated according to **Table 3.4.5.**

Table 3.4.4 Watershed Loading Model Impervious Fractions and Event Mean Concentrations

Land Use	Impervious %[1]	Fecal Coliform	Total Phosphorus	TKN	TSS	Copper	Lead	Zinc
		#/100 ml	mg/l	mg/l	mg/l	µg/l	µg/l	µg/l
Commercial/ Industrial[2]	52%	3,500	0.24	1.5	60	20	22	180
Residential[2]	13%	7,750	0.30	1.4	48	12	12	73
Open/Forest[2]	1%	3,100	0.25	0.60	51	5	5	39
Agriculture[3]	1%	0	0.20	0.0	196	7	7	16

Sources:
1 User's Manual, Watershed Management Model Version 4.1 (CDM, 1998)
2 EMCs from: Shaver, E., Horner, R., Skupien, J., May, C., and R. Graeme, 2007. Fundamentals of Urban Runoff Management, 2nd Edition. North American Lake Management Society.
3 Agriculture not included in Shaver, 2007. CDM Smith maintains a database of published regional EMC values, Wolosoff, S. and A. Greene, 2010. Compilation of a National Storm Event Mean Concentration Database, Internal CDM Smith R&D Memo.

Table 3.4.5 Land Use Consolidation

Consolidated Category	WMM Percent Impervious Category	NLCD Category Used for Watershed Land Use and EMC Calculations
Residential	Low Density Residential	Residential
	Medium Density Residential	
	High Density Residential	
Commercial/Industrial	Commercial	Commercial/ Industrial
	Industrial	Institutional
		Urban-Other
Agricultural	Agricultural/Pasture	Agriculture
Open/Forest	Forest/Rural Open	Forest
		Golf Course
	Urban Open	Open Park/Cemetery
		Transitional
Other	Highways	Quarry
		Water
	Water/Wetlands	Wetlands
		TCU/Limited Access

The percent of impervious cover for each basin reported by the USGS[8] was compared against the calculated percent impervious using the watershed loading model. The USGS reports that the Flint River gage watershed is 13 percent impervious while the watershed loading model calculates 12 percent impervious. The USGS report that the Yellow River gage watershed is 26 percent impervious

[8] U.S> Geological Survey. StreamStats: A Water Resources Web Application. <water.usgs.gov/osw/streamstats/index.html> Accessed 31 Jan 2015.

while the watershed loading model calculates 20 percent impervious. The values are close for both watersheds, indicating that the combination of land use and percent impervious shown in **Table 3.4.4** provides a reasonable representation of the watersheds.

The parameters listed in **Table 3.4.4** were chosen for their relevancy to water quality concerns and impairments within the study area. Total phosphorus and Total Kjeldahl Nitrogen (TKN) represent nutrient loading that may contribute to eutrophication and low dissolved oxygen. Fecal coliform is indicative of bacteria-contaminated runoff that presents a public health risk. Total suspended solids (TSS) loading will be used to estimate changes in sediment loads. Copper, lead, and zinc are common urban stream impairments and contribute to declining aquatic habitat.

The pollutant loadings were calculated for each land use and summed for each watershed, using the following equation and unit conversion factors.

$$Pollutant\ Load_{land\ use\ x, pollutant\ y} = P * IMP_x * EMC_y \quad \text{(Equation 3.4.3)}$$

Where:

P = precipitation depth
IMP = percent directly connected impervious area
EMC = event mean concentration for pollutant

The precipitation values were taken from the baseline and projected future climate variability scenarios described in this work plan and are listed in **Table 3.4.6**.

Table 3.4.6 Monthly Average Precipitation for Baseline and Climate Variability Watershed Loading Scenarios

	Monthly Total Rainfall (in)						
Month	Historic	Central	Hot Dry	Warm Dry	Hot Wet	Warm Wet	Trend Analysis
Jan	5.1	5.2	5.1	4.8	5.2	5.6	5.1
Feb	4.8	5.0	4.9	4.7	5.5	5.5	4.8
Mar	5.6	5.9	5.7	5.4	6.2	6.6	5.6
Apr	4.3	4.9	4.0	4.5	4.8	4.9	3.1
May	4.0	4.3	3.6	3.8	4.6	4.7	4.0
Jun	3.9	4.0	4.0	3.9	5.4	4.4	3.9
Jul	4.9	5.2	4.5	5.1	6.2	5.5	4.9
Aug	3.7	3.9	3.5	3.6	4.5	4.1	3.7
Sep	3.7	4.1	3.8	3.8	4.6	3.8	3.7
Oct	3.1	3.6	3.1	3.2	3.4	3.6	3.1
Nov	3.6	3.8	3.7	3.5	3.9	4.0	5.1
Dec	4.3	4.7	4.8	4.1	4.5	4.7	4.3
Annual Total	50.9	54.6	50.7	50.3	58.8	57.6	51.2

3.5 Infrastructure Considerations

This task, which is a precursor to the adaptive strategies assessment, aims to translate the effects of climate variability determined in the previously outlined vulnerability analyses into impacts and risks to critical infrastructure related to water management throughout the Metro Water District. This information was used to screen potential climate impacts to water resources infrastructure and determine potential risks in order to identify and prioritize the facilities with the greatest need of adaptation strategies. Infrastructure critical to the Metro Water District for the purpose of this climate change vulnerability assessment includes:

- Water treatment plants
- Wastewater treatment plants
- Wastewater collection systems
- Stormwater conveyance systems
- Dams & Levees

The current and future vulnerability of critical infrastructure is a function of the infrastructure's sensitivity and adaptability to future climate impacts. The adaptive capacity of critical infrastructure can be evaluated as its ability to accommodate impacts of climate change with minimal potential damage or cost. Systems or infrastructure with high adaptive capacities are better able to deal with climate change impacts. Evaluating vulnerabilities can help determine which critical infrastructure is least resilient to impacts of climate scenarios and can help identify where comprehensive adaptation strategies are most needed.

For this study, a qualitative evaluation was performed to assess the vulnerability of critical water infrastructure to the six potential climate scenario impacts of: water demand, firm yield, dissolved oxygen, 24-hour storm depths, peak streamflow, and nonpoint source pollutant loads. Water infrastructure relevant to the Metro Water District may be vulnerable to climate scenario impacts beyond the six evaluated as part of this assessment.

The qualitative vulnerability assessment evaluated the relative magnitude to which exposed assets would be impaired by the climate scenario impacts. It is important to protect critical facilities to ensure that service interruption is reduced or eliminated. In addition, negative environmental and water quality impacts may be mitigated. The objective of the vulnerability assessment is to answer the primary question: What are, relatively, the most vulnerable critical facilities?

The following methodology was used in performing the critical infrastructure vulnerability analysis:

1. Determine the climate scenarios which could yield increases or decreases to the following climate impacts:
    - Water demand
    - Firm yield
    - Dissolved oxygen
    - 24-hour storm depths
    - Peak streamflow
    - Nonpoint source pollutant loads

2. Determine the relative sensitivity, if any, on a scale of High, Moderate, or Low, of each of the following water infrastructure components to increases or decreases in the climate impacts:

    - Wastewater treatment plants
    - Water treatment plants
    - Stormwater conveyance systems
    - Wastewater collection systems
    - Dams and levees

    The relative sensitivity represents the extent of impact to operations under the potential projected conditions. Many assumptions are needed to determine the potential impacts to the critical infrastructure, which will be explicitly stated.

3. Determine the extent of impact to the critical infrastructure, if any, on a scale of All, Most, or Few. Many of the climate scenario impacts are evaluated using case studies. The extent to which the case studies exhibit similar trends is used to determine the expected ubiquity of the projected climate impact on each infrastructure component.

Results of this assessment are summarized in vulnerability matrices in **Section 4.5**, with one matrix developed for each of the infrastructure components. These matrices help indicate those infrastructure components which are most vulnerable to changes in climate impacts. An example of a vulnerability matrix is shown below for illustration purposes only.

Table 3.5.1 Example Vulnerability Matrix

Impact to Infrastructure Type	Trend	Associated Climate Scenario	Sensitivity	Adaptive Capacity	Extent of Impact	Assumptions
Climate Impact	increase	CT, HD, HW, WD, WW, HT	Low	Moderate	All	
	decrease	Not Impacted				

* The climate scenarios are abbreviated Central Tendency (CT), Hot/Dry (HD), Hot/Wet (HW), Warm/Dry (WD), Warm/Wet (WW), and Historical Trend (HT).

Section 4

Climate Vulnerability Analysis

This section presents the results of the vulnerability analysis covering potential impacts to water demand, water supply, water quality, watersheds, and infrastructure. Summary conclusions are presented in aggregate in **Section 4.6**, following a discussion of all results.

4.1 Potential Impact to Water Demand

4.1.1 Explaining Water Use

In order to isolate the impacts that future climate can have on water use, the statistical water demand model summarized in **Section 3.1** was used to explain the differences between actual per capita water use between the years 2007 and 2013. It should be noted that the statistical model is not intended to be used to forecast future water demand, but rather it is used to explain the variation of water use using data from 1995 to 2014. **Figure 4.1.1** shows the breakdown in contributing factors that were statistically estimated using the statistical water demand model. While the data for this analysis came specifically from DeKalb, Gwinnett and Fulton counties, for the purposes of this study, the results are assumed to be representative of the District as a whole.

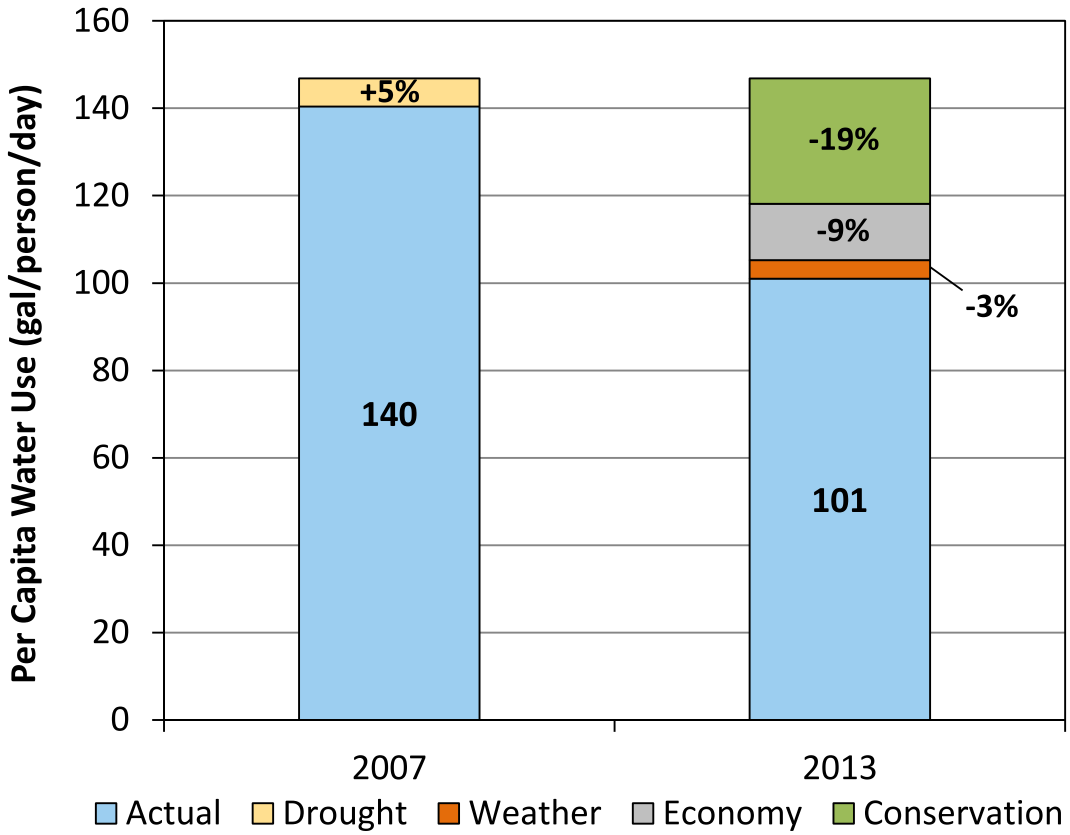


Figure 4.1.1 Statistically Explaining Water Use in Metro Water District Using Demand Model

In 2007, the per capita water use was 140 gallons per person per day, while in 2013 the per capita water use decreased to 101 gallons per person per day. This decrease in per capita water use between 2007 and 2013 is due to many factors. The statistical water demand model presented in **Section 3** indicates that if water use restrictions were not in place in year 2007, then per capita water use would have been 5 percent greater than actual (147 vs. 140 gal/person/day). The model also indicates that cooler and wetter weather in 2013 vs. 2007 resulted in per capita water use being 3 percent lower. The higher unemployment rate in 2013 vs. 2007 resulted in per capita water use being 9 percent lower. And finally, water conservation from plumbing code efficiencies, policy, water pricing, and utility rebates resulted in 2013 per capita water use being 19 percent lower than 2007.

4.1.2 Future Climate Vulnerability on Water Demands

To estimate the impacts of future climate vulnerability on water demands, the statistical demand model was used to compare monthly per capita water use under long-term historical average weather and future monthly climate using the climate scenarios described in **Section 1.** To see the monthly impacts of these future climate scenarios, **Figure 4.1.2** compares monthly temperature and precipitation that are inputs to the statistical water demand.

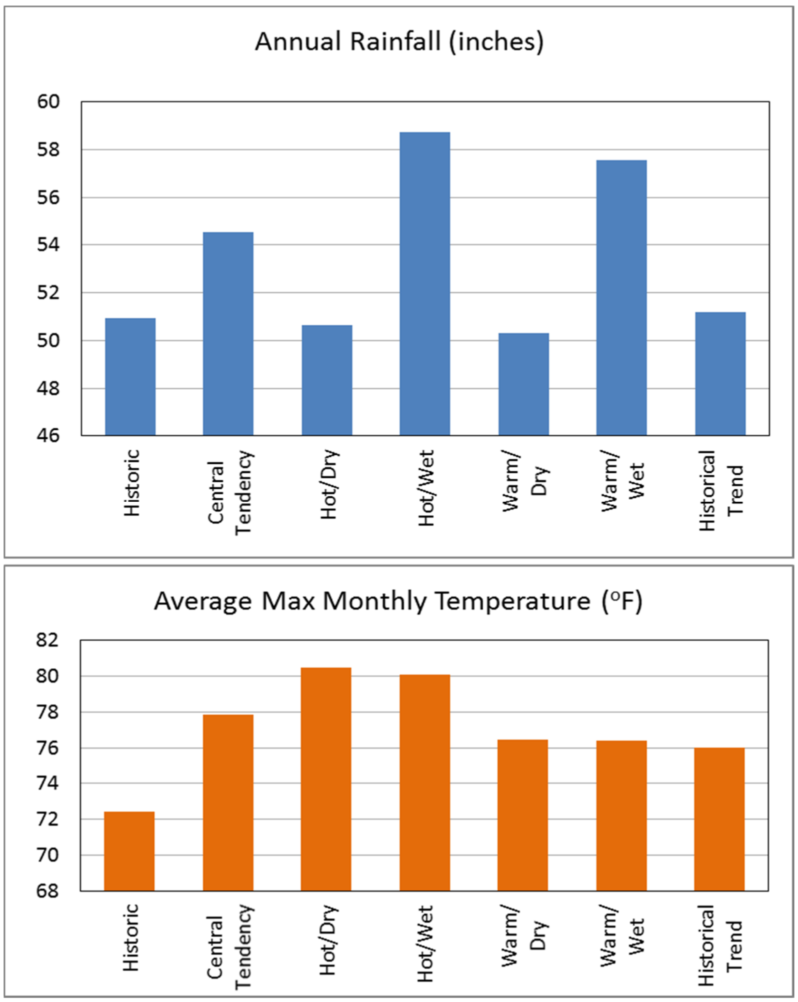


Figure 4.1.2 Comparing Monthly Weather and Future Climate Scenarios

Figure 4.1.3 shows the potential impacts that the climate scenarios have on water demands, all other factors remaining the same. The potential impacts from climate on water use range from 1.3 percent (historical trend climate) to 3.8 percent (hot/dry climate scenario) by 2050. This means that if nothing else changed except for climate, water demand could be between 1.3 and 3.8 percent higher by 2050 on an annual basis. The majority of this increased demand would be expected to occur during the summer months.

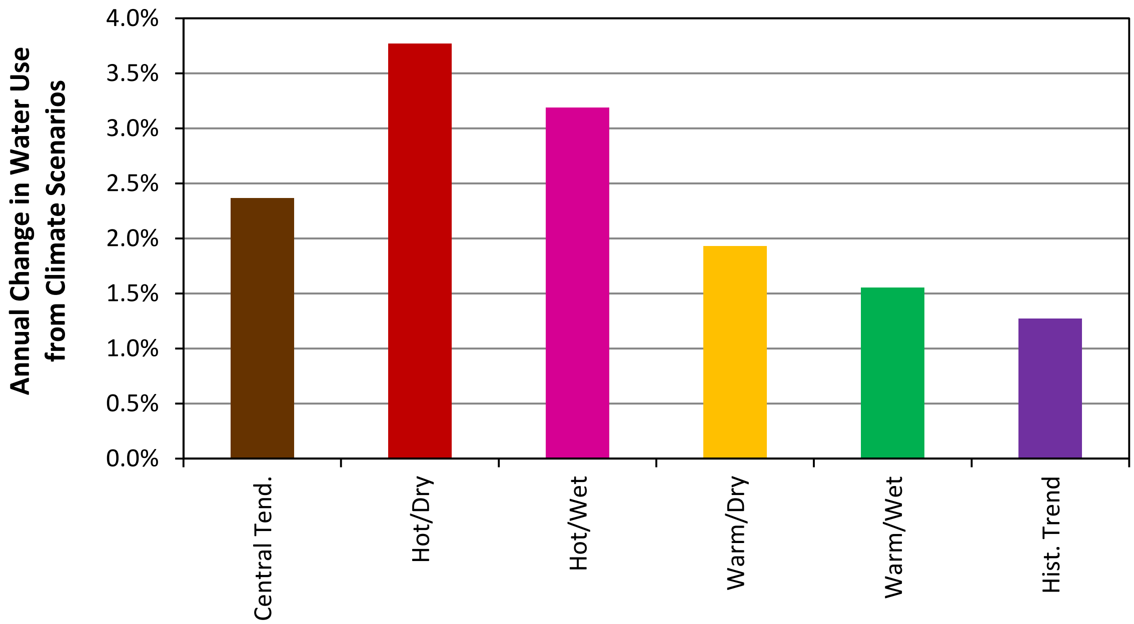


Figure 4.1.3 Potential Impacts on Water Demand from Climate Scenarios in 2050

4.2 Potential Impact to Water Supply

4.2.1 Review of Objectives

The fundamental goal of modeling the selected water supply reservoirs is to determine if possible future climate conditions could affect the firm yield or reliability of these reservoirs. More specifically, these models helped determine how much of the current yield of the reservoirs may be at risk, and what climate trends could alert planners of any potential increases or decreases in future yield. Small and mid-sized reservoirs were selected throughout the Metro Water District that are independently operated by single-purpose utilities primarily for water supply.

Because the output is not intended for permitting purposes but rather for a relative study of current and future conditions, it is not essential that firm yield estimates exactly match other published values, or carry an inherent precision on the order of 0.1 mgd as is often inferred from firm yield studies. Rather, it is important that estimates of current yield be reasonably close to published values in order to establish a credible baseline from which to evaluate potential relative changes due to possible future climate conditions.

For the purposes of this assessment, the following definitions are offered:

- **Firm Yield** = the rate of water withdrawal from a reservoir that can be sustained continuously through the period of record (including the severe drought in the 1950s) without depleting storage.
- **Reliability** = a percentage of the time at which a given level of withdrawal could be achieved. In this study, firm yield has an equivalent reliability of 100 percent, and we also evaluate the amount of water that could be withdrawn successfully 95 percent of the time (95 percent reliability).

Lastly, we examine whether or not the physical or hydrologic features of the reservoirs or their contributing watersheds are indicative of potential vulnerability to future climate scenarios.

In summary, the objectives of this aspect of the vulnerability assessment were to answer the following questions:

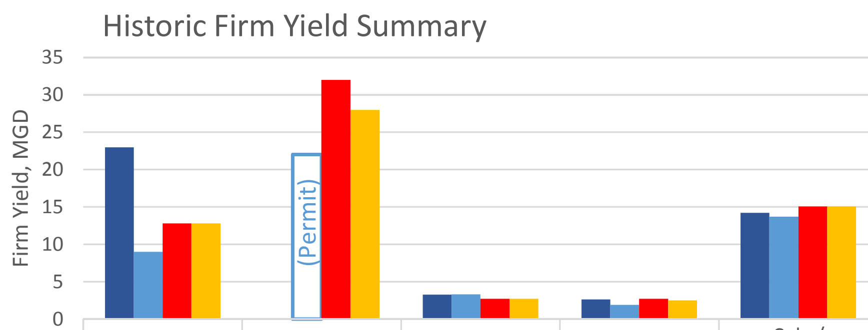
1. What impacts could the possible future climate scenarios have on firm yield?
2. What impacts could the possible future climate scenarios have on 95 percent reliable yield?
3. What aspect of the future climate, precipitation or temperature, is a better indicator of changes in yield?
4. Are there physical or hydrologic features of the reservoirs or their watersheds that could help indicate future risks or changes?

4.2.2 Validation of Historic Yield Estimates

While it was not an explicit objective of this analysis to match previously published firm yield values for the five reservoirs, the baseline values simulated in this study using historic (unadjusted) climate conditions and streamflow were compared against available published information on reservoir yield. Values for the three Henry County Reservoirs (Gardner, Long Branch, and Cole/Upper Tawiliga) were obtained for comparison from the *Henry County Water Authority Long Range Water Supply Plan Update, Section 3.* Values for the Dog River Reservoir were obtained for comparison from *Hydraulic Budget Models: Dog River Reservoir & Bear Creek Reservoir, Black and Veatch Project No. 179756 (July 2013).* Published values of the firm yield of Randy Poynter Reservoir were not immediately available, but it is know that the permitted withdrawal from that reservoir is 22.1 mgd, and this is shown in the figure as a reference value.

Firm yield values were estimated with the spreadsheet models described in **Section 3.2.5.** Historic estimates of monthly runoff (described above), surface precipitation, and surface evaporation were used for the baseline estimates of firm yield. Annual average withdrawal was increased until the demand for at least one month in the simulation could not be satisfied due to depletion of storage.

Figure 4.2.1 illustrates the results of this comparative validation. Generally, the objectives for this comparison were achieved. The historic firm yield values simulated in this study are in reasonably good agreement with other published values of firm yield for these reservoirs. In some cases, recent post-2000 droughts have been more severe than the drought of the 1950s (while climate conditions may be homogenous across a region, the *impacts* of droughts on water supply reservoirs are usually very specific to individual systems and their characteristics). But in general, the firm yield values estimated with the data and assumptions of this study are very close to, or fall within the range of, previously published values of firm yield for these reservoirs. With this affirmation in place, the next step was to examine the potential impacts of future climate scenarios on these estimated firm yield rates.



	Dog River Reservoir	Randy Poynter Reservoir	Gardner Reservoir	Long Branch Reservoir	Cole / Upper Tawiliga Reservoir
Published: 1950s	23		3.29	2.63	14.21
Published: 2000-2013	9	22	3.34	1.9	13.71
This Study: 1950s	12.8	32	2.7	2.7	15.1
This Study: 1950-1999	12.8	28	2.7	2.5	15.1

Figure 4.2.1 Comparison of Simulated Yield with Previously Published Values*
*Henry County published values include both Upper and Lower Tawiliga Reservoirs, but it appears that the majority of the storage and yield originates from Upper Tawiliga (Cole) Reservoir.

4.2.3 Comparative Impacts of Climate Scenarios

Once the baseline historic values of firm yield were established for each reservoir, the streamflow and evaporation timeseries were adjusted using the climate regression models and process discussed earlier. Also, the surface precipitation timeseries associated with the possible future climate scenarios were input into the models. Once the streamflow, surface evaporation, and surface precipitation were adjusted, the firm yield was recomputed for each reservoir, and this process was repeated for each of the six climate scenarios.

Figure 4.2.2 illustrates the findings, and shows that the future climate scenarios could impact the firm yield either positively or negatively, but the magnitude of the changes would not be extreme. The results are fairly intuitive – the two wetter scenarios lead to increased firm yield, the two drier scenarios would tend to produce slightly less firm yield, and the effects of the Central Tendency scenario are fairly muted, as are results for the Trend Projection. It is not surprising to see the large percent increase in firm yield for Dog River and Gardner Reservoir for the wetter scenarios – these reservoirs have the highest ratio of drainage area to storage volume, and hence can refill (and stay full) more readily than the others.

Also, the impacts of climate trends are somewhat buffered by storage. While increasing temperatures (common to all scenarios) would tend to amplify the reductions in streamflow because of additional soil evaporation, such impacts would be more pronounced over short-duration periods and are not likely to have a pronounced effect on yield. Reservoir yield typically results from longer-term hydrologic trends, and one wet event can quickly compensate for short-term extreme stress in the stream network by replenishing storage.

Figure 4.2.3 presents the same results on a relative basis, showing the percent change in yield for each scenario and each reservoir. On the far left side of the graph, the two sets of columns represent changes in average monthly rainfall associated with each climate scenario, and changes in the 5^{th} percentile of annual rainfall (intuitively correlated with low-flow but not extreme low flow, which can be a good indicator of risks to firm yield). Generally, most of the yield results vary within the same relative ranges as the precipitation statistics, again suggesting that precipitation is the primary driver of reservoir yield.

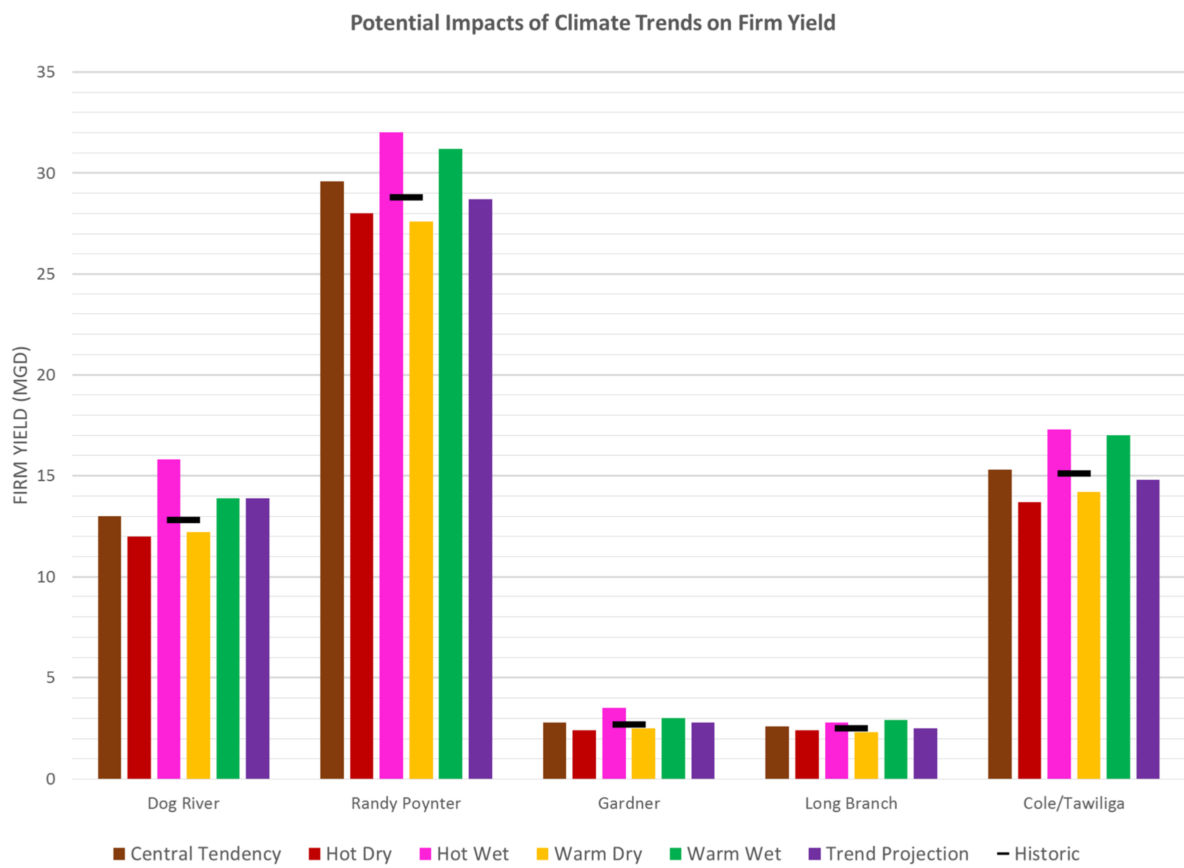


Figure 4.2.2 Firm Yield Sensitivity to Future Climate Scenarios

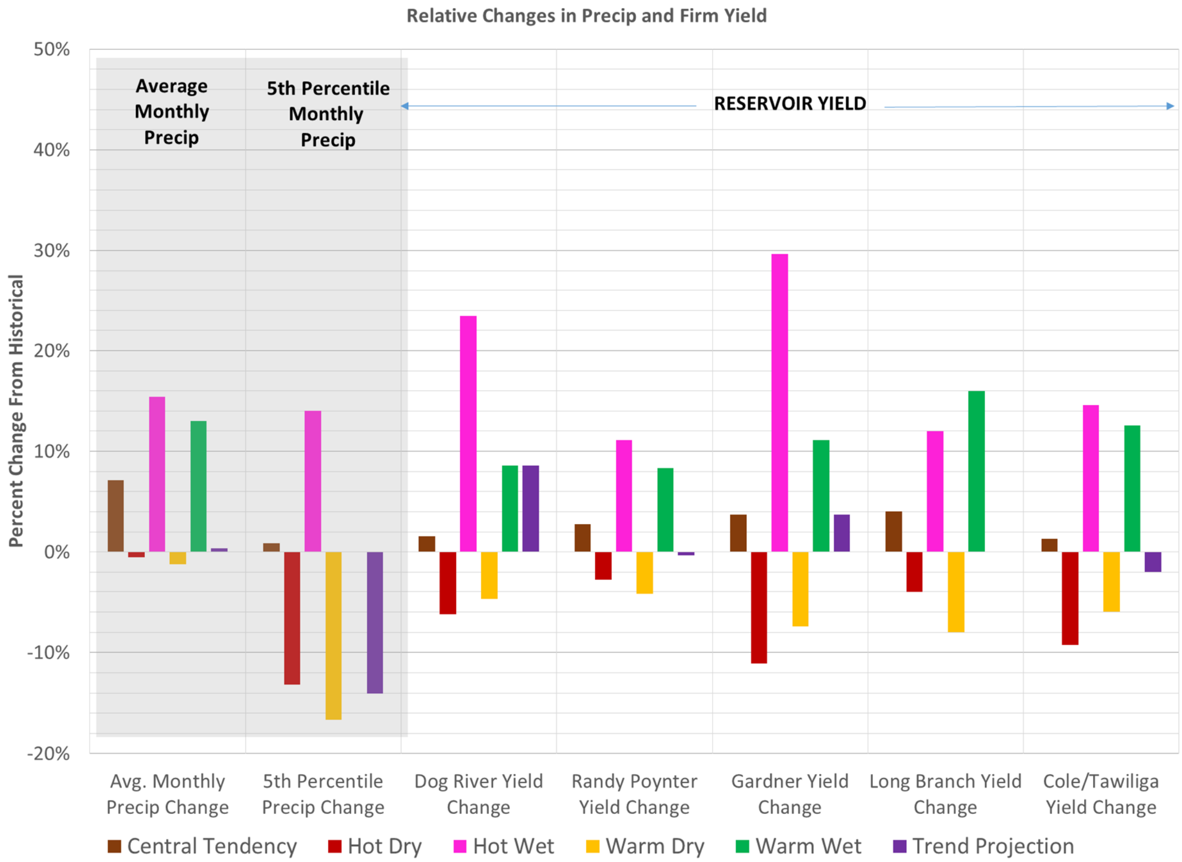


Figure 4.2.3 Relative Changes in Firm Yield Associated with Climate Scenarios

In addition to the vulnerability of the firm yield of the reservoirs, this study also evaluated potential changes in the 95 percent reliable yield rate, or the rate at which water could be successfully extracted from these reservoirs over 95 percent of the months in the 50-year simulation period. In simulation models, when reservoir systems are allowed to be occasionally depleted for experimental purposes only, the allowable withdrawal rate during times of plenty is higher than the firm yield. **Figure 4.2.4** illustrates the simulated 95 percent reliable yield for three representative reservoirs, and for the two climate scenarios with the largest positive and negative impacts on the firm yield. As expected, the wetter scenario would likely result in an increase in reliable yield, while the drier scenario would tend to slightly decrease water availability.

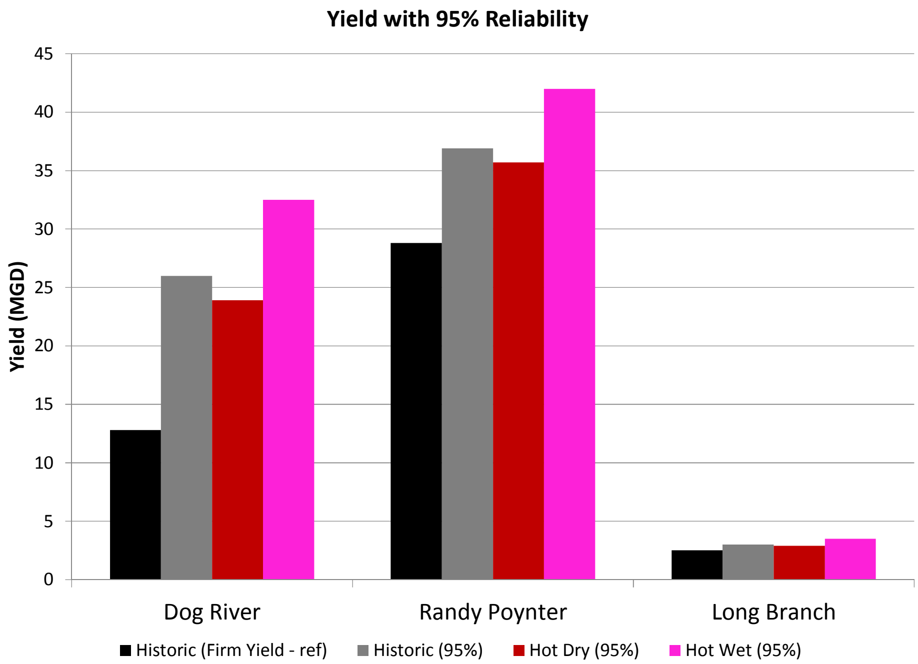


Figure 4.2.4 Potential Changes in 95% Reliable Yield Associated with Climate Scenarios

Lastly, the changes in firm yield were compared against watershed and reservoir characteristics to determine if trends in the impacts of climate scenarios on firm yield could be related to physical or hydrologic features. Features that were tested for relationships to the trends in yield included:

- Reservoir volume
- Watershed drainage area
- Percent of the watershed that is developed
- Percent of the watershed that is impervious
- Average inflow
- Residence time in the reservoir
- Ratio of drainage area to reservoir storage

Of these, drainage area, average flow, and the ratio of drainage area to reservoir storage exhibited the highest potential correlation values with yield changes, but even these were isolated to one or two climate scenarios, and the correlations were not very informative because the trends were fairly flat and sometimes contradictory (for example, the two wet scenarios show one positive and one negative correlation for all three of these physical variables). **Figures 4.2.5** and **4.2.6** summarize these findings, and are reasonably representative of the other variables tested.

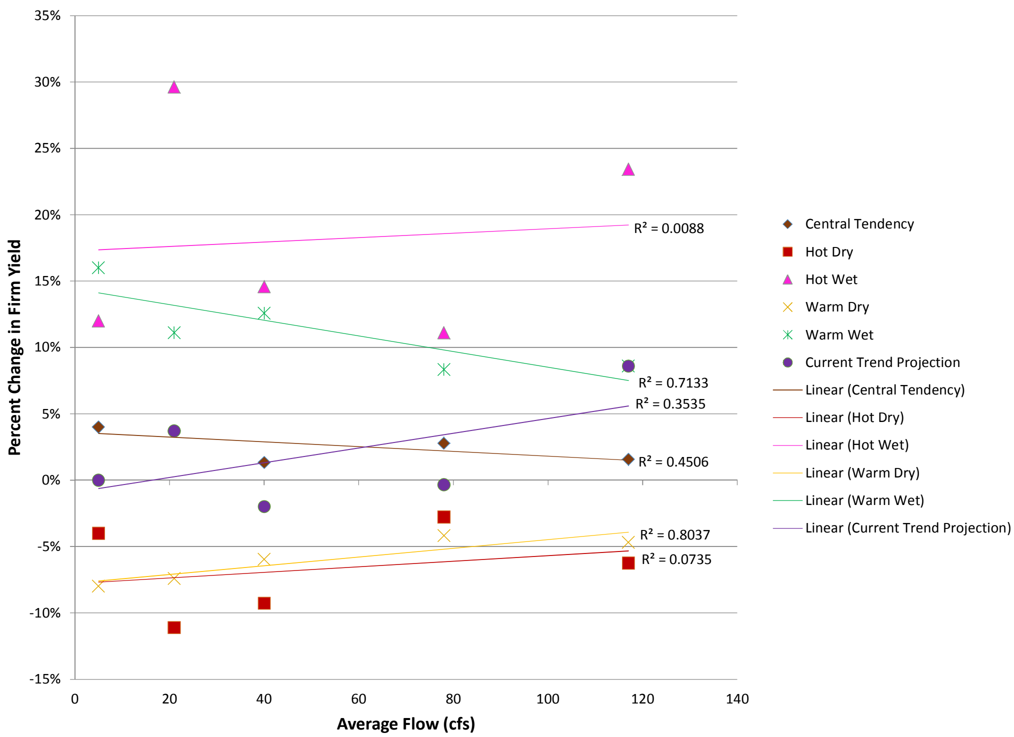


Figure 4.2.5 Correlation Between Yield Changes and Average Flow

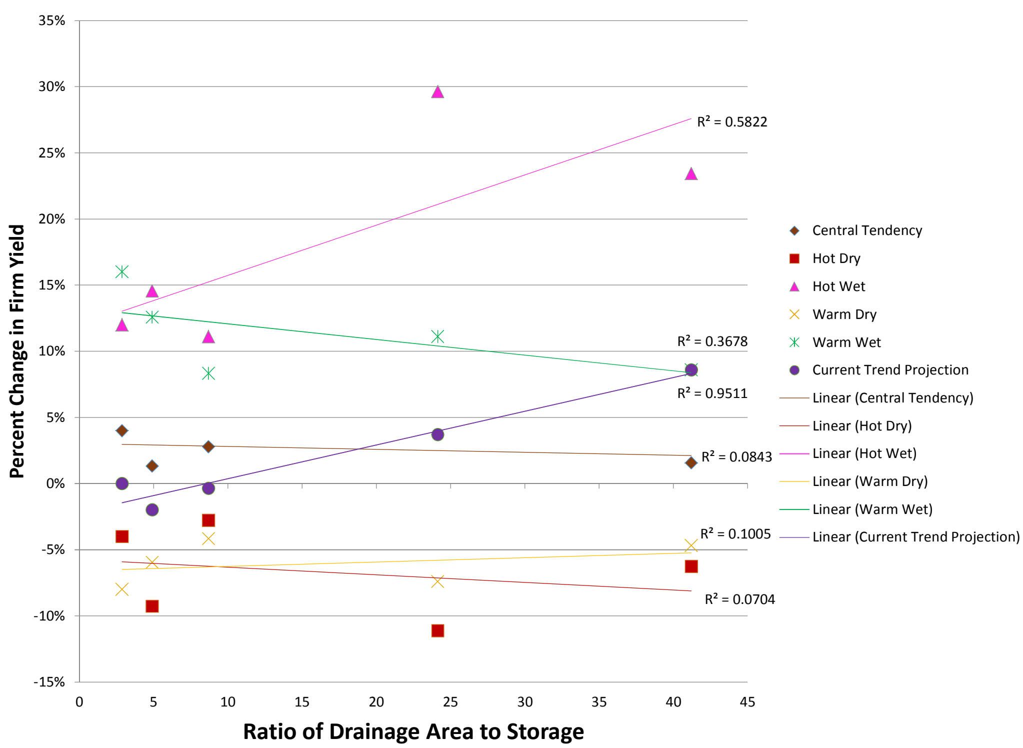


Figure 4.2.6 Correlation Between Yield Changes and Ratio of Drainage Area to Storage

4.3 Potential Impacts to Water Quality

It is well established that the quality of streams and lakes is highly sensitive to both temperature increases and changes in flow regime and consequently will be impacted by climate change. Higher water temperatures can be lethal to key freshwater biota. Higher temperatures also lead to increased pollutant oxidation rates and lower dissolved oxygen (DO) saturation levels, both of which result in decreased DO concentrations. Increased nuisance algal growth rates are also a concern with higher water temperatures. These problems are all exacerbated by lowered flow rates, which increase reach residence times and decrease dilution and assimilative capacities.

In the task described here, an integrated modeling approach was applied to quantify potential impacts of future climate variability on river water quality, specifically DO levels and water temperature, for four case study streams. In line with other vulnerability tasks described above, the focus of this evaluation was on the projection of *relative*, rather than absolute, water quality impacts.

4.3.1 Review of Objectives

The future climate scenarios described in **Section 2** were used to investigate potential impacts on river water quality due to future climate variability. The specific objectives of this task were to:

- Evaluate the potential impacts of future climate scenarios on river water temperature and dissolved oxygen levels;
- Assess water quality sensitivities across a range of hydro-climate conditions and watershed physical characteristics; and
- Consider the implications of this work with respect to future discharge permitting and stream health.

It was *not* an aim of this task to quantify future absolute DO or temperature values specific to a given study site or to establish likelihoods or probabilities of occurrence. There was not enough site specific data analysis or model calibration to support such an objective. Rather, the work should be viewed as a sensitivity analysis where potential vulnerabilities were identified and quantified on the basis of projected relative changes.

4.3.2 Results and Discussion

Results are presented in terms of projected changes in flow and water quality relative to historical baseline model simulations (i.e. modeled future vs. modeled baseline). This approach reduces concerns about model bias or error due to the lack of site specific calibration and is consistent with the “delta” methods applied elsewhere in this study.

The first set of results (**Figure 4.3.1**) shows projected changes in 7-day annual low flow with a 10 year recurrence interval (7Q10) for each of the six climate scenarios, relative to historical baseline flows. Also included, for reference, are the original baseline 7Q10 values calculated from observed flow data. The flow change factors shown were generated using the empirical regression hydrologic models developed for each study basin, as a function of various combinations of long term precipitation and short term temperature projections, as described in **Section 3**. For three of the four case study basins, all six of the climate scenarios result in decreases in late summer low flow. This is despite the fact that a majority of the scenarios project a general *increase* in precipitation. Clearly, the impacts of increasing temperature projections, as captured by the multivariate regression model, out-weigh the impacts of increasing annual precipitation. Quantified decreases range from -7 percent to -100 percent (complete dry up) across the basins and climate scenarios. For the fourth basin (Yellow River), results are mixed. Three of the six scenarios (Hot/Dry, Warm/Dry, and the Historical Trend Projection) result in small decreases in 7Q10, while the other three result in small increases. In general, results for the Yellow River basin suggest minimal sensitivity in summer low flow in this basin to the projected climate scenarios.

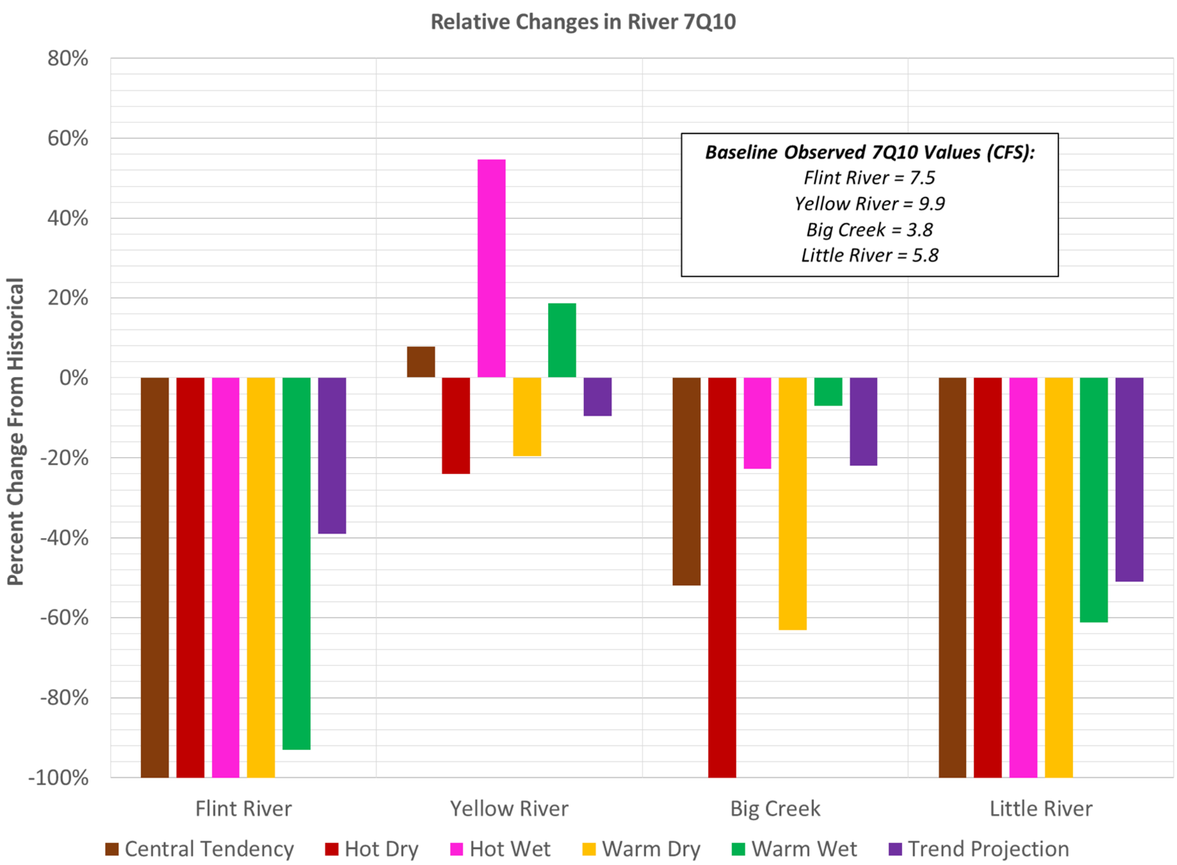


Figure 4.3.1 Projected Changes in River Flow (7Q10)

Note that the projected changes in river low flow presented in **Figure 4.3.1** were applied, in subsequent steps, only to the "naturalized" flow in the water quality models. Changes were not made to the wastewater treatment plant effluent discharge portions of flow in the models, which were assumed to remain constant in the future (i.e. insensitive to climate variability). This is clearly a simplification, as we can surmise that such discharges would indeed change as source water availability and water use change in the future. However, quantifying such changes was outside the scope of the current study.

The second set of results (**Figure 4.3.2**) shows modeled water temperature changes, as predicted by the QUAL2K models. Water temperature changes are quantified in these models as a function of flow changes (**Figure 4.3.1**) and changes in late summer (September) air temperature. As expected, in nearly all scenarios, the models project increases in water temperature, as flows generally decrease and ambient air temperatures increase. Projected water temperature increases range from +0.1 to

+2.9 °F, resulting from projected changes in air temperature of approximately +4 to +7 °F. The upper half of this range agrees well with results from a recent publication that applied a similar methodology for a different part of the county (Cox et al., 2015) and quantified stream temperature changes in the range of 1 to 2 °F for a 2060 planning horizon and a suite of GCM projections. For one scenario and study reach combination (Big Creek, Historical Trend Projection), results indicate a very small *decrease* (-0.1 °F) in water temperature. However, this change should be considered insignificant in the context of the modeling performed here. The variability in stream temperature impacts shown in Figure 4.3.2, across study sites, can be largely attributed to differences in baseline low flow, hydrologic-climate elasticity, reach hydraulics (velocity and depth), and point source influences.

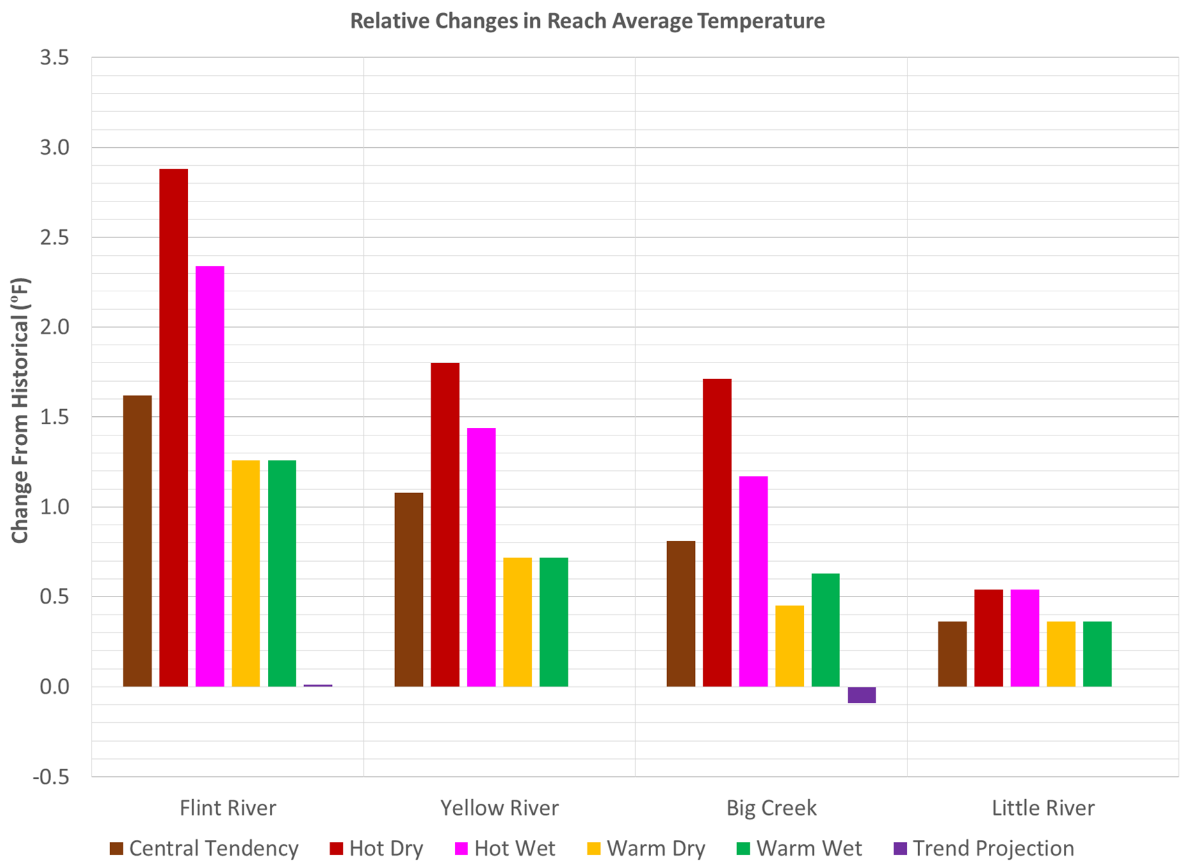


Figure 4.3.2 Projected Changes in River Water Temperature

The final set of results (**Figure 4.3.3**) illustrate the net impact of projected changes in flow and water temperature on reach average dissolved oxygen (DO) levels. In all but one of the scenario-study site combinations (Yellow River, Hot/Wet), we see projected decreases in DO levels. In other words, with near full consensus, water quality is projected to worsen in the future compared to the recent past. Projected DO reductions range from -0.1 to -1.4 mg L^{-1}. The very small increase in stream DO projected for the Yellow River, Hot/Wet scenario (+0.1 mg L^{-1}) is clearly a result of the relatively large flow increase projected for the reach under this scenario.

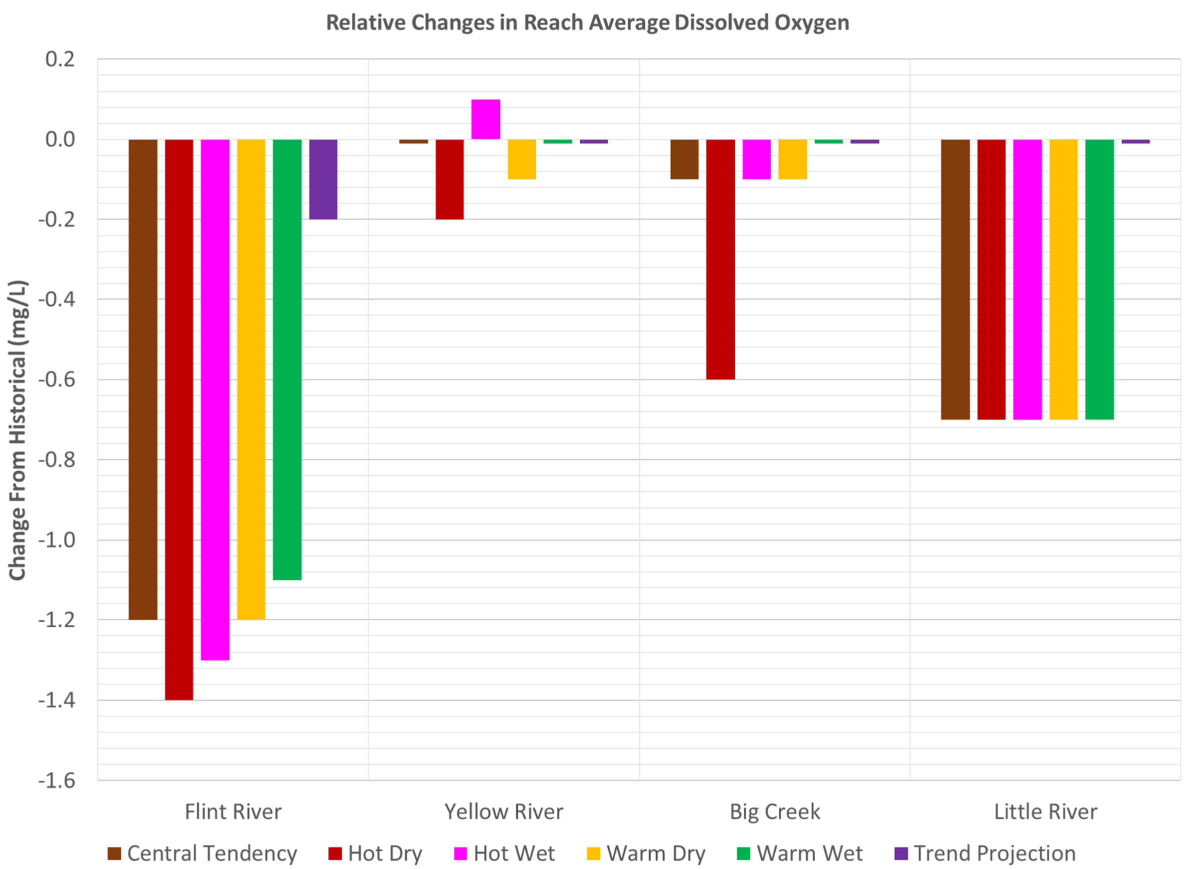


Figure 4.3.3 Projected Changes in River Dissolved Oxygen

Not surprisingly, the sites with the largest projected flow reductions (Flint and Little River) also exhibit the greatest reductions in DO. However, the direct impacts of air temperature change also play a role, as evidenced by the fact that the positive impacts of increased low flow for two of the Yellow River scenarios (Central Tendency and Warm/Wet) are fully offset by the negative impacts of air temperature increase – resulting in a zero net change in DO.

The largest of the projected changes in low flow (-100 percent) result in flows at the extreme end of low flows observed in the historical record. Some of the streams gages, however, do exhibit extreme 7 day low flows at or near zero and baseline observed 7Q10 values range from only 4 to 10 cfs. It therefore does not appear implausible that future 7Q10 values could drop to zero under hotter conditions. It is also important to keep in mind that the quantified flow changes were only applied to natural flows in this modeling exercise. Effluent flows were maintained at existing baseline levels for all future scenarios. In other words, a -100 percent flow factor did not result in a completely dry reach in the model, due to the point source effluent flow.

Differences in low flow sensitivity to climate variability across study sites are reflected in the site-specific hydrologic regression models. More specifically, the coefficient in the temperature term of the regression varies widely across site models. The greater the temperature coefficient, relative to the precipitation term coefficient, the greater the projected sensitivity to future climate variability (which is primarily a temperature change). A mechanistic explanation for this variability is beyond the scope of this study, but we can surmise that differences in soil drainage and land use across sites play an important role.

In terms of water temperature, modeled reach length clearly plays a large role in explaining variability across sites. Longer modeled reach lengths result in greater projected reach-averaged temperature changes. This is expected, as longer reaches allow for greater air-water interaction in the models. This result is largely trivial, however, since model reach lengths were set somewhat arbitrarily (based on previously developed water quality models). It does highlight the fact that headwater sites will likely be less vulnerable to climate variability, with respect to water quality, than downstream sites. The modeled variability in projected water temperature changes across climate scenarios, for a given site, appears to be nearly fully attributable to air temperature variability, rather than differences in projected flows. This is partly due to the significant effluent flows for each site (which were unchanged across climate scenarios). It is also reflective of the fact that we are simulating only daily average air and water temperatures, rather than diurnal fluctuations. We surmise that reduced stream flows would enhance diurnal fluctuations in water temperature, more so than impacting average temperatures, causing potentially larger increases in stream daily maximum temperatures. However, this dynamic is not captured in the simulations performed here.

The projected net changes in dissolved oxygen come with important implications for future discharge permitting. Clearly, for streams at or near full allocation with respect to oxidizing pollutants, the projected decreases in stream average DO (upwards of 1 to 1.5 mg L^{-1}) could affect water quality. The results imply that existing allocations to point source dischargers in these types of streams would no longer be protective of stream water quality, even with no other changes in watershed operations. More restrictive permitting may be required under such scenarios or additional efforts targeted at non-point source pollution. Further, the projected water temperature increases, by themselves, could affect sensitive cold water fish and macro-invertebrate species.

There are a number of limitations in the study performed here that should be noted. As described previously, site specific calibration of the water quality models was not performed as part of this study. We assume that the previously developed Dosag models were calibrated to some extent (e.g. pollutant oxidation rates) using site-specific data. However, this can’t be confirmed. The new QUAL2K water temperature models relied on default model parameterization with respect to heat and light constants. The models themselves are therefore a source of uncertainty that, in future studies, could be reduced through site-specific calibration.

Also as described above, point source discharges were assumed to remain unchanged, in terms of both flow rate and temperature, for future scenario simulations. This is obviously a simplification, as both parameters might be expected to change as a result of environmental and source water changes. Simplified handling of tributary inputs were also required for the work performed here. Uncertainties associated with these simplifications could be reduced in future studies with more holistic modeling approaches, at a watershed, rather than reach, scale.

Lastly, all modeling performed here focused on reach and diurnally averaged temperature and dissolved oxygen levels. Spatial variability in temperatures and concentrations, although simulated, could not be reported with confidence, nor was it necessary for this type of sensitivity analysis. Diurnal variability in both parameters can also be assumed to be significant, but was not captured in our steady state models. This includes DO variability due to aquatic plant photosynthesis and respiration and temperature variability due to daily air temperature and solar radiation cycles. Consequently, projected changes in maximum temperature, or minimum DO levels, for example, were not quantified, despite the fact that they may be of greater concern than the changes in average values reported here.

4.4 Potential Impacts to Watershed Planning Issues

For the purposes of this study, climate variability impacts that affect watershed issues include storm intensity, peak streamflows, flooding, and nonpoint source pollutant loads. Projected climate variability is an important factor to consider during watershed planning. While historical data are essential in understanding current and future climate, nonstationarity in at least some of the data (i.e. a changing climate) dictate the use of supplemental information in long-term planning studies. In other words, the past may no longer be a good predictor of the future (Milly et al., 2008).[9]

The list below identifies potential watershed impacts resulting from climate variability. This list is based on discussions with the Metro Water District, other watershed-based climate variability impact studies, and general watershed planning guidance documentation. The US Environmental Protection Agency's (EPA) Global Change Research Program has released several studies exploring the impact of climate variability on watershed systems[10] [11]. EPA provides a handbook for developing watershed plans, which identifies planning issues pertinent to protection and restoration of local surface water resources[12]. Future watershed planning may include studies to assess the impact of climate variability on these same traditional watershed planning objectives.

Potential Watershed Impacts from Climate Variability

- Pollutant loading
- Habitat quality and biodiversity
- Sedimentation
- Erosion
- Stream morphology
- Flooding
- Public access and recreation
- Floodplain connectivity
- Base flow
- Wetlands
- Hydraulic connectivity
- Riparian buffer and shading
- Fisheries

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[9] Milly PC, Dunne KA, Vecchia AV, 2005. Global pattern of trends in streamflow and water availability in a changing climate. Nature 438:347-350.

[10] US EPA, 2012. Climate and Land-Use Change Effects on Ecological Resources in Three Watersheds: A Synthesis Report.

[11] US EPA, 2013. Watershed modeling to assess the sensitivity of streamflow, nutrient and sediment loads to potential climate change and urban development in 20 U.S. watersheds.

[12] water.epa.gov/polwaste/nps/handbook_index.cfm

4.4.1 Storm Frequency and Intensity

4.4.1.1 Objectives

To quantify changes in frequency and intensity of storm events, trend analysis of climate projection models and historical weather data was performed. This analysis resulted in identification of statistically significant changes in 24-hour storm event frequency and intensity for the 2050 planning horizon relative to the recent past. By 2050, one-day extreme rainfall depths are projected to be five to ten percent higher relative to 20th century conditions, according to estimates presented in EPA's Climate Resilience Evaluation and Awareness Tool (CREAT).[13] This increase concurs with the IPCC (2014), which indicates that "Extreme precipitation events over most mid-latitude land masses and over wet tropical regions will very likely become more intense and more frequent as global mean surface temperature increases."[14] The objective of this analysis is to quantify how climate variability may impact storm depths of varying average recurrence intervals (ARI). The storm frequency and intensity results will also be used to assess climate variability impacts to peak streamflows.

4.4.1.2 Comparative Impacts of Climate Scenarios

Storms in the future may not follow the same patterns as storms of the past. Larger storms may occur more often, which would result in greater ARI depths. In other words, the storm depths at the bottom of **Table 3.4.1** may increase in the future. Planners will need to account for more rain when meeting the same design requirements (e.g. the 10-year, 24-hour storm). EPA's CREAT software was used to project 5-, 10-, and 25-year ARI rainfall. As described in the next section, one to four day rainfall correlates well with daily peak flow records. **Table 4.4.1** shows projected frequency estimates, reflecting the projected 2050 storm totals for three scenarios offered by the tool: hot/dry, median, and warm/wet. These scenarios are similar to those used in the rest of this study, but were developed by EPA for CREAT from a subset of models in the Coupled Model Intercomparison Project Phase 3 (CMIP3) dataset. The CREAT scenarios are:

- Hot and dry model projection – model nearest the 5th percentile of precipitation and 95th percentile of temperature projections (larger increase in temperature with lower total precipitation)
- Central model projection – model nearest the 50th percentile of both precipitation and temperature projections (central condition, among models, for temperature and total precipitation)
- Warm and wet model projection – model nearest the 95th percentile of precipitation and 5th percentile of temperature projections (smaller increase in temperature with larger total precipitation)

Figure 4.4.1 shows a visual comparison of the projections.

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[13] EPA, 2013. Climate Resilience Evaluation and Awareness Tool. http://water.epa.gov/infrastructure/watersecurity/climate/creat.cfm

[14] Intergovernmental Panel on Climate Change (IPCC), 2014. Fifth Assessment Synthesis Report. www.ipcc.ch/pdf/assessment-report/ar5/syr/SYR_AR5_LONGERREPORT.pdf

Table 4.4.1 Projected 2050 Storm Depths for Various Recurrence Intervals and Durations

Average Recurrence Interval (y)	Climate Scenario	Rainfall (in) 1-day	2-day	3-day	4-day
5	Historic	4.5	5.4	5.7	6.1
	2050 Hot/Dry	4.7	5.6	6.2	6.6
	2050 Median	4.6	5.4	6.0	6.4
	2050 Warm/Wet	4.7	5.5	6.1	6.5
10	Historic	5.2	6.2	6.6	7.0
	2050 Hot/Dry	5.5	6.5	7.1	7.7
	2050 Median	5.2	6.1	6.7	7.2
	2050 Warm/Wet	5.3	6.3	6.9	7.4
25	Historic	6.1	7.4	7.9	8.3
	2050 Hot/Dry	6.6	7.8	8.6	9.3
	2050 Median	6.0	7.1	7.8	8.4
	2050 Warm/Wet	6.3	7.5	8.2	8.8

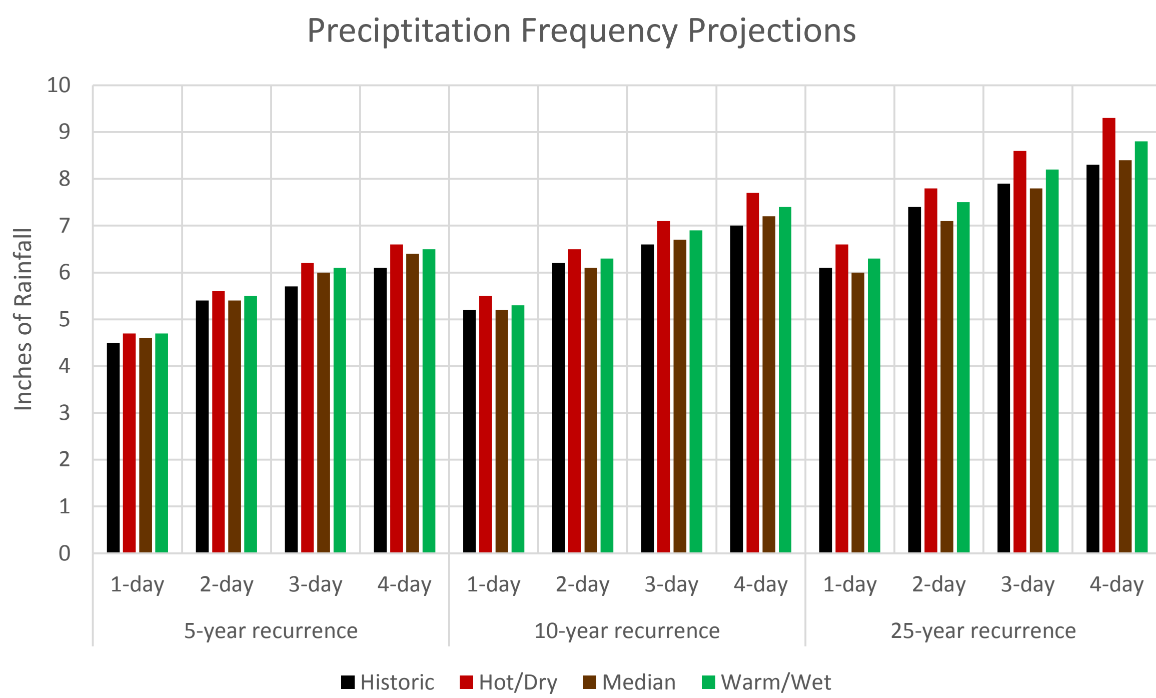

Figure 4.4.1 Projected 2050 Storm Depths for Various Recurrence Intervals and Durations

The Hot/Dry scenario results in the largest increases in projected ARI depth, ranging from 4 percent to 12 percent increases from the historic totals. The largest projected increase is for the 25-year, 4-day rainfall, which is projected to increase 12 percent from 8.3 to 9.3 inches of precipitation. The Median climate scenario projects decreases as well as increases in ARI depths, ranging from a 2 percent decrease to a 5 percent increase from the historic totals. In all three scenarios, longer duration depths are projected to increase more than shorter duration projections. **Figure 4.4.2** illustrates these findings, showing the percent increase for each duration, recurrence interval, and scenario. While it may be counterintuitive that the drier scenario produces the largest increase in storm depths, this highlights the potential for changing precipitation patterns where rain is less frequent on an annual average basis but occurs in more intense storms. Similarly, the fact that some of the larger storms under the median climate scenario (10 and 25-year recurrence) are projected to decrease in the future compared to the historical baseline, despite an overall projected increase in annual precipitation, implies more frequent, but less intense, rainfall patterns under this scenario.

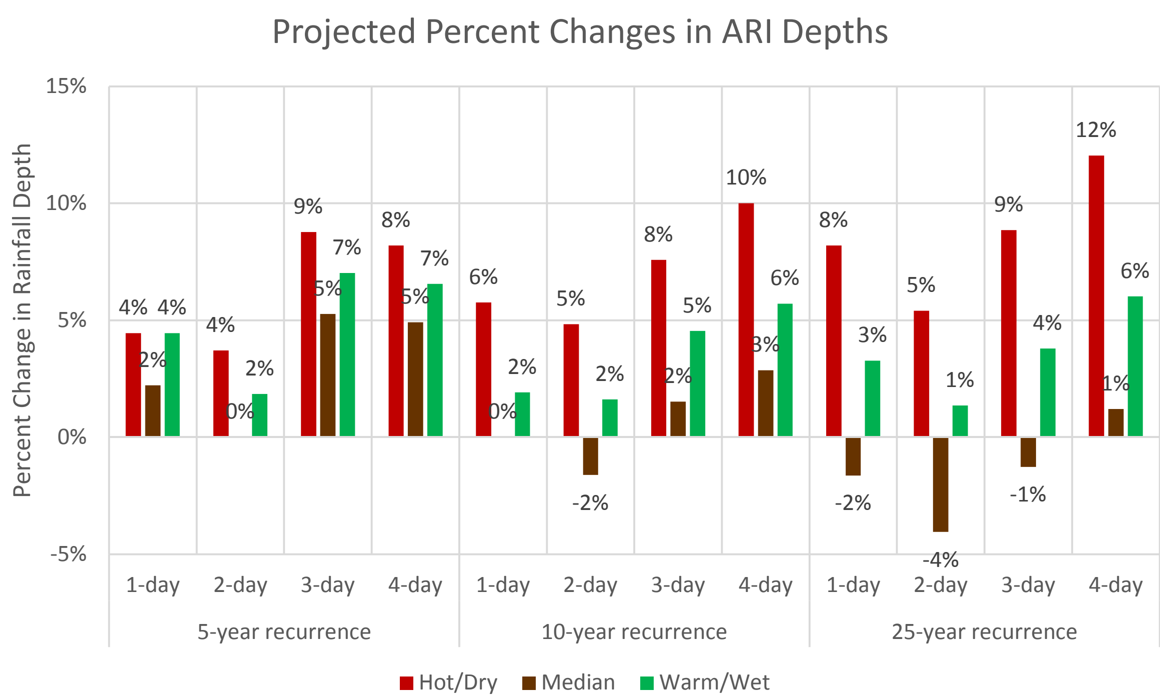

Figure 4.4.2 Projected Change in ARI Depths from Historic Observations to 2050

4.4.2 Peak Streamflow Analysis

4.4.2.1 Objectives

The peak streamflow analysis estimates the potential for increased streamflows, and therefore increased risk of flooding and erosion, from future climate variability. The objective is to relate the results of the rainfall frequency and intensity analysis to peak streamflow levels as a method of estimating the potential impacts of climate variability on flooding potential.

4.4.2.2 Comparative Impacts of Climate Scenarios

The regression models were applied using projected one through four day precipitation events to estimate the potential increase in peak flows due to climate variability. The results are presented as percent-change to provide an overall assessment of the potential streamflow increases rather than a prediction of future streamflows.

Figure 4.4.3 shows the results of applying the peak flow regression models (Equations 3.4.1 and 3.4.2) using one to four year storm event precipitation totals developed with EPA's CREAT, which estimates future storm statistics considering climate variability. The percentages reflect the difference between modeled peak streamflow using historic storm totals and modeled peak streamflow using projected storm totals for the three climate variability scenarios.

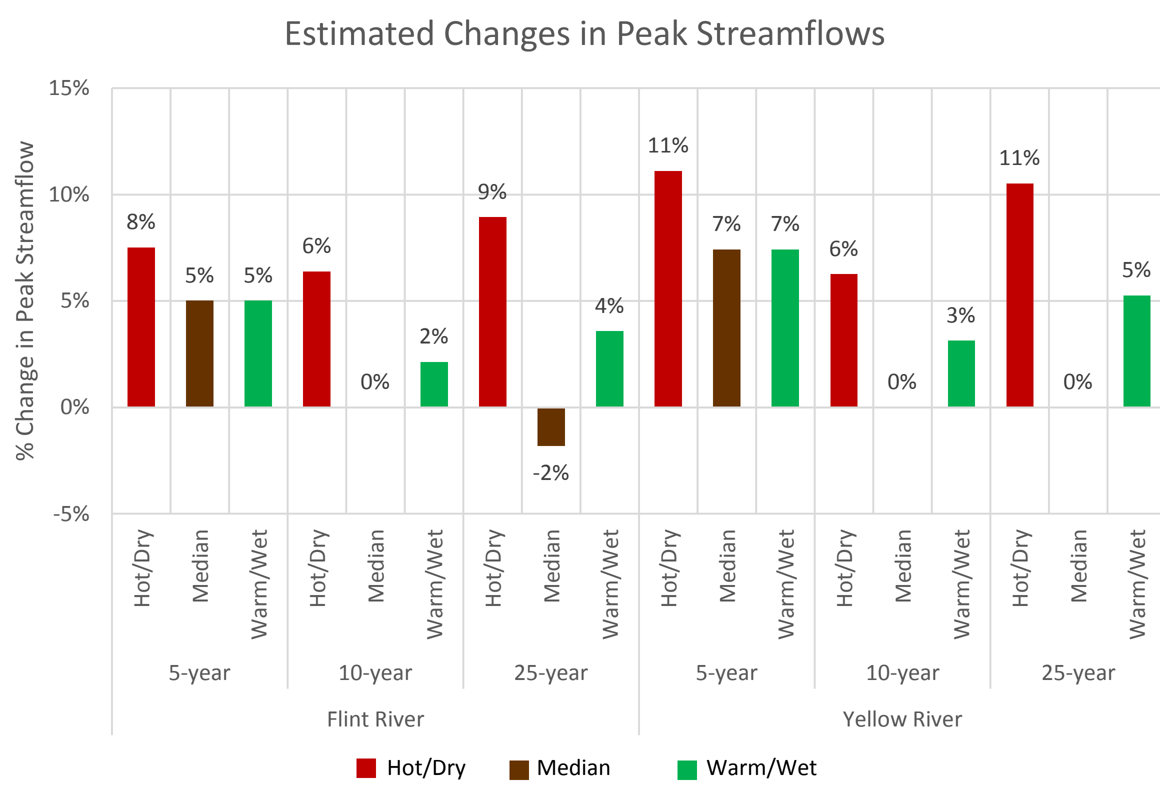

Figure 4.4.3 Estimated Change in Peak Streamflows for Various Intensity and Duration Storms Due to Climate Variability

These analyses suggest that peak streamflow may increase as much as 11 percent as a result of climate variation. Estimated peak streamflow increases are highest for the hot/dry CREAT scenario. The hot/dry scenario projects the largest change in precipitation totals (Figure 4.4.2) and yields the largest estimated increase in peak streamflow. The regression model predicts that the five-year recurrence interval rainfall for all three scenarios will cause increased peak streamflow in the Flint and Yellow Rivers compared with historic storm peak flows. For the 10- and 25-year rainfall, the median climate scenario predicts no change or a slight decrease in peak streamflows in both rivers.

4.4.3 Watershed Loading Analysis

4.4.3.1 Objectives

Annual and monthly average pollutant loading were modeled using land use data, projected rainfall totals, and event mean concentrations (EMCs). This is a coarse approach to estimating nonpoint source pollutant loading from watersheds. Other, more detailed models that simulate build-up and wash-off of pollutants over time may give a more refined estimate of watershed loading. However coarse, the EMC method has been widely used in watershed planning and is appropriate for determining the impacts of climate variability on seasonal watershed loads.

The watershed loading model uses average monthly precipitation totals to generate baseline and scenario monthly pollutant loading rates. The monthly time scale is valuable in determining if watershed loading changes are seasonal. Higher loading rates during the summer months may be of interest to future watershed management efforts, including nonpoint source reduction strategies and permitting of point source discharges.

Table 4.4.2 shows the mass loading results of the watershed models. These are coarse estimates and should not be used for permitting or regulatory decisions such as developing Total Maximum Daily Load allocations. The highest loading rates occur in March and the lowest in October, corresponding to the months with the highest and lowest rainfall totals. Changes to these monthly patterns due to climate variability will be explored in the next section.

Table 4.4.2 Baseline Watershed Pollutant Loading

Month	Fecal Coliform	Total Phosphorus	TKN	TSS	Copper	Lead	Zinc
	# colonies	*lbs*	*lbs*	*lbs*	*lbs*	*lbs*	*lbs*
Flint River							
Jan	4.98E+14	5,500	29,500	1.14E+06	330	350	2,670
Feb	4.72E+14	5,200	27,900	1.08E+06	310	340	2,530
Mar	5.50E+14	6,000	32,600	1.26E+06	370	390	2,950
Apr	4.25E+14	4,700	25,100	9.73E+05	280	300	2,280
May	3.94E+14	4,300	23,300	9.03E+05	260	280	2,110
Jun	3.81E+14	4,200	22,500	8.72E+05	250	270	2,040
Jul	4.86E+14	5,300	28,700	1.11E+06	320	350	2,600
Aug	3.59E+14	3,900	21,200	8.22E+05	240	260	1,920
Sep	3.59E+14	3,900	21,300	8.23E+05	240	260	1,920
Oct	3.07E+14	3,400	18,200	7.03E+05	200	220	1,640
Nov	3.55E+14	3,900	21,000	8.14E+05	240	250	1,900
Dec	4.20E+14	4,600	24,800	9.60E+05	280	300	2,250
Annual	5.01E+15	55,000	296,100	1.15E+07	3,340	3,570	26,810
Yellow River							
Jan	4.25E+14	4,700	26,100	9.88E+05	300	320	2,440
Feb	4.02E+14	4,500	24,700	9.36E+05	280	300	2,310
Mar	4.70E+14	5,200	28,800	1.09E+06	330	350	2,690
Apr	3.62E+14	4,000	22,300	8.43E+05	260	270	2,080
May	3.36E+14	3,800	20,700	7.82E+05	240	250	1,930
Jun	3.25E+14	3,600	20,000	7.55E+05	230	240	1,860
Jul	4.14E+14	4,600	25,500	9.63E+05	290	310	2,380
Aug	3.06E+14	3,400	18,800	7.12E+05	220	230	1,760
Sep	3.07E+14	3,400	18,800	7.13E+05	220	230	1,760
Oct	2.62E+14	2,900	16,100	6.09E+05	180	200	1,500
Nov	3.03E+14	3,400	18,600	7.05E+05	210	230	1,740
Dec	3.58E+14	4,000	22,000	8.32E+05	250	270	2,050
Annual	4.27E+15	47,600	262,300	9.93E+06	3,010	3,220	24,490

4.4.3.2 Comparative Impacts of Climate Scenarios

The watershed loading models were used to simulate the climate variability scenarios described in **Section 2** by adjusting the monthly precipitation totals from average historical to average projected. The changes in pollutant loading follow the trends of changing seasonal precipitation patterns in the projection scenarios. **Table 4.4.3** lists the percent change in loading, which is the same for all pollutants, for the six climate scenarios for each watershed. **Figure 4.4.4** shows the relative changes, where each bar is sized proportionally to the percent change in the table. Note that for the scenario based on the historic trend analysis, only precipitation in April and November was found to have a statistically significant trend which is why there are predicted pollutant loading impacts in these two months but not the others under this scenario.

Table 4.4.3 Relative Change in Watershed Pollutant Loading Due to Climate Variability

Month	Flint River						Yellow River					
	Central	Hot Dry	Warm Dry	Hot Wet	Warm Wet	Trend Analysis	Central	Hot Dry	Warm Dry	Hot Wet	Warm Wet	Trend Analysis
Jan	2%	0%	-6%	2%	10%	0%	2%	0%	-6%	2%	11%	0%
Feb	4%	2%	-2%	13%	13%	0%	4%	2%	-2%	14%	15%	0%
Mar	5%	2%	-4%	9%	16%	0%	5%	2%	-4%	10%	19%	0%
Apr	12%	-8%	3%	11%	11%	-38%	13%	-7%	3%	12%	13%	-28%
May	6%	-12%	-5%	13%	15%	0%	7%	-10%	-5%	15%	18%	0%
Jun	4%	3%	1%	28%	12%	0%	4%	3%	1%	38%	14%	0%
Jul	5%	-9%	3%	20%	11%	0%	5%	-9%	3%	26%	12%	0%
Aug	6%	-5%	-1%	19%	12%	0%	7%	-5%	-1%	23%	13%	0%
Sep	12%	3%	4%	20%	5%	0%	13%	3%	4%	25%	5%	0%
Oct	13%	1%	3%	7%	13%	0%	15%	1%	3%	8%	15%	0%
Nov	6%	2%	-4%	8%	10%	28%	6%	2%	-4%	8%	11%	40%
Dec	8%	11%	-5%	6%	9%	0%	9%	12%	-5%	6%	10%	0%
Annual	7%	-1%	-1%	13%	11%	0%	7%	-1%	-1%	15%	13%	0%

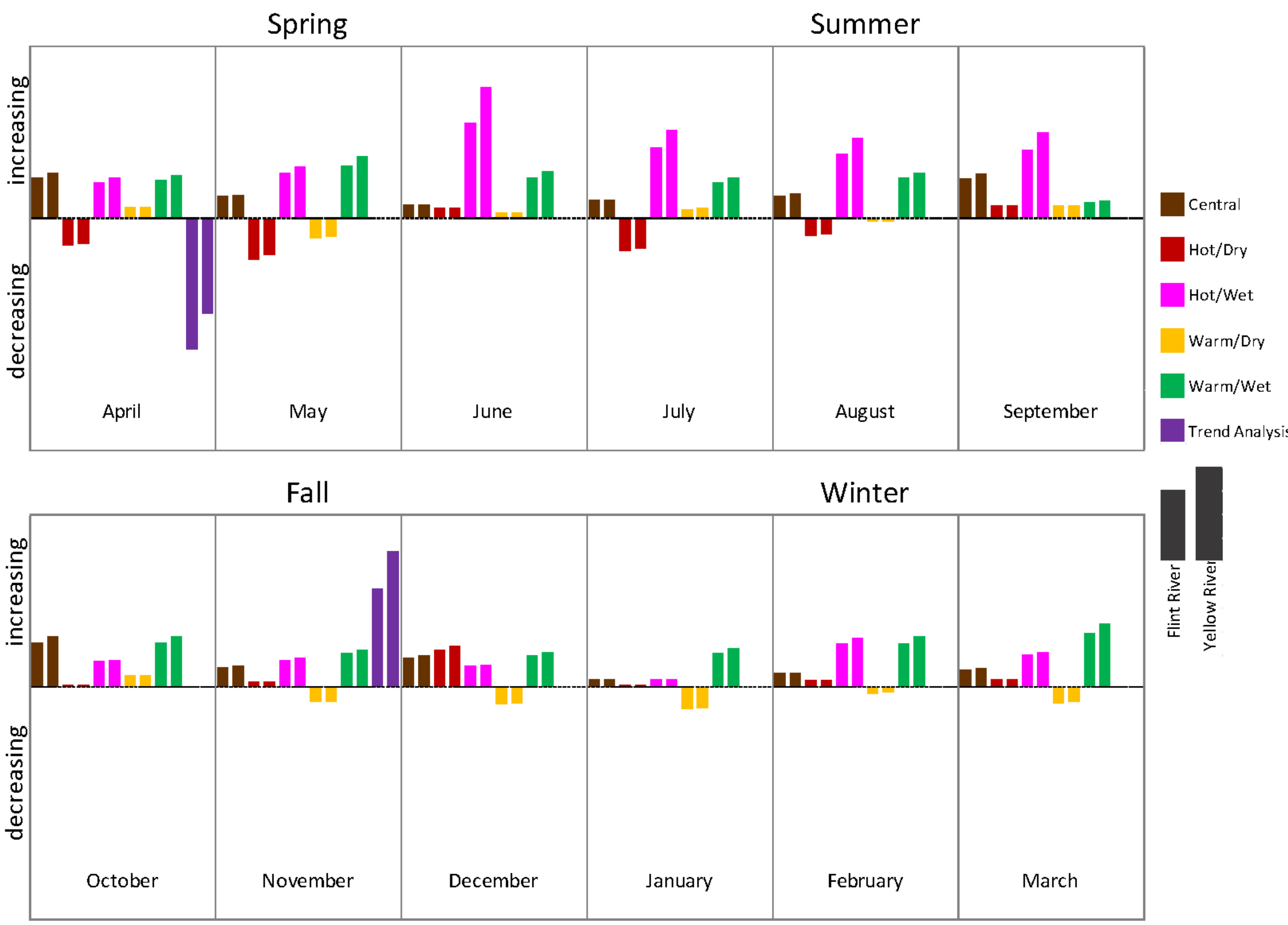

Figure 4.4.4 Relative Change in Watershed Pollutant Loading Due to Climate Variability

With a greater percent impervious cover, nonpoint source pollutant loading in the Yellow River watershed is more vulnerable to climate variability than the Flint River. This is evident in the larger increases in loading for the hot/wet and warm/wet scenarios. As land uses change throughout the region, watershed planners should be cognizant of the potential vulnerabilities introduced by increasing impervious land cover.

The different climate scenarios produce average annual precipitation changes between -1 and 15 percent change from the historic records. Additionally, the seasonal distribution of the precipitation is different for each scenario. The watershed loading model allows for the following observations of seasonal loading rate changes:

- **Central:** The average annual precipitation increases by 7 percent. The increased pollutant loading is well-distributed throughout the year with slightly more of the impact seen in April, September, and October. The maximum month load increase is in October: 13 percent for the Flint River and 15 percent for the Yellow River.

- **Hot/Dry:** The average annual precipitation decreases by 1 percent. The seasonal distribution of precipitation and loading changes dramatically, with the months of April, May, July, and August seeing decreases while December sees an increase. The other months are within 3 percent of the historical values, mostly showing small increases. The maximum month load increase is in December: 11 percent for the Flint River and 12 percent for the Yellow River.

- **Warm/Dry:** The average annual precipitation decreases by 1 percent. Each month sees a small change in loading between -6 and 4 percent. In this scenario, the seasonal variation in precipitation and loading is largely unchanged from the historic records.
- **Hot/Wet:** The average annual precipitation increases by 15 percent. Every month sees an increase in loading. The least significant increase is in January: 2 percent for both rivers. The maximum month load increase is in June: 28 percent for the Flint River and 38 percent for the Yellow River. The summer months, June through September, all see a significant increase in pollutant load in this scenario.
- **Warm/Wet:** The average annual precipitation increases by 13 percent. Every month sees an increase in loading and the changes are evenly distributed throughout the year. The range of changes in loading is 5 to 16 percent for the Flint River and 5 to 19 percent for the Yellow River. The increases are slightly less significant in the summer months, June through September.
- **Trend Analysis:** The average annual precipitation does not change (0.5 percent difference). There are only two months with projected precipitation changes: a 28 percent decrease in April and a 42 percent increase in November which are some of the largest monthly changes of any scenario. These changes translate into loading decreases of 38 and 28 percent for the Flint and Yellow Rivers in April, and loading increases of 28 and 40 percent for the Flint and Yellow Rivers in November. All other months have no predicted loading changes since the rainfall was not changed from the baseline for these months.

4.5 Potential Risks to Water Resource Infrastructure

The purpose of this exercise was to screen potential climate impacts to water resources infrastructure and determine potential risks in order to identify and prioritize the facilities with the greatest need of adaptation strategies. Existing and future climate variability has the potential to impact critical infrastructure related to water management in the District, including wastewater treatment plants, water treatment plants, stormwater conveyance systems, wastewater collection systems, and dams and levees. Discussion of the vulnerability assessment process is found in **Section 3**. Potential impacts to each water sector (water demand, water supply, water quality, etc.) are described in **Section 4.1** through **Section 4.4**. The results and trends from the water sector analysis is the basis for the qualitative assessment of water resources infrastructure presented in this section.

Selected impacts are evaluated for each infrastructure type: water demand, firm yield, dissolved oxygen, 24-hour storm depths, peak streamflow, and nonpoint source pollutant loads, as a result of the different climate scenarios. Water resources infrastructure may be vulnerable beyond these impacts, but additional conditions are not evaluated as part of this assessment. Results of this infrastructure assessment identifies the relative vulnerability of each of the critical water resources infrastructure types and may be used to identify potential adaptation strategies.

4.5.1 Definition of Matrix Terms

A vulnerability matrix is presented for each infrastructure type (wastewater treatment plants, water treatment plants, etc.). The five potential impacts to specific water sectors are listed for each infrastructure type. The associated climate scenarios (**Section 2**) are grouped by an increasing or decreasing trend based on the results for each impact. They are abbreviated to: Central Tendency (CT), Hot/Dry (HD), Hot/Wet (HW), Warm/Dry (WD), Warm/Wet (WW), and Historical Trend (HT). Since the 24-hour storm depths and peak streamflow impacts were developed using outputs from EPA CREAT, only the Hot/Dry, Central Tendency (or Median), and Warm/Wet climate scenarios were evaluated.

Next, the sensitivity, adaptive capacity, and extent of impact are assessed from low to moderate to high in an attempt to answer the following questions for each impact.

1. Sensitivity: If no action is taken, how much will the climate impact worsen the stress on the facility?
2. Adaptive capacity: Is the system or operation already able to accommodate changes in climate? If so, is current adaptability likely to remain intact when the analysis year is reached? What is the ability of the facility to accommodate future impacts with minimum disruption or cost?
3. Extent of impact: How many facilities of this infrastructure type may be impacted by an increase or decrease of the impact?

Sensitivity	Adaptive Capacity	Extent of Impact
Low sensitivity	High adaptability	Few
Moderate sensitivity	Moderate adaptability	Some
High sensitivity	Low adaptability	All

The final column of the vulnerability matrix provides assumptions regarding potential impacts to the infrastructure type. For instances when a change in the potential impact is not expected to have an effect on the infrastructure type, the entry is grayed out.

4.5.2 Wastewater Treatment Plants

As part of the 2009 Wastewater Management Plan, it is anticipated that there will be 87 wastewater treatment plants within the District by 2035 (MNGWPD, 2009a). The vulnerability of wastewater treatment plants to the effects of climate scenarios was qualitatively assessed considering the wastewater treatment plant facility, inclusive of pumps, influent, effluent, and its receiving water body. Based on this assessment, wastewater treatment plants appear to be most vulnerable to increases in 24-hour storm depths and pollutant loads, as they are highly sensitive to an increase in these conditions with minimal adaptive capacity.

An increase in 24-hour storm depths may increase inflow and infiltration within the collection system, which may exceed wastewater treatment plant capacity, causing the potential for sewer overflows. This is especially an issue at any plants that still treat combined sewage. If storms occur more frequently as the result of increased 24-hour storm depths this may also result in the increased frequency of sewer overflows. An increase in precipitation may also place additional strain on equipment.

Wastewater treatment plants are typically located in low-lying areas near waterbodies. Assuming that an increase in peak streamflow is related to a potential increase in stage of the nearby water body, the wastewater treatment plant may be subject to flooding. This may cause equipment or power failure, complications with discharging effluent, system backups, and the inability to treat wastewater.

An increase in pollutant loads may also require a change in treatment capabilities. If pollutant loads are expected to increase in receiving water bodies, pollutant load regulations on treatment plant effluent may become more stringent. However, there is a temporal variation in pollutant loading over the course of a typical year, which may affect the extent of its impact on wastewater treatment plants.

To a lesser degree, wastewater treatment plants may also be vulnerable to a decrease in dissolved oxygen levels in receiving water bodies and changing water quality. It is assumed that regulatory standards of wastewater treatment plant effluent may change in the event that receiving water body dissolved oxygen levels decrease. However, it is anticipated that wastewater treatment plants have the capacity to adapt to these conditions. Similarly, wastewater treatment plants may also be vulnerable to a decrease in low flows of the receiving waterbody, which could require changes to treatment processes for wastewater treatment plant effluent.

While all climate scenarios show an increase in water demands, the impacts of increasing water demands to wastewater treatment plants will likely be minimal. This is due to the fact that most of the increase in water use from changing climate will be increased water needs for irrigation, which does not impact the wastewater system. Any potential changes in firm yield and drought are not expected to have an effect on wastewater treatment plants. This information is summarized in the vulnerability matrix provided in **Table 4.5.1**.

4.5.3 Water Treatment Plants

As part of the 2009 Water Supply and Water Conservation Management Plan, it is anticipated that there will be 44 water treatment plants within the District by 2035 (MNGWPD, 2009b). The vulnerability of water treatment plants to the effects of climate scenarios was qualitatively assessed considering water treatment plant facilities, inclusive of pumps, distribution pipes, and influent. Results of the qualitative assessment suggest that water treatment plants are most vulnerable to increases in water demand and 24-hour storm depths. Water treatment plants may be highly sensitive to these conditions with minimal adaptive capacity, with most of these conditions impacting all water treatment plants under certain climate scenarios.

Water treatment plants may not be able to meet increasing water demands, which are anticipated with all evaluated climate scenarios, based on system capacity limitations or inadequate water supply. Water treatment plants have a low adaptive capacity to meet increased demands when water supply is limited. Water treatment plants are also highly sensitive to an increase in 24-hour storm depths and nonpoint source pollutant loads. The water treatment plant infrastructure is considered to have a moderate adaptive capacity to such changes. An increase in 24-hour storm depths may result in surface flooding, submerging the facility and pumps. Additionally, an increase in storm depths may also alter source water chemistry, increasing turbidity released from erosion and runoff. Water treatment plant infrastructure may be moderately adaptable to such conditions. Water treatment plants may not be designed to adequately treat increased nonpoint source pollutant loads in influent, and therefore may be vulnerable to such changes. The intake infrastructure of a water treatment plant may also be vulnerable during times of drought or low flow if the water level in the receiving water body of the water treatment plant drops.

To a lesser degree, water treatment plants may be vulnerable to an increase in peak streamflow. An increase in peak streamflow may result in an increase in sedimentation, which has the potential to minimize reservoir storage capacity, and may also alter water quality. Water treatment plants may not be prepared to handle influent with varied water quality or reduced supply. Additionally, if the increased peak streamflow exceeds the capacity of the stream, it may result in an increase in stream stage, and potential flooding. If the water treatment plant is within the floodplain, the facility and pumps may be subject to flooding. This information is summarized in **Table 4.5.2**.

4.5.4 Stormwater Conveyance Systems

The local utilities, which are part of the Metro Water District, manage and maintain public stormwater infrastructure in 15 counties, and provide water, sewer, and/or stormwater services. Stormwater conveyance systems are responsible for directing stormwater to receiving waterbodies in many separated systems, or these systems direct combined stormwater and wastewater to the wastewater treatment plant. These systems include pipe networks, catch basins, pump stations, and outfalls. Stormwater conveyance systems are most vulnerable to an increase in 24-hour storm depths, as the system may be highly sensitive to precipitation changes with a minimal ability to adapt.

The existing stormwater system may not have the capacity to convey the increased stormwater runoff associated with increased 24-hour storm depths. An undersized system for the increased 24-hour storm depth has the potential to cause system flooding. In addition, higher flows have the potential to carry significant debris, which may clog or deteriorate the conveyance system.

Stormwater conveyance systems are also highly sensitive to an increase in peak streamflow. If an increase in peak streamflow results in an increase in stream stage, stormwater outfalls may be inundated. If the system is not designed for this condition, submerged outfalls may result in backflow from the stream into the conveyance system, and inhibit the release of stormwater from the system leading to additional upstream flooding. A stormwater conveyance system, however, may be moderately adaptable to these conditions.

To a lesser degree, stormwater conveyance systems may be vulnerable to an increase in nonpoint source pollutant loads and associated water quality impacts. Polluted stormwater runoff is the leading source of water quality degradation and source of impaired waters in the Metro Water District (MNGWPD, 2014). An increase in nonpoint source pollutant loads may result in stricter regulations on stormwater discharge, which the conveyance system may not currently be designed to meet. While not a direct impact, a decrease in dissolved oxygen levels may also trigger changes in regulations which stormwater discharge may be expected to comply with. In addition, stormwater conveyance systems may be vulnerable to an increase in drought conditions. Increased frequency and extremity of droughts could lower the water table, thus stimulating the growth of deeper tree root systems, which may penetrate and block stormwater conveyance systems (WERF, 2009).

Stormwater conveyance systems are assessed to have a low adaptive capacity to an increase in nonpoint source pollutant loads with impacts expected to affect the entire system. This information is summarized in **Table 4.5.3**.

4.5.5 Wastewater Collection Systems

There are approximately 16,000 miles of sewers and more than 450,000 manholes in the Metro Water District. Sewers and manholes within the District range in age from new to over 100 years old (MNGWPD, 2009a). With the proposed expansion of the wastewater treatment plants, additional miles of sewers and wastewater collection infrastructure may be needed. Wastewater collection systems include the pipe networks and pumps that convey sanitary flows to the wastewater treatment plant.

Based on the qualitative vulnerability assessment, wastewater collection systems are most vulnerable to an increase in 24-hour storm depths. An increase in 24-hour storm depths will result in an increase in infiltration should the groundwater table be elevated as a result of the increase in precipitation, and an increase in inflow volumes. Wastewater conveyance systems are sensitive to potential flooding when flows exceed hydraulic system capacity with few adaptation opportunities. The increased wastewater flow may put strain on the system and increase wear and tear. These risks are even greater within the City of Atlanta's combined system carrying both sanitary and stormwater flows.

An increase in peak streamflow may also leave wastewater collection systems vulnerable. An increase in stream stage may occur as a result of the increase in peak streamflow if capacity is limited. Depending on the configuration of the wastewater collection system, outfalls within the system may be highly sensitive to stream stage increases caused by peak streamflow increases. If outfalls become submerged, it may inhibit flow from the wastewater collection system and cause backups and associated flooding. Streambanks may also be sensitive to erosion around sewer outfalls with the need to reinforce stream banks to protect piping during peak flows.

While all climate scenarios show an increase in water demands, the impacts to wastewater collection systems due to increased water demands will likely be minimal. This is due to the fact that most of the increase in water use from changing climate will be increased water needs for irrigation, which does not impact the wastewater system. Wastewater collection systems may be vulnerable to a decrease in the elevation of the water table associated with drought conditions. Extreme and frequent drought conditions can lead to the migration of tree roots, which may interfere with underground wastewater piping networks. This information is summarized in **Table 4.5.4**.

4.5.6 Dams and Levees

In the Metro Water District, dams and levees are used for both flood protection and for surface water supply reservoirs. The vulnerability of dams and levees was qualitatively assessed considering the physical, structural component and any supporting infrastructure (e.g., spillways, pumps). Results of this qualitative assessment suggest that dams and levees are moderately vulnerable to an increase in 24-hour storm depth and peak streamflow, and are also vulnerable to an increase in water demand. Dams and levees are not impacted by changes to dissolved oxygen or firm yield.

Dams and levees may be subject to overtopping if an increase in 24-hour storm depths causes an increase in flows and water levels in lakes and water supply reservoirs. Floodwaters may result in bank erosion or scour of dam or levee toe. Increase debris flow and sedimentation behind the dam are other potential hazards. The capability for dams and levees to adapt to certain climate scenarios is considered moderate for both sensitivity and adaptive capacity. Current freeboard requirements allow for a certain factor of safety. In addition, inspection requirements from Georgia Environmental Protection Division provide for detailed criteria, which may identify dams or levees with current deficiencies that may be adapted for future climate scenarios.

Dams and levees are also vulnerable to changes in water demand and pollutant loads. An increase in water demand may result in a change in dam operations at water supply reservoirs. If water demand increases and water supply reservoirs can support it, then changes in dam operations to adjust the holding capacity of the reservoir may occur. Some utilities may consider the need to raise dam heights to impound more water. An increase in total suspended solids may cause more deposition behind the dam, which may accelerate the reduction of storage capacity. This information is summarized in **Table 4.5.5**.

Table 4.5.1 Wastewater Treatment Plant Vulnerability Matrix

Impact to Wastewater Treatment Plants	Trend	Associated Climate Scenario	Sensitivity	Adaptive Capacity	Extent of Impact	Assumptions
Water Demand	Increase	Not Impacted				An increase in water demand would be related to outdoor use and thus not impacting the wastewater treatment plants.
	Decrease	Not Impacted				
Firm Yield	Increase	Not Impacted				Changes in firm yield and in withdrawals from water supply reservoirs will not impact operations of wastewater treatment plants.
	Decrease					
Dissolved Oxygen	Increase	Not Impacted				Dissolved oxygen levels in effluent to receiving water bodies may need enhanced treatment in order to comply with regulatory standards.
	Decrease	CT, HD, HW, WD, WW, HT	High	Moderate	All	
24-Hour Storm Depth	Increase	CT, HD, WW *	High	Low	All	If storm intensity increases, increased inflow and infiltration may exceed the capacity of the wastewater treatment plants, leading to releases of untreated or partially treated sewage into water ways. Treating more intense storms may increase wear and tear on wastewater treatment plant equipment. Flooding may also occur at the wastewater treatment plant as a result of surface flooding from intense storms.
	Decrease	Not Impacted				
Peak Streamflow	Increase	CT, HD, WW *	Moderate	Moderate	All	In the event that increases in peak flows exceed the stream capacity, it may lead to increases in stream stage. This may cause complications with treatment plant effluent and system backups or surface flooding of the facility.
	Decrease	Not Impacted				
Nonpoint Source Pollutant Loads	Increase	CT, HD, HW, WD, WW, HT	High	Low	All	An increase in pollutant loads in receiving waters may lead to more stringent effluent pollutant load regulations, which wastewater treatment plants may not be currently configured to meet.
	Decrease	Not Impacted				
Drought	Increase	Not Impacted				
	Decrease					
Low Flow	Increase	Not Impacted				A decrease in low flows in receiving waters may result in changes to effluent regulations, which wastewater treatment plants may not be currently configured to meet.
	Decrease	CT, HD, HW, WD, WW, HT	Moderate	Moderate	All	

*Note: Only the Central Tendency, Hot/Dry, and Warm/Wet climate scenarios were evaluated for 24-Hour Storm Depths and Changes in Peak Streamflow.

** Note: Historic Trends were not evaluated for Drought

Table 4.5.2 Water Treatment Plant Vulnerability Matrix

Impact to Water Treatment Plants	Trend	Associated Climate Scenario	Sensitivity	Adaptive Capacity	Extent of Impact	Comments
Water Demand	Increase	CT, HD, HW, WD, WW, HT	High	Low	All	If water demand increases, water treatment plants may have difficulty meeting demands due to treatment capacity limitations.
	Decrease	Not Impacted				
Firm Yield	Increase	Not Impacted				Changes in firm yield may not impact water treatment plants.
	Decrease					
Dissolved Oxygen	Increase	Not Impacted				Changes in dissolved oxygen in receiving water bodies is a primary concern for wastewater effluent, but may not impact water treatment plant processes and distribution.
	Decrease					
24-Hour Storm Depths	Increase	CT, HD, WW*	High	Moderate	All	Water treatment plants are at risk of surface water flooding.
	Decrease	Not Impacted				
Peak Streamflow	Increase	CT, HD, WW*	Low	Moderate	All	An increase in peak streamflow may cause changes in sedimentation and water quality, which the water treatment plant may not be configured to treat. An increase in peak streamflow may also result in potential flooding of the water treatment plant.
	Decrease	Not Impacted				
Nonpoint Source Pollutant Loads	Increase	CT, HD, HW, WD, WW, HT	High	Moderate	All	An increase in pollutant loads may alter water supply chemistry, turbidity, and contaminants to levels that water treatment plants may not be configured to treat.
	Decrease	Not Impacted				
Drought	Increase	CT, HD, HW, WD**	Moderate	High	All	Intake infrastructure at the water treatment plant may not be designed to pull water from a lower water surface elevation.
	Decrease	Not Impacted				
Low Flow	Increase	Not Impacted				A decrease in low flows at water bodies used for water supply may make it difficult for water treatment plants to intake water.
	Decrease	CT, HD, HW, WD, WW, HT	Moderate	High	All	

*Note: Only the Central Tendency, Hot/Dry, and Warm/Wet climate scenarios were evaluated for 24-Hour Storm Depths and Peak Streamflow.

** Note: Historic Trends were not evaluated for Drought

Table 4.5.3 Stormwater Conveyance System Vulnerability Matrix

Impact to Stormwater Conveyance Systems	Trend	Associated Climate Scenario	Sensitivity	Adaptive Capacity	Extent of Impact	Comments
Water Demand	Increase	Not Impacted				Changes in water demand may not impact stormwater conveyance systems.
	Decrease					
Firm Yield	Increase	Not Impacted				Changes in firm yield and in withdrawals from water supply reservoirs may not impact stormwater conveyance systems.
	Decrease					
Dissolved Oxygen	Increase	Not Impacted				Dissolved oxygen may not directly impact stormwater conveyance systems. However, secondary impacts associated with the dissolved oxygen balance due to nutrient enrichment and eutrophication may affect receiving waters.
	Decrease					
24-Hour Storm Depths	Increase	CT, HD, WW*	High	Low	All	If storm intensity increases, combined sewage and stormwater may exceed the capacity of the stormwater conveyance system, leading to backups in the system and street flooding. Runoff carries organic detritus, debris and trash, which can cause blockages within the system. Treating more intense storms may wear and tear on the stormwater conveyance system.
	Decrease	Not Impacted				
Peak Streamflow	Increase	CT, HD, WW*	High	High	All	In the event that an increase in peak flows exceed the stream capacity, it may lead to an increase in stream stage. This may cause system backups if drainage outfalls are submerged and are not designed for the increased water level.
	Decrease	Not Impacted				
Nonpoint Source Pollution Loads	Increase	CT, HD, HW, WD, WW, HT	Moderate	Low	All	Polluted stormwater runoff is the leading source of water quality degradation and source of impaired waters in the Metro Water District (MNGWPD, 2014d). Stormwater conveyance systems may not be configured to store additional nonpoint source pollution loads.
	Decrease	Not Impacted				
Drought	Increase	CT, HD, HW, WD**	Moderate	Moderate	All	A decrease in the water table elevation as a result of extreme drought or increased drought frequency may cause downward migration of tree roots, which have the potential to interfere with the stormwater conveyance system.
	Decrease	Not Impacted				
Low Flow	Increase	Not Impacted				A decrease in the low flow condition may result in changes to stormwater discharge regulations, which the existing systems may not have capacity to meet.
	Decrease	CT, HD, HW, WD, WW, HT	Moderate	Moderate	All	

*Note: Only the Central Tendency, Hot/Dry, and Warm/Wet climate scenarios were evaluated for 24-Hour Storm Depths and Peak Streamflow.
** Note: Historic Trends were not evaluated for Drought

Table 4.5.4 Wastewater Collection System Vulnerability Matrix

Impact to Wastewater Collection Systems	Trend	Associated Climate Scenario	Sensitivity	Adaptive Capacity	Extent of Impact	Comments
Water Demand	Increase	Not Impacted				An increase in water demand would be related to outdoor use and thus not impact the wastewater collection systems.
	Decrease					
Firm Yield	Increase	Not Impacted				Firm yield may not impact wastewater collection systems.
	Decrease					
Dissolved Oxygen	Increase	Not Impacted				Dissolved oxygen levels may not impact wastewater collection systems, but may impact wastewater treatment plants.
	Decrease					
24-Hour Storm Depths	Increase	CT, HD, WW*	High	Low	All	If storm intensity increases, combined sewage and stormwater may exceed the capacity of the wastewater collection system, leading to backups in the system and into homes and businesses, combined system overflows and street flooding. Conveying more intense storms with increased inflow/infiltration (I/I) may increase wear and tear on the wastewater collection system.
	Decrease	Not Impacted				
Peak Streamflow	Increase	CT, HD, WW*	High	High	All	In the event that an increase in peak flows exceed the stream capacity, it may lead to an increase in stream stage. This may cause backups in the system if combined sewer outfalls become submerged and are not designed for the increased water level.
	Decrease	Not Impacted				
Nonpoint Source Pollution Loads	Increase	Not Impacted				Changes in pollutant loads on a watershed-scale may not impact wastewater collection systems, but may impact wastewater treatment plants.
	Decrease					
Drought	Increase	CT, HD, HW, WD**	Moderate	Moderate	All	A decrease in the water table elevation as the result of extreme drought or increased drought frequency may cause migration of tree roots, which have the potential to interfere with the wastewater collection system.
	Decrease	Not Impacted				
Low Flow	Increase	Not Impacted				A decrease in the low flow condition may result in changes to the receiving water body and changes to the combined system overflow discharge regulations, which the existing systems may not have capacity to meet.
	Decrease	CT, HD, HW, WD, WW, HT	Low	Moderate	All	

*Note: Only the Central Tendency, Hot/Dry, and Warm/Wet climate scenarios were evaluated for 24-Hour Storm Depths and Peak Streamflow

** Note: Historic Trends were not evaluated for Drought

Table 4.5.5 Dam and Levee Vulnerability Matrix

Impact to Dams and Levees	Trend	Associated Climate Scenario	Sensitivity	Adaptive Capacity	Extent of Impact	Comments
Water Demand	Increase	CT, HD, HW, WD, WW, HT	Moderate	High	All	An increase in water demand may result in a change in dam operations or the need to review the volume of impounded water.
	Decrease	Not Impacted				
Firm Yield	Increase	Not Impacted				Changes in in firm yield may not result impact dams and levees.
	Decrease					
Dissolved Oxygen	Increase	Not Impacted				Dissolved oxygen levels may not impact dams and levees.
	Decrease					
24-Hour Storm Depths	Increase	CT, HD, WW*	Moderate	Moderate	All	An increase in storm intensity and volume may result in an increase in flows to water supply reservoirs. If the water levels in water supply reservoirs or waterways increase, dam or levee crests may be overtopped. An increase in rainfall intensity may also increase peak discharge and peak velocities, which may scour the toe of these structures. An increase in storm intensity may result in an increase in debris which may cause complications in dam operations and maintenance.
	Decrease	Not Impacted				
Peak Streamflow	Increase	CT, HD, WW*	Moderate	Moderate	All	An increase in peak streamflow may lead to an increase in bank erosion and scour, which can impact dams and levees. An increase in sedimentation may also occur behind dams if more sediment is mobilized by the increased streamflow.
	Decrease	Not Impacted				
Nonpoint Source Pollutant Loads	Increase	CT, HD, HW, WD, WW, HT	Moderate	Moderate	All	An increase in pollutant loads, such as total suspended solids, may cause more deposition behind the dam, which may accelerate the reduction of storage capacity.
	Decrease	Not Impacted				
Drought	Increase	Not Impacted				Operations of dams and levees may need to change to accommodate increased frequency and/or intensity of drought. Systems may need to pass more flow through dams to satisfy instream flow requirements, but the infrastructure itself is not necessarily vulnerable.
	Decrease					
Low Flow	Increase	Not Impacted				Operations of dams and levees may need to change to accommodate increased frequency and/or intensity of drought. Systems may need to pass more flow through dams to satisfy instream flow requirements, but the infrastructure itself is not necessarily vulnerable.
	Decrease					

*Note: Only the Central Tendency, Hot/Dry, and Warm/Wet climate scenarios were evaluated for 24-Hour Storm Depths and Peak Streamflow.

** Note: Historic Trends were not evaluated for Drought

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4.6 Summary Impacts

4.6.1 Conclusions on Water Demand

The following conclusions can be drawn from the water demand vulnerability analysis:

- Water demands are sensitive to weather, but also to changes in economy and conservation effectiveness.
- When all other factors are held constant, future climate can increase water use from 1.3 percent to 3.8 percent by 2050, depending on ranges of future temperature and precipitation.
- The hot/dry climate scenario shows the largest impact to water demand. Under this scenario, future conservation would have to increase over the current 19 percent to over 23 percent to be equal to today's level of efficiency.

4.6.2 Conclusions on Water Supply

The following conclusions can be drawn from the water supply vulnerability analysis:

- Monthly streamflow is driven more by precipitation than by temperature. Note that this conclusion is different from other analysis presented in this report on extreme low-flow conditions, which can be more susceptible to the impacts that higher temperatures have on soil moisture and evaporation.
- Tests reveal that yield is dominated by inflow and storage, not evaporation.
- The wetter climate scenarios will likely increase the firm yield from small and midsize water supply reservoirs.
- The drier climate scenarios could reduce firm yield 5 to 10 percent in small to midsize water supply reservoirs.
- The Central Tendency and Trend Projection scenarios will have a less pronounced effect on firm yield than the wetter and drier scenarios.
- The 95 percent reliable yield will exhibit similar trends to the firm yield: wetter scenarios will likely increase the amount of time that certain amounts of water can be withdrawn, while the drier scenarios will likely reduce the amount of time that the same amounts can be withdrawn.
- It does not appear that physical or hydrologic features of the watersheds or reservoirs are good indicators of specific water supply risks, although the reservoirs with high ratios of drainage area to storage could see larger relative increases in yield than those with smaller ratios if the climate trends in a direction of more precipitation. This is because those with high ratios can refill faster.
- Trends in monthly and annual precipitation will likely be the best indicators of changes in yield.

4.6.3 Conclusions on Water Quality

Key conclusions on the potential impacts of the future climate scenarios on water quality are listed below:

- River low flow is, for most study sites, shown to be highly sensitive to summer temperature variability (via ET losses). Seven day annual low flows, at all but one of the study sites, are projected to decrease for future climate scenarios, despite projected increases in basin precipitation.
- Projected air temperature changes (4 – 7 ºF) translate into reach-averaged water temperature changes of 0.1 – 3 ºF.
- Projected decreases in reach-averaged dissolved oxygen range from 0 to 1.5 mg/L, depending largely on hydrology. There was a projected increase in average dissolved oxygen in only one reach/climate scenario combination (out of 24).
- A major implication of these results is that, for fully or near fully allocated streams, existing discharge permits may not be protective of stream health in the future, due solely to changes in climate.
- Sources of uncertainty in these analyses have been noted, included uncertainty about how future discharge loads will be impacted by climate variability.
- Future studies might look to extend this work by developing more comprehensive water quality models at a basin, rather than reach, scale to better incorporate climate impacts on small tributaries and point source discharges and to extend study reaches from headwater to mouth.

4.6.4 Conclusions on Watershed Impacts

4.6.4.1 Conclusions on Storm Frequency and Intensity

The Hot/Dry scenario results in the largest increases in projected ARI depth, ranging from 4 percent to 12 percent increases from the historic totals. The largest projected increase is for the 25-year, 4-day rainfall, which is projected to increase 12 percent from 8.3 to 9.3 inches of precipitation. The Median climate scenario projects decreases as well as increases in ARI depths, ranging from a 2 percent decrease to a 5 percent increase from the historic totals. In all three scenarios, longer duration depths are projected to increase more than shorter duration projections.

4.6.4.2 Conclusions on Peak Streamflow

The results suggest that peak streamflow is likely to increase due to climate variability in mid-sized streams such as the upper Flint and Yellow Rivers. The primary driver for the increase is total rainfall for storms longer than 24 hours. Shorter storms and other climate factors, such as temperature, were not good predictors of peak streamflow.

The smaller, more frequent rain events (5-year storms) are likely to become larger and produce increases in peak flows between five and 11 percent, as shown by the EPA's CREAT precipitation predictions and a peak streamflow regression model relating storm totals to peak streamflow. This analysis suggests that the peak streamflow changes from larger, less frequent storm events (10- and 25-year storms) are less certain. Some scenarios show no change or a decrease in peak streamflow while other scenarios show an increase of up to 11 percent compared to historic storm-driven peak streamflows.

4.6.4.3 Conclusions on Pollutant Loading

The watershed loading model was used to compare the estimated changes in pollutant loading in two watersheds with different land uses, for the six climate scenarios described in **Section 2**. The increased precipitation projected by the hot/wet and warm/wet climate scenarios results in greater increases in loading in the Yellow River than the Flint River, indicating that a higher percent of impervious cover could cause a watershed to be more susceptible to nonpoint source loading increases from climate variability. The climate scenarios produce different average annual precipitation totals, from slight decreases (-1 percent) to more significant increases (15 percent). The distribution of rainfall over the year is different for each scenario and results in different seasonal loading patterns in the watersheds. The hot/wet scenario causes the most significant loading change from baseline historic conditions. This scenario results in a 13 percent increase in annual precipitation that is largely focused in the summer months. Increased loads in the summer months may be of particular importance in watershed planning and permitting because of the impact of increased nutrients and algal growth on dissolved oxygen during the growing season, and bacteria concentration impacts on public health during the recreational season.

4.6.5 Conclusions on Water Resource Infrastructure

The infrastructure vulnerability assessment synthesized the impacts from each water sector and climate scenario in order to qualitatively determine the potential sensitivity, adaptive capacity, and extent of impact to six different water resources infrastructure types: wastewater treatment plants, water treatment plants, stormwater conveyance systems, wastewater collection systems, and dams and levees. The result of this high level assessment are the infrastructure vulnerability matrices that summarize the potential impacts and results based on an increase or decrease of the water sector impact. These results will be used to prioritize the infrastructure with the greatest need for adaptation strategies.

The infrastructure types that are considered most vulnerable are those that are highly sensitive to changes in water sector impact and have minimal capacity to adapt to climate scenarios. The facilities and the associated water sector impact are listed in **Table 4.6.1**:

Table 4.6.1 High Sensitivity, Low Adaptive Capacity Infrastructure Types

Infrastructure Type	Greatest Risk
Wastewater Treatment Plants	Increase in 24-hour Storm Depths
	Increase in Nonpoint Source Pollutant Loads
Water Treatment Plants	Increase in Water Demand and/or Droughts
Stormwater Conveyance Systems	Increase in 24-hour Storm Depths
Wastewater Collection Systems	Increase in 24-hour Storm Depths
Dams and Levees	Increase in 24-hour Storm Depths

Three of the infrastructure types are interrelated: combined sewer and stormwater systems that are eventually treated at the wastewater treatment plant are all highly susceptible to changes in storm severity and have the least capacity to adapt to such changes. Many of the systems are aging or are past their useful life. Some of these facilities have already been decommissioned by local utilities, but with the potential climate scenarios, facilities that are being designed and built now may not have the adaptability to change. An increase in 24-hour storm depths pose the greatest risk to water resources infrastructure. Only three climate scenarios were analyzed for changes in 24-hour storm depths and changes in peak flows. The climate scenarios were the Central Tendency, Hot/Dry, and Warm/Wet scenarios. All three climate scenarios resulted in increases in 24-hour storm depths and peak flows. These three climate scenarios also produced increases in pollutant loads, decreases in dissolved oxygen, and increases in water demand.

In addition, water supply reservoirs and water treatment plants are susceptible to changes in water demand, low flows, and drought conditions. All six climate scenarios indicated an increase in water demand. For three out of four case studies, low flows are expected to decrease across the board for all climate scenarios. For drought conditions, four out of five of the climate scenarios analyzed indicate a trending towards drier or drought-like conditions by 2100.

Section 5

Adaptation Strategies

5.1 Objectives of Adaptation Strategies

Numerous objectives guided the formulation of adaptation strategies for the Metro Water District. The fundamental objective was to recommend a suite of relevant, proven measures that could help address or reduce the specific risks identified in this study. Secondarily, it is important for the District as it moves into its next phase of planning to distinguish between projects and policies that could offer universal benefits regardless of future climate conditions from those that would be targeted at mitigating the impacts of just one or two future climate trends. Hence, another objective of the study was to recommend a suite of "preemptive" adaptation measures that could be implemented immediately with no regrets, and also a group of measures that would only be implemented if triggered by specific future climate trends once they are clearly evident.

Also, because there are so many climate adaptation measures that have been applied in other areas, it was important to identify the measures most suitable for the Metro Water District. Hence, a number of other secondary objectives helped frame this work, specifically:

- Understand the most significant risks to the District
- Understand the future climate conditions that would create the broadest risks
- Identify risks that would result from ANY future shift in climate conditions

Understanding these risks and their causes allowed the project team to identify the most relevant, universal, and least risky adaptation measures based on the specific risks to the Metro Water District identified during this study.

5.2 Summary of Risks

This section summarizes the risks associated with the climate impacts on water resource sectors and on water and wastewater system infrastructure components. Risks to the Metro Water District from various climate scenarios were summarized in three ways:

1. Risks were first categorized by the most significant risks by water sector impact (e.g., non-point source pollutant load, 24-hour storm depths). In other words, this summary evaluates the climate scenarios that will produce the greatest impact.
2. Secondly, the broadest risks to water and wastewater infrastructure (e.g., stormwater conveyance systems, dams and levees) were summarized. The evaluation of broadest risks is based on determining the climate scenario that is likely to have the greatest impact on water and wastewater infrastructure.
3. Lastly, risks were identified for water and wastewater infrastructure that could occur under any of the climate scenarios evaluated as part of this study.

5.2.1 Review of Most Significant Risks by Water Resource Impact

This section summarizes the climate scenario that has the potential to pose the greatest risk to each of the water resource sectors evaluated: water demand, water supply, water quality, watershed impacts, and water availability (i.e., drought). The results from **Section 2**, Future Climate Scenarios, and **Section 4**, Climate Vulnerability Analysis, were used to characterize the climate impacts that may have an effect on the region. The vulnerability analysis in these sections was based on analysis conducted on watersheds, representative river reaches, or the entire Metro Water District region. The scale of the analysis depended on the water resources sector evaluated. Watersheds and representative river reaches may not respond uniformly to the given climate scenarios, so for the purposes of summarizing risk, the general trend of the majority of the watersheds or river reaches was considered. The range of impacts on water resources for all scenarios and the most severe climate scenarios are summarized in **Table 5.2.1**.

The Hot/Dry climate scenario creates the most significant risks to the water resources sectors. Only three climate scenarios were analyzed for changes in 24-hour storm depths and changes in peak flows. The climate scenarios were the Central Tendency, Hot/Dry, and Warm/Wet scenarios. All three climate scenarios resulted in increases in 24-hour storm depths and peak flows. For the three categories of Watershed Impacts, Hot/Wet scenario is assumed to be more severe than Hot/Dry.

Table 5.2.1 Summary of Water Resource Impact by Climate Scenario

Water Resource	Range of Impacts Across all Climate Scenarios	Study Reference	Most Severe Climate Scenario
Water Demand	- Between a 1-4% increase in 2050 due solely to climate.	Figure 4.1.3	Hot/Dry
Water Supply	- Up to an 11% decrease (from historical) in firm yield for small to midsize reservoirs in drier climate scenarios and the potential for increased yield in wetter scenarios.	Figure 4.2.3	Hot/Dry
Water Quality	- A decrease in annual low flows with potential for some basins to be completely dry. - Increase in river water temperature between 0-3°F. - Between 0-1.5 mg/L decrease in dissolved oxygen.	Figure 4.3.1 Figure 4.3.2 Figure 4.3.3	Hot/Dry Hot/Dry Hot/Dry
Watershed Impacts	- Up to a 12% increase in rainfall depth. - Up to an 11% increase in peak streamflow. - Up to a 40% increase in pollutant loading.	Figure 4.4.2 Figure 4.4.3 Figure 4.4.4	Hot/Wet* Hot/Wet* Hot/Wet*
Water Availability (Drought)	- Between 2050-2100, climate scenarios indicate an average Palmer Drought Severity Index (PDSI) from near (0.21) normal conditions to extreme drought (-4.49).	Figure 2.3.2	Hot/Dry

* Storm frequency, storm intensity, and peak streamflow impacts were only analyzed for three climate scenarios (Hot/Dry, Median, and Warm/Wet). Assume that impacts from a Hot/Wet scenario would be more severe than Hot/Dry for these impacts.

5.2.2 Climate Conditions that Create the Broadest Risks to Water and Wastewater Infrastructure

Climate scenarios evaluated as part of this study pose risks to water and wastewater utility infrastructure in the Metro Water District. This section summarizes, based on qualitative analyses, which climate scenario is likely to pose the greatest risk to water and wastewater infrastructure including wastewater treatment plants, water treatment plants, stormwater conveyance systems, wastewater collection systems, and dams and levees**.** As part of the vulnerability assessment (**Section 4.5**), risk to different infrastructure types were evaluated based on the impact to the water resource sector (i.e., how wastewater treatment plants are affected by a change in water quality caused by a decrease in dissolved oxygen). Some climate impacts may not affect every type of water and wastewater infrastructure. Risk to each infrastructure type was qualitatively evaluated based on a combination of three factors: sensitivity, adaptive capacity, and extent of impact to each infrastructure type.

The greatest perceived risk to the majority of the infrastructure types are related to an increase in 24-hour storm depths and therefore, a possible increase in flooding (**Table 5.2.2**). As described above, only three climate scenarios were evaluated for watershed impacts. The Hot/Wet scenario is assumed to be more severe than Hot/Dry***. The Hot/Wet climate scenario may result in broadest risk to wastewater treatment plants, stormwater conveyance systems, wastewater collection systems, and dams and levees.***

Table 5.2.2 Summary of Risk by Infrastructure Type and Climate Scenario

Infrastructure Type	Climate Impact	Climate Scenario
Wastewater Treatment Plants	Increase in 24-hour Storm Depths	Hot/Wet*
	Increase in Nonpoint Source Pollutant Loads	Hot/Wet
Water Treatment Plants	Increase in Water Demand	Hot/Dry
	Increase in Drought	Hot/Dry
Stormwater Conveyance Systems	Increase in 24-hour Storm Depths	Hot/Wet*
Wastewater Collection Systems	Increase in 24-hour Storm Depths	Hot/Wet*
Dams and Levees	Increase in 24-hour Storm Depths	Hot/Wet*

* Storm frequency, storm intensity, and peak streamflow impacts were only analyzed for three climate scenarios (Hot/Dry, Median, and Warm/Wet). Assume that impacts from a Hot/Wet scenario would be more severe than Hot/Dry for these impacts.

5.2.3 Risks Resulting from Any Climate Condition

Impacts to water resource sectors are expected to occur under all of the climate scenarios evaluated as part of this study. The severity of those impacts vary depending on the analysis methods, the climate scenario, and how they eventually impact infrastructure. **Section 4.5** discusses the vulnerability analysis used to determine the water and wastewater infrastructure that are at risk.

Water demand is expected to increase due to climate variability under all of the climate scenarios evaluated as part of this study. Depending on the season, non-point source pollution loads are also expected to increase for the majority of the climate scenarios. Dissolved oxygen levels are expected to decrease in nearly all of the climate scenarios evaluated. The response of 24-hour storm depths and peak streamflows were only evaluated for the Central Tendency, Hot/Dry, and Warm/Wet climate scenarios, all of which produce increasing trends. Drought conditions are likely to occur under almost all climate scenarios (excluding the Warm/Wet scenario). These impacts to water resource sectors, which are likely to occur under any climate condition, pose risks to water and wastewater infrastructure as described below.

Water and wastewater treatment plants are considered the two major infrastructure elements that are the least capable to adapt but are at increased risk to climate variability. Due to the complexities of each individual facility, the required regulatory compliance, and the aging infrastructure, identification and implementation of adaptation measures are a necessity in order for these facilities to mitigate future risks.

Wastewater Treatment Plants

Wastewater treatment plants may be affected by several water resource sector impacts which are expected to occur under any climate scenario evaluated. Increases in nonpoint source pollutant loads, expected to occur under nearly all climate scenarios evaluated, may pose risks to wastewater treatment plants if more stringent effluent pollutant load regulations are initiated due to pollutant loads in receiving water bodies. Similarly, decreases in dissolved oxygen levels in receiving water bodies, expected to occur under any of the climate conditions evaluated, may also result in risks of meeting changing regulatory standards in wastewater treatment effluent. Increases in 24-hour storm depth and peak streamflow, which are expected to increase under the climate scenarios evaluated for these water resource sectors could result in surface flooding of wastewater treatment facilities, increased wear and tear on wastewater treatment plant infrastructure, system backups, and capacity limitation risks. In summary, there are several risks to wastewater treatment plants which are expected to occur under any given climate scenario.

Water Treatment Plants

Water treatment plants are subject to several risks which are expected to occur under any of the evaluated climate scenarios. Increases in water demands could pose risks to water treatment plants based on their capacity to meet those demands, which are expected to increase under all climate scenarios. In addition, increases in nonpoint source pollutant loads in source waterbodies, expected to occur under all climate conditions, may create risks with regard to the water treatment plant's ability to meet water quality criteria. Increases in 24-hour storm depth and peak streamflow, which are expected to increase under all the climate scenarios for which it was evaluated, could result in surface flooding of water treatment facilities, and may cause risks to water treatment facilities with regard to sedimentation and water quality changes within source waterbodies. Regardless of which climate scenario may occur, there may be some risks posed to water treatment plant facilities.

Stormwater and Wastewater Conveyance

Stormwater conveyance systems and wastewater conveyance systems may face similar risks under any climate scenario that may occur. Both systems are sensitive to increases in 24-hour storm depths and peak streamflows. Increases to these parameters could result in system capacity risks and associated backups, especially when outlet structures become submerged and system flow rates increase. For wastewater collection systems in particular, the increase in demand predicted for all climate scenarios may result in increased system baseflows, which may place additional wear and tear on the collection system and cause risks with regard to system capacity. Increases in nonpoint source pollutant loads in receiving water bodies may pose risks to stormwater conveyance systems, which may not be design to meet water quality effluent standards which may exist under any future climate scenario. Therefore, some risks may be evident to both stormwater and wastewater conveyance systems under any climate scenario which may occur.

Water Supply Infrastructure

Water supply reservoirs managed by dams/levees and water treatment plants are interrelated infrastructure. An increase in drought is expected to occur in 2050-2100 based on the PDSI analysis where nearly all of the climate scenarios (except for the Warm/Wet scenario) yields worsening drought conditions than what is expected in the first half of this century (2000-2049). Additionally, for the studied water supply reservoirs, a decrease in firm yield was expected in the Hot/Dry and Warm/Dry climate scenarios, adding stress to the systems. Dams and levees may also be at risk under any climate scenario to handle increased storm intensity and increased peak streamflow. Such increases may result in risks of overtopping of dam and levee crests. In addition, increases to streamflow velocities and discharges may result in scouring, and increased debris and sedimentation, which may pose risks to the longevity and operation of dam and levee infrastructure.

5.2.4 Conclusions on Risks Related to Climate Conditions

It is expected that the Hot/Wet and Hot/Dry climate scenarios pose the greatest risk to the Metro Water District. The Hot/Dry climate scenario is predicted to have the greatest effect on the water resource sectors evaluated through water demand, water supply, water quality, and water availability (drought) impacts. These impacts have the potential to affect the entire region and the health and livelihood of its people. However, the Hot/Wet climate scenario has the potential to affect the greatest range of infrastructure systems given the estimated increases in storm severity under this scenario. It will be important to continue to track the climate and identify indicators to assess which direction the future climate is trending. Additionally, for some water resource sectors, regardless of the climate scenario, impacts may produce negative effects that the Metro Water District needs to consider when planning for the future.

5.3 Relevant Adaptation Strategies

Adaptation strategies were identified to address the major risks identified to water, wastewater, and stormwater systems and infrastructure. A literature review was performed to initially identify potential adaptation strategies, this was combined with a review of the 2009 Water Supply and Water Conservation Management Plan, Wastewater Management Plan, and Watershed Management Plan to evaluate the current recommendations and identify which should be prioritized or modified to increase their adaptive capacity.

5.3.1 Literature Review

Several references were used in the development of adaptation strategies for the Metro Water District under various climate scenarios. A description of the main references are provided below:

- The United States Environmental Protection Agency (USEPA) developed the ***Adaptation Strategies Guide for Water Utilities* (2013).** It was developed as an informal guide for water and wastewater utility owners to help them understand and address risks associated with climate. The goals of the *Adaptation Strategies Guide for Water Utilities* are to (1) provide water and wastewater utilities with an understanding of how future climates can impact operations and missions, and (2) provide examples of actions that utilities can take to prepare for these impacts. Several actions from this publication were adopted into this report and identified as potential adaptation strategies to address impacts of future climate scenarios for the Metro Water District.

- The Water Environment Research Foundation (WERF) published ***Implications of Climate Change for Adaptation by Wastewater and Stormwater Agencies* (2009)**. The publication provides a risk management paradigm approach, including the identification, assessment and characterization, and management of risks associated with climatic variability. Several of the management techniques presented in this publication may be applicable to water and wastewater utilities in the Metro Water District, and were incorporated into this report.

- In 2014, CDM Smith developed a vulnerability assessment and adaptation plan for the City of Salem, Massachusetts. The report entailed a detailed risk assessment for the city, and identified immediate, actionable adaptation priorities to be incorporated into existing and future projects and policies. Concepts and management strategies pertaining to water and wastewater utilities, management approaches, and planning were adopted from this report for the Metro Water District.

In addition to these resources, other potential adaptation measures included in this report were developed based on the experience and expertise of engineers and planners at CDM Smith. Additional adaptation strategies exist beyond those included in this report but those provided compose an initial suite of relevant, proven measures. **Appendix D** contains a full listing of adaptive strategies developed during the literature review, while those most relevant to the identified greatest risks are highlighted later in this section.

5.3.2 Review of District 2009 Plans

As part of the original legislation creating the Metro Water District, three long-term regional plans were required to address water resources challenges: a Water Supply and Water Conservation Management Plan, a Wastewater Management Plan, and a Watershed Management Plan. The first plans were adopted in 2003, updated in 2009, and are currently undergoing another round of revisions with newly updated plans expected in 2016. As part of this study, the recommendations from the 2009 plans were reviewed to identify actions that could improve the adaptive capacity of the District to future climate variability. A full listing of action items from these plans and the climate impacts they could aid in addressing are provided in **Appendix D** while those most relevant to the identified greatest risks are highlighted in the following section.

5.3.3 Adaptation Strategies for the Greatest Infrastructure Risks

For each of the greatest risks identified for the infrastructure types analyzed, a list summarizing the potential issues, key adaptation strategies and links to the recommendations in the 2009 Water Supply and Water Conservation Management Plan, Wastewater Management Plan, and Watershed Management Plan are provided in **Table 5.3.1** through **Table 5.3.8**. The climate scenarios under which each specific risk is assumed present have also been highlighted.

Table 5.3.1 Adaptation Strategies for Increase in Storm Depths for Wastewater Treatment Plants

ISSUE	INCREASE IN STORM DEPTHS FOR WWTPs

Impact

Increased storm frequency and intensity (0-12% depth increase). Highest increases under the Hot/Dry scenario and for longer duration storms.

Potential Issues

Overflows, plant capacity, decreased service life, flooding

Critical Scenarios

- ✓ Central
- ✓ Hot/Dry
- ✓ Hot/Wet
- ✓ Warm/Dry
- ✓ Warm/Wet
- Trend

Key Adaptation Strategies

- **Increase capacity** for wastewater treatment and discharge, including **redundancies** to hedge against infrastructure losses and disruptions.
- Improve effluent piping for **backflow prevention** if receiving water levels rise.
- Minimize flooding by **relocating facilities** to higher ground, or **build flood barriers** to protect infrastructure from flooding.
- Identify and protect vulnerable facilities, including developing **operational strategies** that isolate these facilities and re-route flows.
- Mitigate increased storm volume through **green infrastructure** design.

Links to 2009 Wastewater Plan

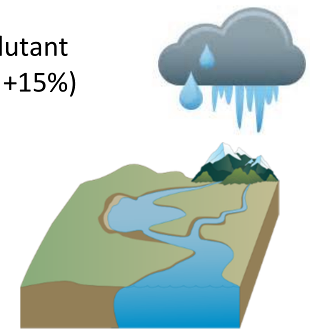
- Consider **design storm depth increases** for planned new and expanded WWTPs (Actions 6.1, 6.2, 6.5).
- Increase priority on **system maintenance**, rehab and capacity certifications prior to authorizing new connections to ensure capacity maintained (Actions 7.1-7.6).
- Increase priority on sewer system overflow **emergency response program** (Action 7.8).

Table 5.3.2 Adaptation Strategies for Increase in Nonpoint Source Pollutant Loads for Wastewater Treatment Plants

ISSUE	INCREASE IN NONPOINT SOURCE POLLUTANT LOADS FOR WWTPs

Impact

Increased pollutant loading (-1 to +15%)



Potential Issues

More stringent effluent regulations

Critical Scenarios

- ✓ Central
- ✓ Hot/Dry
- ✓ Hot/Wet
- ✓ Warm/Dry
- ✓ Warm/Wet
- ✓ Trend

Key Adaptation Strategies

- **Regulate** point sources and non-point source pollutant sources.
- **Land use planning** changes.
- Mitigate non-point source pollution increases through **green infrastructure**.

Links to 2009 Wastewater Plan

- Consider potential for more stringent regulation during planned **plant upgrades** (Action 6.3).
- Help protect water quality through better planning and **maintenance of septic and decentralized systems** (Actions 8.1-8.6).

Table 5.3.3 Adaptation Strategies for Increase in Water Demand on Water Treatment Plants

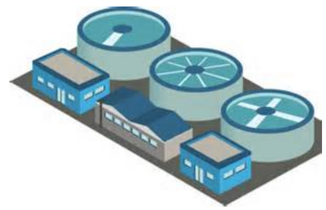
ISSUE	INCREASE IN WATER DEMAND ON WTPs

Impact

Water demand due to climate is predicted to increase 1.3 – 3.8%

Potential Issues

Difficulty meeting demand, especially if combined with lower yields during drier scenarios.



Critical Scenarios

- ✓ Central
- ✓ Hot/Dry
- ✓ Hot/Wet
- ✓ Warm/Dry
- ✓ Warm/Wet
- ✓ Trend

Key Adaptation Strategies

- **Monitor and inspect** the integrity and capacity of existing infrastructure.
- Practice **demand management** through communication to public on water conservation actions.
- **Diversify** options to complement current water supply, including recycled water and stormwater capture.
- Establish **mutual aid agreements** with neighboring communities.
- Implement **adaptive water rates** to correspond with water supply.

Links to 2009 Water Supply Plan

- Increased priority on **conservation programs** to balance increased demand (Actions 5.1 – 5.19).
- Explore opportunities for returning **reclaimed water** to Lake Lanier and Allatoona Lake to supplement water supply (Action 7.1).
- Consider increased demands when planning new/expanded water supply reservoirs and treatment plants (Actions 8.1 - 8.3).

Table 5.3.4 Adaptation Strategies for Increase in Storm Depths for Stormwater Conveyance Systems

ISSUE	INCREASE IN STORM DEPTH FOR STORMWATER CONVEYANCE SYSTEMS

Impact

Increased storm frequency and intensity (0-12% depth increase). Highest increases under the Hot/Dry scenario and for longer duration storms.

Potential Issues

Capacity issues leading to increased street flooding and potential flooding of structures.

Critical Scenarios

- ✓ Central
- ✓ Hot/Dry
- ✓ Hot/Wet
- ✓ Warm/Dry
- ✓ Warm/Wet
- ○ Trend

Key Adaptation Strategies

- **Increase capacity** of stormwater collection, conveyance, and storage systems.
- Design **green infrastructure** to reduce stormwater volumes.
- Conduct **extreme precipitation event analyses** to understand the risk of impacts to the stormwater water collection system.
- **Monitor and inspect** the integrity of existing infrastructure.

Links to 2009 Watershed Plan

- Consider increased storm depths for criteria in sizing new development stormwater management infrastructure (Action 5.A.1).
- Ensure **best practices** in place for stormwater design (Action 5.C.2).
- Effectively **manage existing assets** to maintain capacity (Actions 5.D.1 – 5.D.5).

Table 5.3.5 Adaptation Strategies for Increase in Storm Depths for Wastewater Conveyance Systems

ISSUE	INCREASE IN STORM DEPTH FOR WASTEWATER CONVEYANCE SYSTEMS

Impact

Increased storm frequency and intensity (0-12% depth increase). Highest increases under the Hot/Dry scenario and for longer duration storms.

Potential Issues

Overflows, backups into homes and businesses

Critical Scenarios

- ✓ Central
- ✓ Hot/Dry
- ✓ Hot/Wet
- ✓ Warm/Dry
- ✓ Warm/Wet
- Trend

Key Adaptation Strategies

- **Monitor and model** inflow and infiltration in the sewer system and modify the sewer system to reduce impacts.
- **Design extra capacity** to avoid SSOs and CSOs.
- **Monitor and inspect** the integrity of existing infrastructure.
- Conduct **extreme precipitation events analyses** to understand the risk of impacts to the wastewater collection system.
- Prevent **illegal connections** to reduce flow volumes.

Links to 2009 Wastewater Plan

- Increase priority on **system maintenance**, rehabilitation and capacity certifications prior to authorizing new connections to ensure capacity maintained (Actions 7.1-7.6).
- Increase priority on **sewer system overflow emergency response** program (Action 7.8).

Table 5.3.6 Adaptation Strategies for Increase in Storm Depths for Dams and Levees

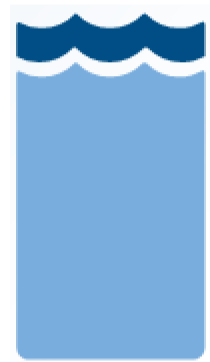
ISSUE	INCREASE IN STORM DEPTH FOR DAMS AND LEVEES

Impact

Increased storm frequency and intensity (0-12% depth increase). Highest increases under the Hot/Dry scenario and for longer duration storms.

Potential Issues

Overtopping, scouring from higher intensity storms, O&M issues from increase debris



Critical Scenarios

- Central
- Hot/Dry
- Hot/Wet
- Warm/Dry
- Warm/Wet
- Trend

Key Adaptation Strategies

- **Monitor and inspect** the integrity of existing infrastructure.
- **Evaluate** the level of control provided by existing dams and levees.
- Consider **raising crest elevations** of dams and levees.
- Design **green infrastructure** to hold more rain volume where it falls.

Links to 2009 Watershed Plan

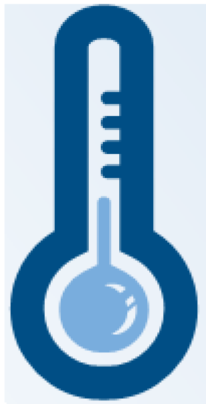
- Post-Development **Stormwater Management** (Action 5.A.1).

Table 5.3.7 Adaptation Strategies for Increased Drought for Water Treatment Plants

ISSUE	INCREASED DROUGHT FOR WTPs

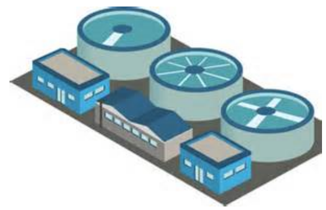
Impact

Increased drought (change in Palmer Drought Severity Index of up to -4.29)



Potential Issues

Intake infrastructure at the water treatment plant may not be designed to pull from a lower water surface elevation



Critical Scenarios

- ✓ Central
- ✓ Hot/Dry
- ✓ Hot/Wet
- ✓ Warm/Dry
- ✗ Warm/Wet
- Trend

Key Adaptation Strategies

- **Monitor and inspect** existing infrastructure's capacity to handle drought.
- **Retrofit intakes** to accommodate lower water levels in reservoirs and decreased late season flows.
- Form utility-specific **drought management plans** that include both conservation (education and outreach) and supply side management (reservoir re-operations) options in order to address short term needs.
- Implement strategies to encourage the replacement of high water using fixtures, equipment and appliances with high efficiency fixtures, equipment and appliances to **reduce demands** over the long term.

Links to 2009 Water Supply Plan

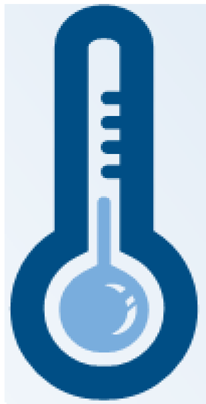
- Prioritize actions associated with the **water conservation** program (Actions 5.1-5.19).
- Prioritize development of **local emergency water plans** (Action 9.2).

Table 5.3.8 Adaptation Strategies for Increased Drought for Stormwater & Wastewater Collection Systems

ISSUE	INCREASED DROUGHT FOR STORMWATER & WASTEWATER COLLECTION SYSTEMS

Impact

Increased drought (change in Palmer Drought Severity Index of up to -4.29)



Potential Issues

A decrease in water table elevation may cause migration of tree roots.

Critical Scenarios

- ✓ Central
- ✓ Hot/Dry
- ✓ Hot/Wet
- ✓ Warm/Dry
- ✗ Warm/Wet
- Trend

Key Adaptation Strategies

- Increase **system inspection and maintenance**.
- **Anticipate damage** to the conveyance pipes due to the increased growth depth of tree roots.
- Review utility-specific **drought management plans**.

Links to 2009 Wastewater and Watershed Plans

- Wastewater Collection System **Inspection and Maintenance** Actions (Section 7 of WW Plan).
- **Asset Management** (Section 5.D of Watershed Plan).

5.3.4 Multi-Benefit Strategies

One method to prioritize adaptation strategies for implementation is to first consider those with wide ranging, multiple benefits. Two types of adaptation strategies that show up multiple times when considering the greatest risks are highlighted below.

- **Green Infrastructure**: Use of green infrastructure aims to protect and restore the natural water cycle. It allows for water to be absorbed and filtered by soil and plants instead of running directly through the engineered collection system. Implementation of green infrastructure throughout the District has the potential benefit of reducing flooding from increased storm depths by retaining more water where it falls and slowing its travel to receiving water bodies. This can reduce the need for increased dam and levee level of service, reduce flooding risks of key infrastructure and limit overflow concerns in stormwater and wastewater conveyance systems. Green infrastructure can also help reduce non-point source pollutant loads through the filtering and absorption benefit of soil and plants as well as the opportunity for settlement as water is slowed and detained. This reduction in pollutant loads may limit the need for changes in water treatment processes or wastewater effluent regulations. Finally, some green infrastructure can result in additional local water supply. Additional resources concerning green infrastructure can be found in **Section 7**.

- **Asset Management**: General asset management including regular inspection and maintenance of key infrastructure is a valuable tool in addressing future uncertainty. By keeping the current infrastructure in good condition (i.e. efficient treatment processes, maintaining conveyance capacities), it will have the most flexibility in meeting future challenges.

5.3.5 Preemptive versus Trigger Based Strategies

As the District progresses into the next phase of planning and considers possible future risks associated with climate trends, it will be important to distinguish between projects and policies that could offer universal benefits regardless of future climate conditions from those that would be targeted at mitigating the impacts of just one or two future climate trends. This section is aimed at summarizing a suite of "preemptive" adaptation measures that could be implemented immediately with no regrets, either because they address risks regardless of climate trends, or because they represent sound preparedness planning without large infrastructure investment. Infrastructure or policies designed to protect against risks isolated to one or two climate trends would be triggered if such a trend becomes plainly evident or likely in the future. **Table 5.3.9** below lists the recommended preemptive adaptation measures that could be adopted in the near term with very low risk and broad benefits:

Table 5.3.9 Recommended Preemptive Climate Adaptation Measures

Preemptive Measures	Relevant Climate Conditions	Specific Risks	Benefits of the Measure
Implement climate tracking protocols	All	- Future climate trends are uncertain	- Specific response measures can be triggered by the onset of actual, recognizable trends
Green Infrastructure	All	- Increased Storm Depth/frequency/Intensity - Increased nonpoint source pollution - Reduced reservoir yields	- Mitigate storm depth and volume - Reduce nonpoint pollution loads - Increased local water supply
Drought Management Plans	All	- Increased tendency toward more severe/frequent drought conditions from all scenarios - Potential reduction of reservoir yield from the dry scenarios	- Specific drought triggers for each utility and supply system - Unified guidance from the District on drought response - Correlation with Demand Management (below) - Potential for supply side management
Demand Management	All	- Increase in water demand	- Help conserve water by lowering demand
Integrate Reclaimed Water into Supply Planning (possibly through policy incentives that do not yet exist)	All conditions could increase demand and all tend toward more drought risk. Dry scenarios also reduce reservoir yield	- Increase in water demand - Reduction in reservoir yield - Increased drought frequency and/or severity	- Utilizes an available resource to offset demand without new hydrologic stresses - Policies and incentives could foster regional collaboration
Extreme Precipitation Analysis	Central, Hot Dry, Warm Wet	- Increased Storm Depth/frequency/Intensity	- Prioritize specific facilities at the greatest risk (conveyance, treatment, retention, etc.) that would benefit from climate-triggered enhancements
Conveyance system inspection and maintenance	All	- Increased flows during storm events - Damage due to lowering water table and tree root migration	- Prioritize upgrades to conveyance systems.

The adaptation measures in the table above are somewhat universal, in the sense that most would offer benefits to the District regardless of the future climate trends. They would either help protect against future climate-induced impacts, or provide information with which to manage the impacts when they occur. Because they are not site-specific, they can be integrated into regional planning for the overall benefit of all member counties and utilities. As part of the regional planning process, they can also be codified through regional policy (or decision frameworks) as a first step without large upfront investment. As such, these measures could be implemented in the near term with broad benefits and "no regrets", regardless of future climate trends.

Most of the rest of the recommended adaptation measures would help protect against specific risks caused by one or two specific climate trends, and many are structural solutions that require investment in site-specific infrastructure. For these reasons, such measures should be implemented based on identifying triggers in climate patterns (such as five continuous years of more frequent storm events, for example).

5.4 Relevance to the Case Study Basins

Nine case study basins from throughout the District were selected to evaluate specific climate vulnerabilities; four basins were selected for water quality evaluation (and two of these were also used for flood frequency and pollution vulnerabilities), and five additional basins were selected for reservoir yield vulnerability analysis. The following paragraphs discuss the relevance and importance of certain recommended adaptation strategies for these basins.

5.4.1 Reservoir Yield Basins

The increased propensity toward more frequent drought conditions could be exacerbated by increases in water demand. Both of these future trends are likely to occur regardless of the way the climate trends. Under certain dry scenarios, reservoir yield in small-to-midsize reservoirs in the case study basins is projected to decrease from 5 to 10 percent, and this could be compounded by a corresponding climate-induced increase in demand of 1 to 4 percent. Add to this the potential for demand to increase in response to population and industrial growth, and the water supply issue is one that requires careful management.

Two "No Regret" or "Preemptive" adaptation strategies that are recommended to help reduce the risks to water supply respond directly to these potential threats:

- **Drought Management Plans that are Specific to Each Utility**: The analysis in this study suggests that the five reservoirs evaluated are susceptible to different types of droughts. While Dog River, Gardner, and Cole Reservoirs are most vulnerable to a drought similar to that of the 1950s, Randy Poynter and Long Branch Reservoirs were more susceptible to droughts occurring later, and with different characteristics. For this reason, generalized drought responses based on regional climate indicators are not sufficient – each system responds to regional climate trends differently, based on storage, drainage area, water consumption rates, etc.

  One of the most important protections against the possibility of increased frequency and/or severity of future droughts are utility-specific drought management plans. Local drought management plans are a component of the overall Georgia Drought Management Plan and these should be reviewed and potentially expanded to include both supply and demand management (where feasible), and trigger levels for response actions that are based on time of year, demand, and the status of water availability (storage in reservoirs, flows in rivers, etc.). These variables can be combined into a probabilistic analysis of specific supply systems, but because different types and sizes of systems are vulnerable to different types of droughts, utility-specific plans are highly encouraged. For example, a small reservoir in a comparatively large drainage basin may be susceptible to sudden short-term (several months) reductions in rainfall, but would recover quickly with a few heavy rainstorms. Conversely, a large reservoir may be more susceptible to gradual, multi-year rainfall deficits, and would require longer, sustained recovery periods. The specific vulnerabilities of each system must be understood and addressed.

The District could provide generalized planning guidance so that each member utility could develop a drought management plan with a consistent template, but with unique triggers and response actions aimed specifically at their individual protection.

- **Demand Management:** The District has been promoting various forms of demand management for many years, with measureable results. Because climate-induced demand increases could compound the increases associated with other cultural and economic causes, it will be important to continue and enhance these efforts. One opportunity to do this will be to incorporate enhanced conservation practices into the 2016 Plan Integration as a key component of any overarching water management strategy.

The case study reservoirs selected for this study were chosen based on their single-purpose use and affiliation with individual utilities. However, drought management and conservation should be planned for all reservoirs within the District because these two forms of "no-regret" planning can help to counter the compounded effect of increased demand and decreased water availability. If the combined effects of drought management and conservation (not entirely mutually exclusive) can help reduce the use of reservoir water during droughts by approximately 5 to 15 percent, the climate-induced risks could be largely avoided in the case study basins.

5.4.2 Water Quality, Flooding, and Pollution Loads

Four basins were evaluated for water quality, and a subset of these were evaluated for changes in flood characteristics and pollutant loading. In all of these basins, it is evident that two key recommended adaptation measures could yield significant benefits in terms of prioritizing future actions, and in reducing the potential climate-induces risks: Better understanding of event-based precipitation potential, and the encouragement of green infrastructure.

- **Better Understanding of Event-Based Precipitation Dynamics:** Hydrologic and Hydraulic computer modeling of individual river basins will refine the planning-level assessments in this study. It will be important to know which rivers throughout the District are least likely to adapt to higher intensity or more frequent rain, and which are most likely to exhibit the most severe consequences. Through detailed physically-based modeling, rivers and adjoining infrastructure and communities can be prioritized for protective measures.

- **Green Infrastructure:** This study has posed green infrastructure as a potential way to guard against increased flows and increased pollutant loading. It is not inconceivable that creative encouragement of infiltration could help reduce the risk of lower low-flow conditions, too. All of these potential benefits could be realized in the case study basins. For example, according to the 2009 Wastewater Plan, the Flint River Basin (one of the four case study basins in this study) had 30 wastewater treatment plants (public and private) permitted to discharge up to 17.1 mgd. All of this effluent could be subject to stricter regulation if background pollutant loads increase, or low flows become lower. Many of these facilities would also likely be at risk of flooding, due to their close proximity to the riverways. Green infrastructure can potentially alleviate stress in all of these areas by helping to reduce high flows and higher nonpoint source pollutant loads, and also by potentially encouraging more infiltration to preserve low flows in between storm events.

5.5 Recommendations

The most important recommendation of this study is for the District to integrate policies and projects into its 2016 Plan Integration process that will protect against climate conditions regardless of future climate trends, or which would yield a better understanding of specific risks for some of the prevailing indications of future climate conditions. These recommendations are listed in **Section 5.3.5** as the Preemptive Adaptation Measures. In **Section 6** (Recommendations for Future Work), we recommend that a workshop be held to prioritize these activities and discuss the best ways to integrate them into the 2016 Plan Integration process. Some of the recommendations will fit naturally into the Plan Integration, while others may be worthwhile supplements. The list of recommended preemptive adaptation strategies includes:

- Integration of Green Infrastructure
- Drought Management Planning
- Demand Management
- Incentivized use of Reclaimed Water for Indirect Potable Use
- Refined Hydrologic Analysis of Precipitation Events and Frequency
- Conveyance System Inspection and Maintenance (Water and Wastewater)

The adaptation measures that provide multiple benefits, such as Green infrastructure, are also recommended for detailed consideration in the Plan Integration process, both at the region-wide policy level and at the site-specific project level. Any project that can help reduce the risk of more damaging flows and higher pollutant loading should be prioritized, as these can have broad reaching ecological benefits as well as economic benefits by reducing the need for enhanced facilities.

The remaining adaptive measures are considered to be more specific to certain climate trends, and are aimed specifically at reducing isolated risks. For these measures, appropriate triggers should be identified so that as the climate trends in certain directions, action can be taken before risks become extreme. This is discussed in more detail in **Section 6**. The triggers and corresponding adaptive measures could be easily included in the Plan Integration process.

Planning for uncertain future climate conditions should be preemptive and adaptive to the extent that it can be. This report has recommended a number of preemptive measures that would likely yield benefits regardless of future climate conditions, and for which the District should have few, if any, regrets about implementing. Because it is impossible to forecast actual future conditions, other planning should be adaptive; that is, decisions should be made in response to climate trends as they develop, with triggers established to initiate decisions before the trends create unacceptable risks.

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Section 6

Recommendations for Future Work

The following list identifies near term activities that should be undertaken by the District, either as part of the 2016 Plan Integration or separately. These activities will help prepare the District for future climate eventualities, regardless of what they may be. They are not prioritized here, but are listed for consideration based on the interpretations of the findings of this study:

1. **Establish climate tracking protocols**: Establish procedures for data collection, storage, quality assurance, and interpretation for rainfall (event, seasonal, and annual), and temperature (minimums, maximums, averages). This dataset will be used for Item #2 below (identifying indicators of statistically significant trends, and trigger levels for adaptive measures). Because the study period examined climate patterns through the year 2000, it would be advisable to include the years 2001 – 2015 in this data collection process.

2. **Identify indicators of climate trends and trigger levels for adaptive measures**: Specifically, identify indicators that temperatures, rainfall volumes, storm frequency, etc. are trending in certain directions with high statistical confidence levels. Because the study period examined climate patterns through the year 2000, it would be advisable to include the years 2001 – 2015 in this assessment. Use hydrologic and other models to establish thresholds of increases or decreases in climate variables that would trigger certain adaptation measures not included in the preemptive list in Section 3.6.

3. **Workshop on the preemptive adaptation measures recommended in Section 5.3.5:** As part of the 2016 Plan Integration, conduct a workshop on the suggested measures that are recommended regardless of future climate trends. Generally, these measures are comparatively low cost, low risk, and potentially have broad benefits to help protect against a variety of climate conditions in the future. The workshop should aim to prioritize the recommended preemptive measures, decide which ones should be included in the 2016 Plan Integration as specific recommendations, and identify those that may need further evaluation or definition. An example is green infrastructure; while it may be advisable to codify the green infrastructure philosophy into the plan, specific implementation alternatives would require additional evaluation and prioritization.

4. **Drought Management Plans:** Because of the prevailing tendency toward increased drought conditions regardless of the specific climate trends, it is highly recommended that guidelines are developed for utility-specific drought management plans. This is one of the preemptive measures discussed in Section 5.3.5 and also in Item #3 above, but this study leads to the conclusion that drought preparedness planning is essential for the District, and it is therefore recommended here. Such plans should include both supply and demand management (where feasible), and should include trigger levels for response actions that are based on time of year, demand, and the status of water availability (storage in reservoirs, flows in rivers, etc.). These variables can be combined into a probabilistic analysis of specific supply systems, but because different

types and sizes of systems are vulnerable to different types of droughts, utility-specific plans are highly encouraged. For example, a small reservoir in a comparatively large drainage basin may be susceptible to sudden short-term (several months) reductions in rainfall, but would recover quickly with a few heavy rainstorms. Conversely, a large reservoir may be more susceptible to gradual, multi-year rainfall deficits, and would require longer, sustained recovery periods. For these reasons, regional climate indicators are insufficient to adequately gird all supply systems against drought. The specific vulnerabilities of each system must be understood and addressed.

Section 7

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Appendix A

Summary Figures for the Five GCM Based Climate Scenarios

This Appendix contains a series of summary plots and tables to characterize the future climate conditions as projected by the Global Climate Models. Included are mean monthly seasonal plots, annual time series plots and percentile plots for both precipitation and temperature. Annual mean, minimum, maximum, and standard deviation values of precipitation and temperature have also been tabulated for each ensemble.

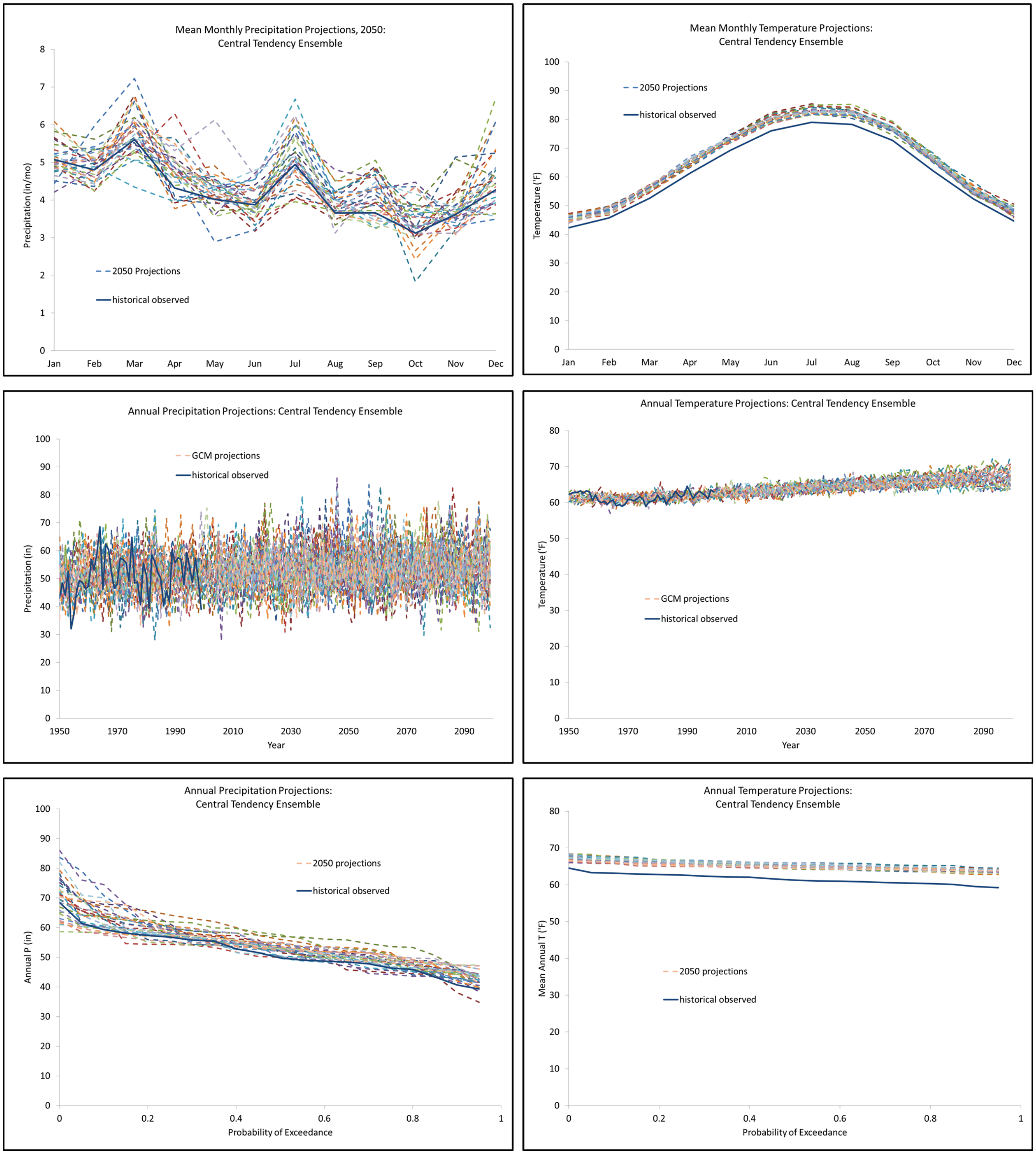

Figure A.1: Central Tendency Climate Scenario Summary Plots

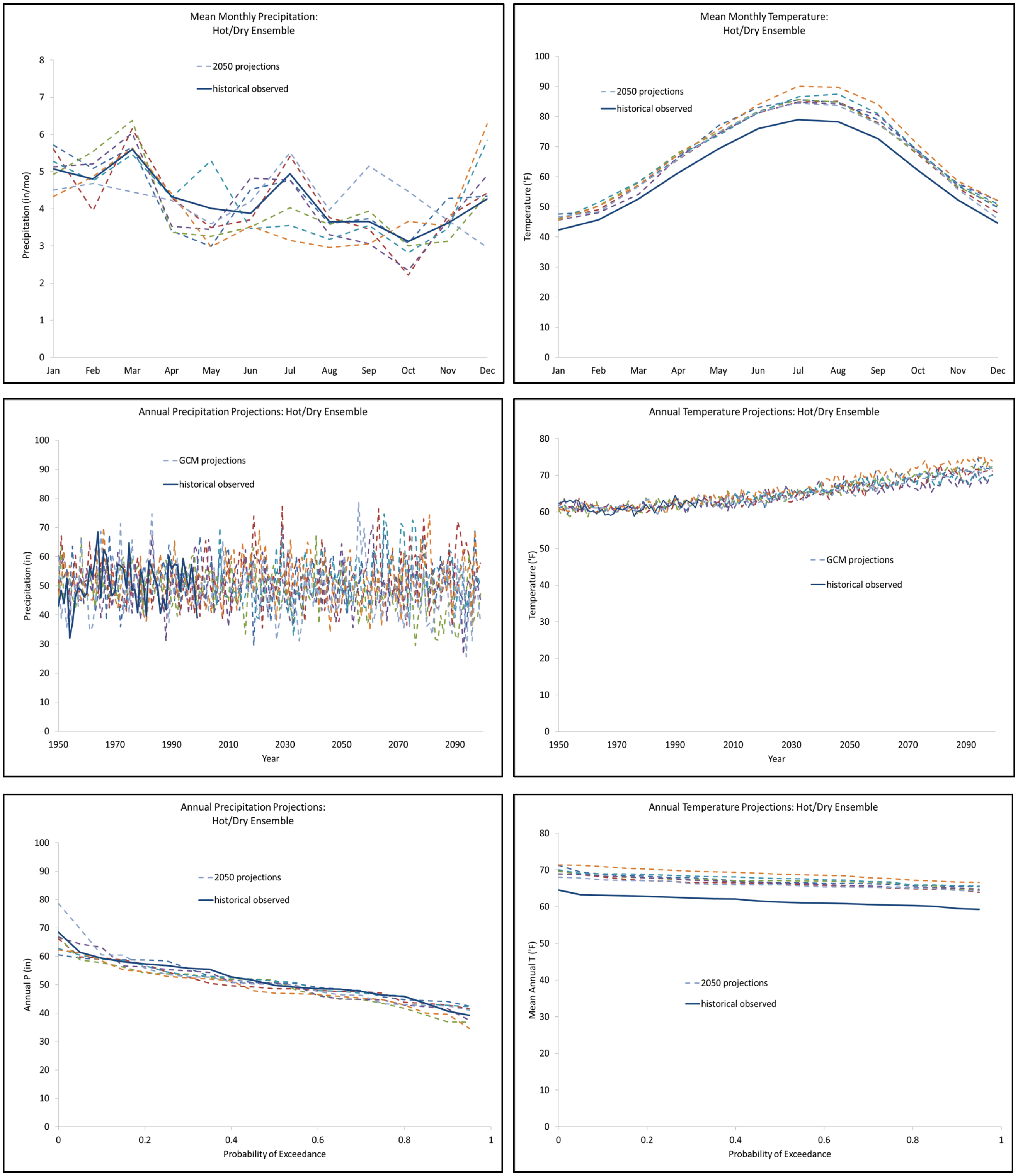

Figure A.2: Hot/Dry Climate Scenario Summary Plots

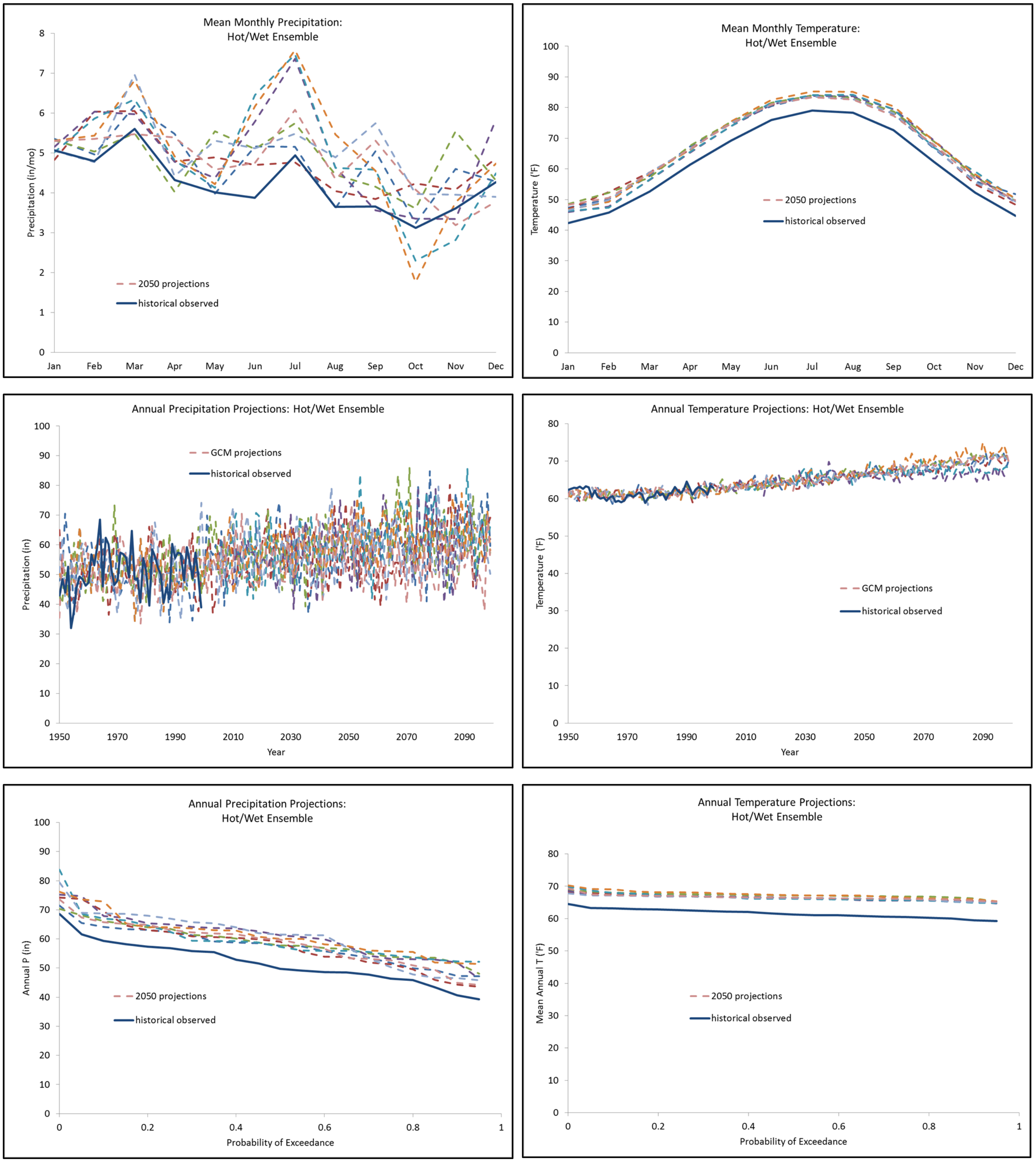

Figure A.3: Hot/Wet Climate Scenario Summary Plots

Figure A.4: Warm/Dry Climate Scenario Summary Plots

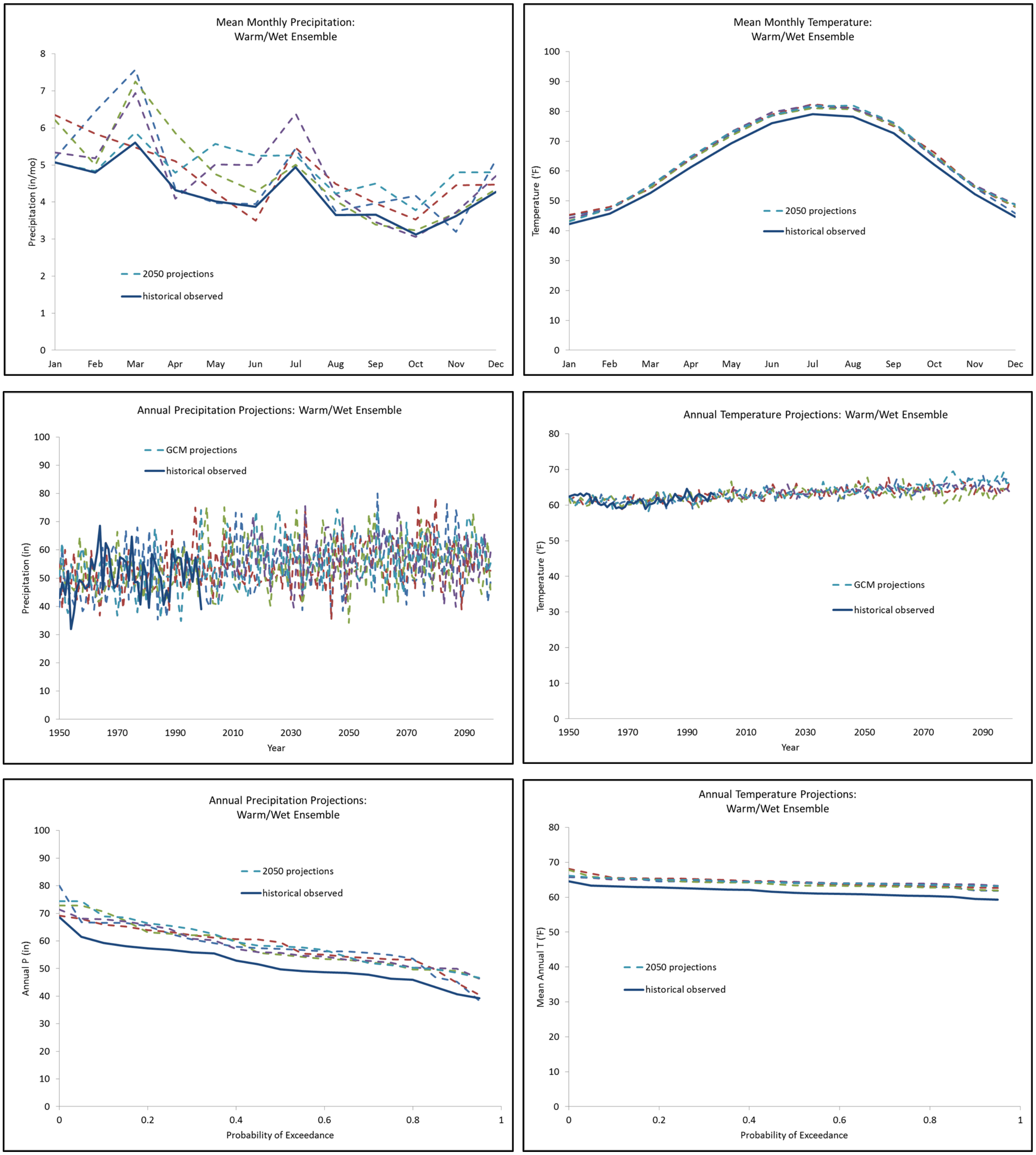

Figure A.5: Warm/Wet Climate Scenario Summary Plots

Table A.1: Annual Statistics for Projections in the Central Tendency Climate Ensemble

Statistics	*access1-0.1.rcp45*	*bcc-csm1-1.1.rcp60*	*bcc-csm1-1-m.1.rcp85*	*canesm2.1.rcp26*	*canesm2.1.rcp45*	*cesm1-bgc.1.rcp45*	*cnrm-cm5.1.rcp45*	*cnrm-cm5.1.rcp85*	*csiro-mk3-6-0.1.rcp26*	*gfdl-esm2g.1.rcp60*	*gfdl-esm2g.1.rcp85*
Mean Annual Precipitation (in)	53.2	51.9	56.3	55.4	53.4	56.2	53.8	54.0	55.2	53.2	52.5
Maximum Annual Precipitation (in)	78.3	69.5	65.2	75.2	74.2	70.4	76.1	71.6	66.9	76.8	69.6
Minimum Annual Precipitation (in)	39.5	34.4	43.0	41.1	40.3	37.2	37.7	43.8	39.3	37.2	37.2
Std Dev in Annual Precipitation (in)	7.8	9.9	6.4	9.2	8.6	9.5	9.6	7.5	8.2	10.2	8.4
Mean Annual Temperature ('F)	65.5	65.2	65.5	65.3	65.9	65.6	64.5	65.6	64.5	64.6	65.7
Maximum Annual Temperature ('F)	67.4	67.1	67.8	67.2	67.6	68.0	67.0	68.3	66.6	66.9	67.7
Minimum Annual Temperature ('F)	62.7	63.2	63.4	63.7	64.3	63.6	62.8	63.4	63.0	62.8	63.3
Std Dev in Annual Temperature ('F)	1.3	1.3	1.0	1.1	0.8	1.3	1.1	1.2	1.0	1.1	1.3

Table A.1: Annual Statistics for Projections in the Central Tendency Climate Ensemble Cont.

Statistics	*gfdl-esm2m.1.rcp85*	*giss-e2-r.1.rcp45*	*hadgem2-ao.1.rcp26*	*hadgem2-es.1.rcp60*	*ipsl-cm5a-lr.1.rcp60*	*ipsl-cm5a-mr.1.rcp26*	*ipsl-cm5b-lr.1.rcp45*	*miroc5.1.rcp26*	*miroc5.1.rcp60*	*miroc-esm.1.rcp26*	*miroc-esm.1.rcp45*
Mean Annual Precipitation (in)	55.2	55.5	51.7	52.5	54.1	52.2	54.3	51.8	52.4	51.7	53.2
Maximum Annual Precipitation (in)	79.4	83.7	71.1	64.8	86.1	72.1	72.9	63.1	62.3	58.6	65.9
Minimum Annual Precipitation (in)	36.5	37.6	40.2	40.1	38.6	41.5	37.3	40.7	39.0	42.7	38.9
Std Dev in Annual Precipitation (in)	9.7	12.0	7.7	6.6	12.8	7.7	8.7	6.4	5.7	5.0	6.6
Mean Annual Temperature ('F)	65.0	64.9	65.3	65.7	64.9	64.8	64.6	65.1	64.6	65.1	65.1
Maximum Annual Temperature ('F)	67.7	67.3	67.4	68.4	66.0	66.7	66.8	68.0	66.4	66.5	66.6
Minimum Annual Temperature ('F)	61.3	62.4	63.1	63.8	62.6	63.0	62.5	63.1	62.9	63.3	63.3
Std Dev in Annual Temperature ('F)	1.6	1.1	1.2	1.3	0.9	0.9	1.2	1.1	0.8	0.9	0.9

Table A.1: Annual Statistics for Projections in the Central Tendency Climate Ensemble Cont.

Statistics	*miroc-esm.1.rcp60*	*miroc-esm-chem.1.rcp26*	*miroc-esm-chem.1.rcp45*	*miroc-esm-chem.1.rcp60*	*mpi-esm-mr.1.rcp45*	*noresm1-m.1.rcp45*	*noresm1-me.1.rcp45*	*noresm1-me.1.rcp60*	*observed*
Mean Annual Precipitation (in)	52.6	53.1	53.5	52.5	54.5	55.4	53.8	54.4	50.9
Maximum Annual Precipitation (in)	61.0	61.6	65.5	62.3	72.5	68.5	82.2	70.5	68.5
Minimum Annual Precipitation (in)	43.9	44.4	43.3	37.5	47.2	42.1	42.4	40.2	32.0
Std Dev in Annual Precipitation (in)	5.8	4.7	6.0	5.2	7.0	7.2	10.1	9.1	7.5
Mean Annual Temperature ('F)	65.4	65.0	65.7	65.2	64.9	64.9	65.6	64.7	61.4
Maximum Annual Temperature ('F)	68.2	66.5	67.5	66.3	67.3	68.5	67.2	66.7	64.5
Minimum Annual Temperature ('F)	63.5	63.5	64.0	63.9	61.5	62.5	63.7	62.1	58.9
Std Dev in Annual Temperature ('F)	1.2	0.8	1.0	0.7	1.5	1.3	1.0	1.0	1.4

Table A.2: Annual Statistics for Projections in the Hot/Dry Climate Ensemble

Statistics	*access1-0.1.rcp85*	*cmcc-cm.1.rcp85*	*fgoals-g2.1.rcp85*	*hadgem2-cc.1.rcp45*	*hadgem2-es.1.rcp45*	*hadgem2-es.1.rcp85*	*ipsl-cm5a-mr.1.rcp85*	*observed*
Mean Annual Precipitation (in)	51.2	50.3	49.0	50.2	51.0	48.4	51.4	50.9
Maximum Annual Precipitation (in)	60.5	66.2	67.1	66.7	62.8	62.3	78.7	68.5
Minimum Annual Precipitation (in)	39.7	37.7	36.5	35.6	41.6	33.9	40.3	32.0
Std Dev in Annual Precipitation (in)	6.3	7.0	8.2	8.5	6.3	7.8	9.6	7.5
Mean Annual Temperature ('F)	67.1	66.2	66.9	66.6	67.6	68.9	65.9	61.4
Maximum Annual Temperature ('F)	71.3	69.8	69.6	69.0	70.0	71.4	68.0	64.5
Minimum Annual Temperature ('F)	65.4	63.5	64.1	64.6	65.5	66.6	64.2	58.9
Std Dev in Annual Temperature ('F)	1.5	1.5	1.4	1.3	1.3	1.5	1.1	1.4

Table A.3: Annual Statistics for Projections in the Hot/Wet Climate Ensemble

Statistics	*ccsm4.1.rcp85*	*cesm1-bgc.1.rcp85*	*cesm1-cam5.1.rcp85*	*gfdl-cm3.1.rcp26*	*gfdl-cm3.1.rcp45*	*gfdl-cm3.1.rcp85*	*noresm1-m.1.rcp85*	*noresm1-me.1.rcp85*	*observed*
Mean Annual Precipitation (in)	57.0	57.1	58.3	60.2	58.9	60.8	59.6	57.6	50.9
Maximum Annual Precipitation (in)	71.4	74.2	70.3	75.2	83.8	76.2	79.4	73.6	68.5
Minimum Annual Precipitation (in)	45.6	41.6	42.1	44.5	41.8	51.5	42.0	41.4	32.0
Std Dev in Annual Precipitation (in)	6.9	9.3	6.8	8.2	8.3	7.2	10.0	8.4	7.5
Mean Annual Temperature ('F)	66.5	66.5	67.1	66.2	66.4	67.4	66.3	66.5	61.4
Maximum Annual Temperature ('F)	68.8	68.0	68.8	68.6	69.9	70.3	67.8	69.4	64.5
Minimum Annual Temperature ('F)	64.8	65.0	64.3	64.0	63.5	65.1	64.5	65.2	58.9
Std Dev in Annual Temperature ('F)	1.1	0.8	1.0	1.0	1.4	1.3	0.8	0.9	1.4

Table A.4: Annual Statistics for Projections in the Warm/Dry Climate Ensemble

Statistics	*bcc-csm1-1.1.rcp26*	*fgoals-g2.1.rcp26*	*gfdl-esm2g.1.rcp26*	*gfdl-esm2m.1.rcp26*	*gfdl-esm2m.1.rcp45*	*gfdl-esm2m.1.rcp60*	*inmcm4.1.rcp45*	*inmcm4.1.rcp85*	*ipsl-cm5a-mr.1.rcp60*	*mpi-esm-lr.1.rcp26*	*observed*
Mean Annual Precipitation (in)	51.1	50.8	51.4	49.9	50.9	49.1	50.7	49.1	46.0	51.1	50.9
Maximum Annual Precipitation (in)	73.4	61.9	65.2	69.5	74.2	66.7	66.7	71.1	62.0	64.1	68.5
Minimum Annual Precipitation (in)	29.7	34.1	39.9	32.3	28.6	33.7	30.8	37.4	26.3	39.8	32.0
Std Dev in Annual Precipitation (in)	9.3	6.6	7.4	10.6	11.9	9.2	9.8	7.8	8.8	7.0	7.5
Mean Annual Temperature ('F)	64.5	64.5	63.9	64.2	64.5	64.4	63.4	64.1	64.4	64.2	61.4
Maximum Annual Temperature ('F)	67.2	66.2	65.8	67.4	67.5	68.8	65.5	66.1	65.8	67.2	64.5
Minimum Annual Temperature ('F)	62.0	63.2	61.3	61.5	62.4	62.2	61.9	62.2	62.3	61.8	58.9
Std Dev in Annual Temperature ('F)	1.3	0.9	1.3	1.6	1.4	1.8	0.8	1.1	0.9	1.3	1.4

Table A.5: Annual Statistics for Projections in the Warm/Wet Climate Ensemble

Statistics	*giss-e2-r.1.rcp60*	*giss-e2-r-cc.1.rcp45*	*mpi-esm-mr.1.rcp26*	*noresm1-m.1.rcp26*	*noresm1-m.1.rcp60*	*observed*
Mean Annual Precipitation (in)	57.1	56.9	57.0	57.1	58.7	50.9
Maximum Annual Precipitation (in)	80.1	69.2	72.9	71.3	74.4	68.5
Minimum Annual Precipitation (in)	36.3	35.2	34.2	41.4	45.7	32.0
Std Dev in Annual Precipitation (in)	9.9	8.9	9.5	8.0	8.8	7.5
Mean Annual Temperature ('F)	63.8	64.3	63.8	64.4	64.3	61.4
Maximum Annual Temperature ('F)	65.8	68.1	67.8	66.0	66.2	64.5
Minimum Annual Temperature ('F)	61.1	62.1	61.9	63.3	63.1	58.9
Std Dev in Annual Temperature ('F)	1.2	1.5	1.4	0.7	0.9	1.4

Appendix B

HDe Method Results

This Appendix contains the results of the Hybrid Delta Ensemble (HDe) method applied to adjust the historical climate record to reflect the five future climate scenarios. Monthly timeseries for the full 50 year adjusted period is provided as well as percentile plots of both temperature and precipitation.

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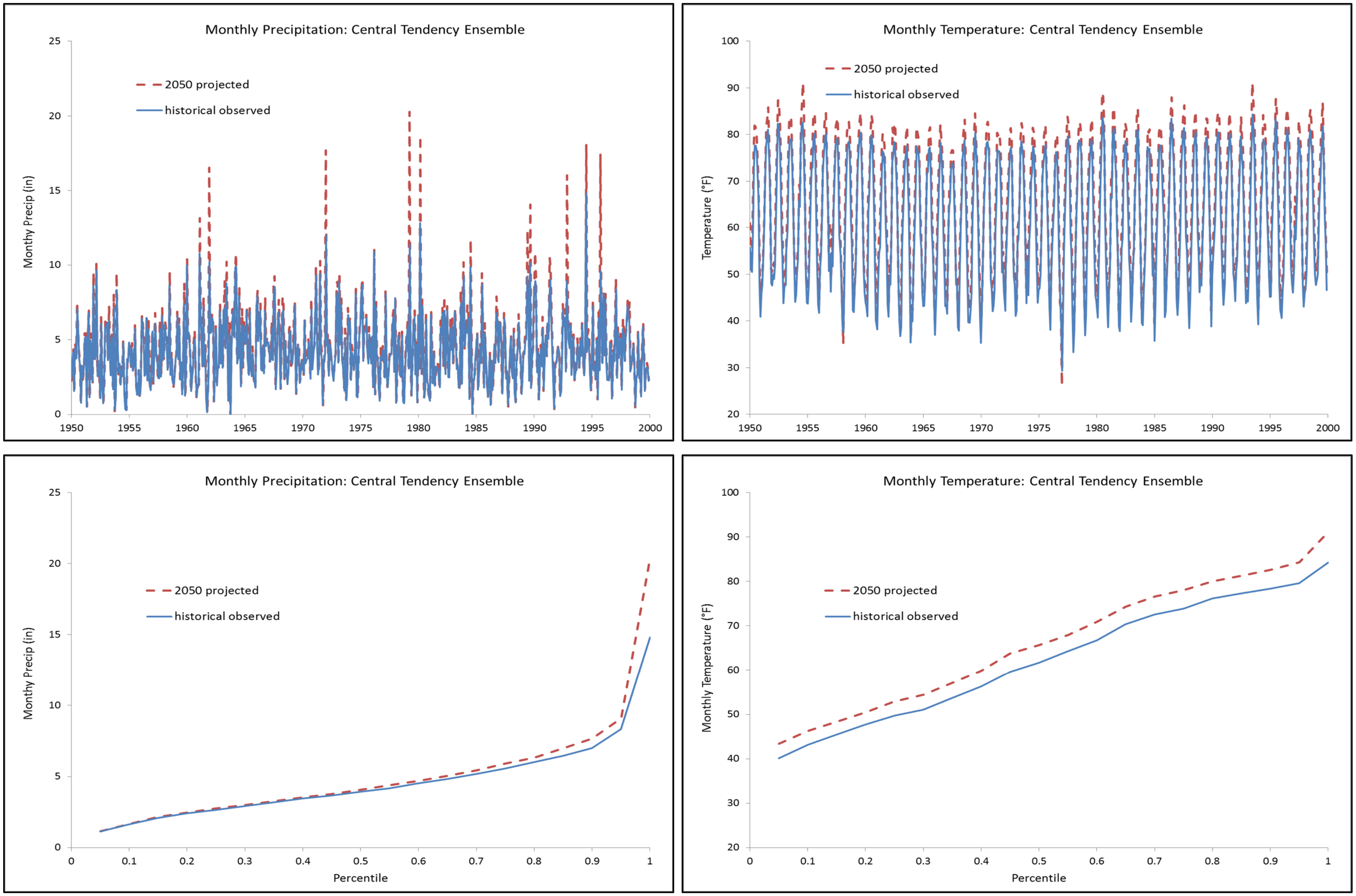

Figure B.1: Central Tendency Ensemble

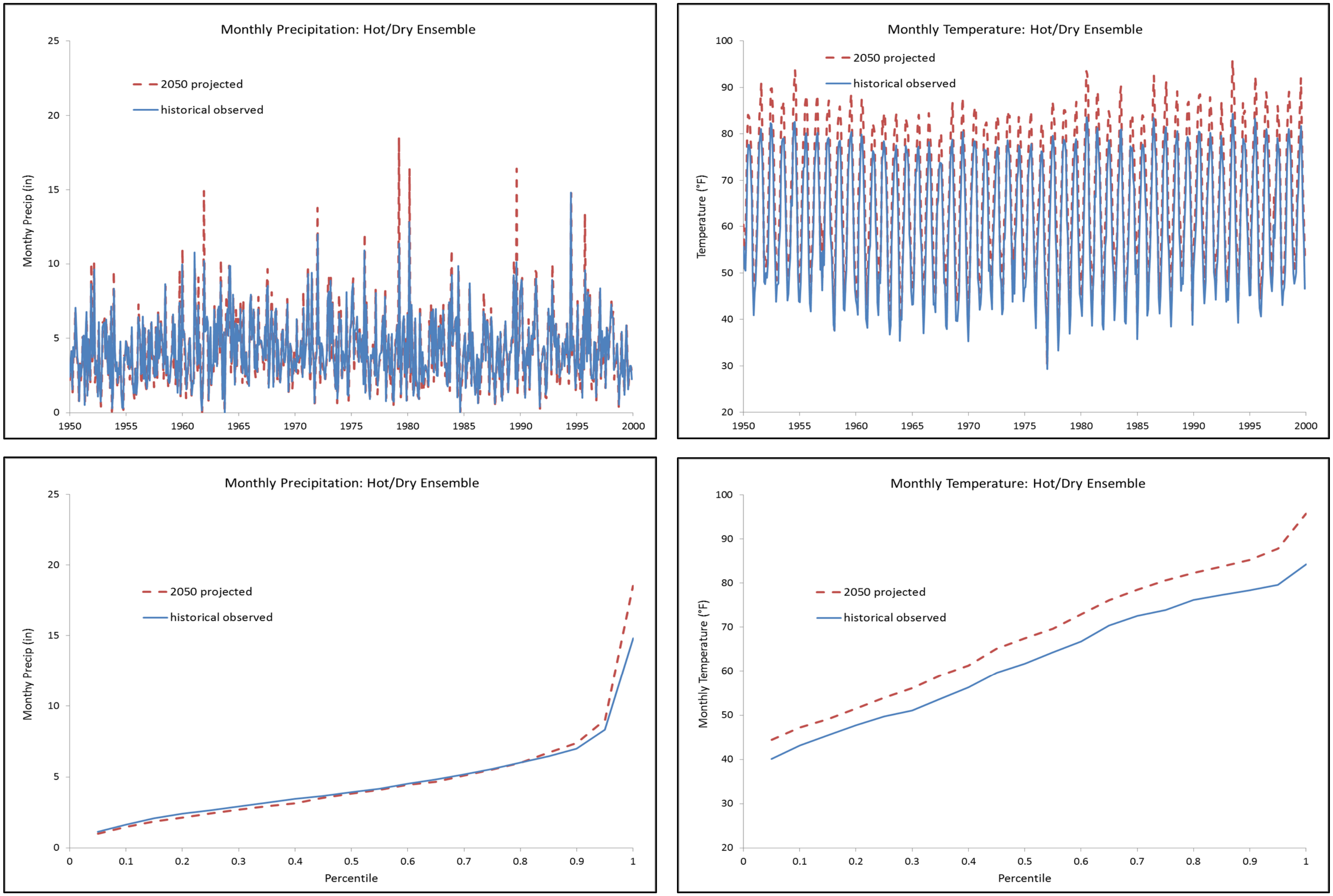

Figure B.2: Hot/Dry Ensemble

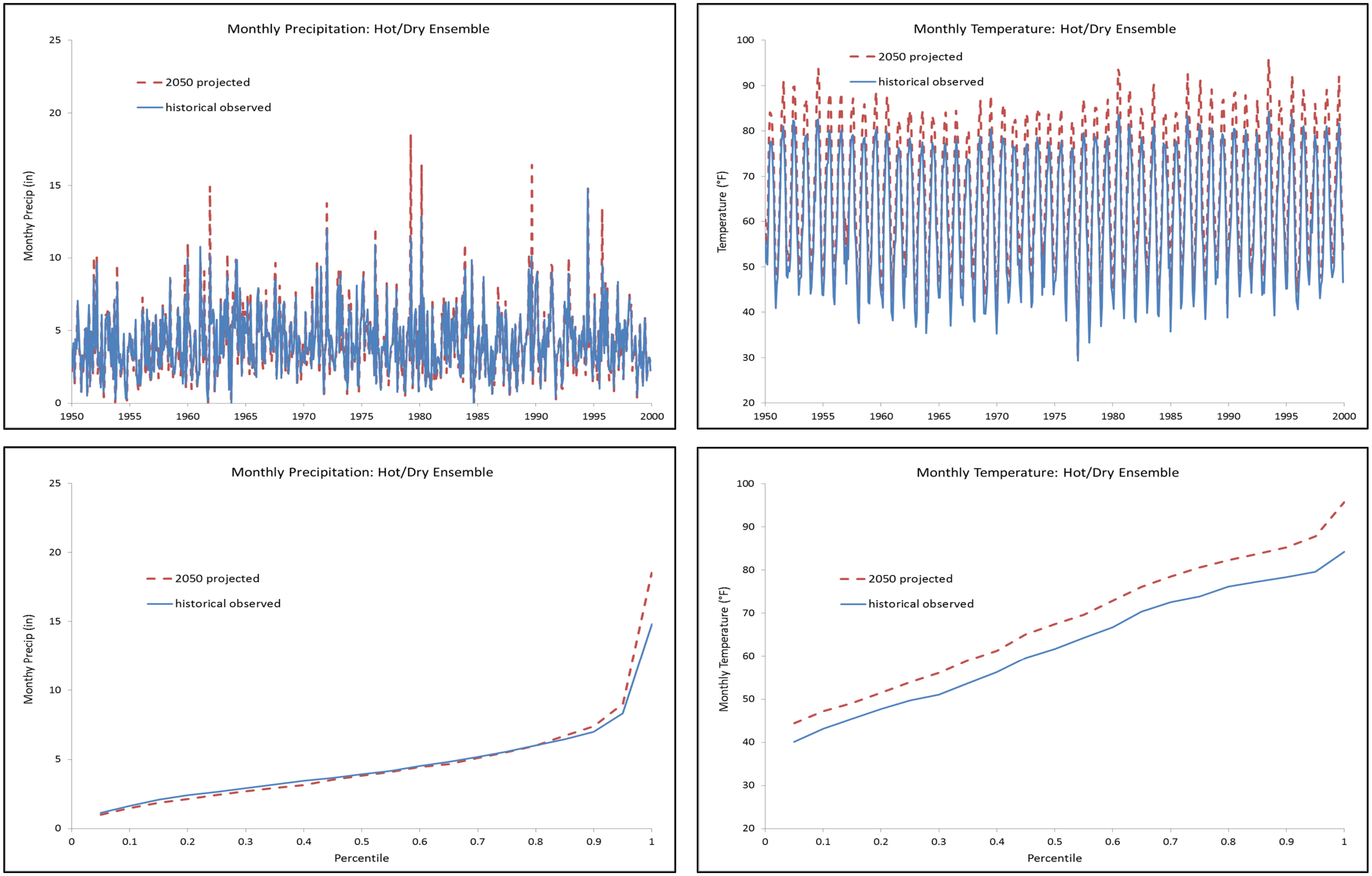

Figure B.3: Hot/Wet Ensemble

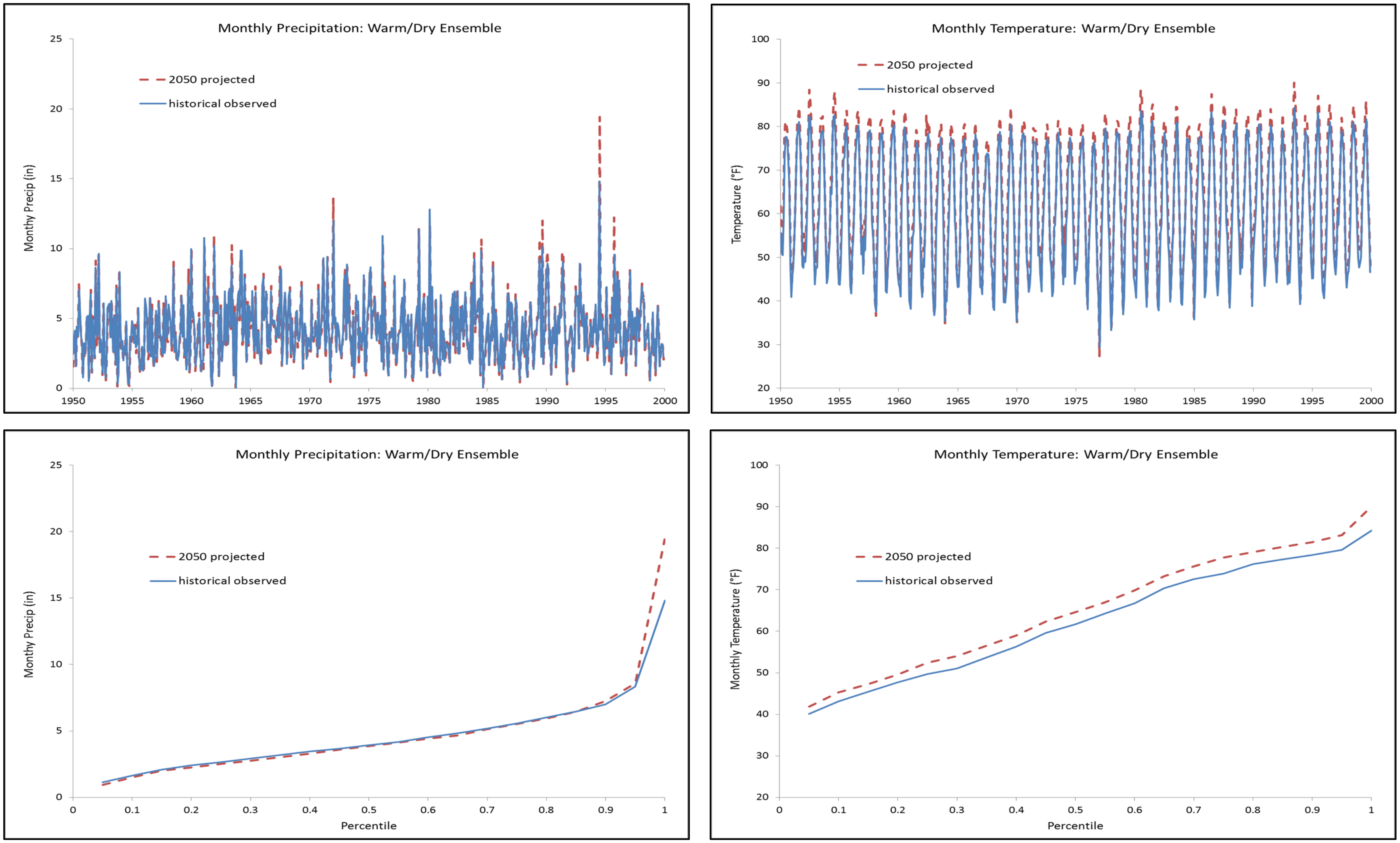

Figure B.4: Warm/Dry Ensemble

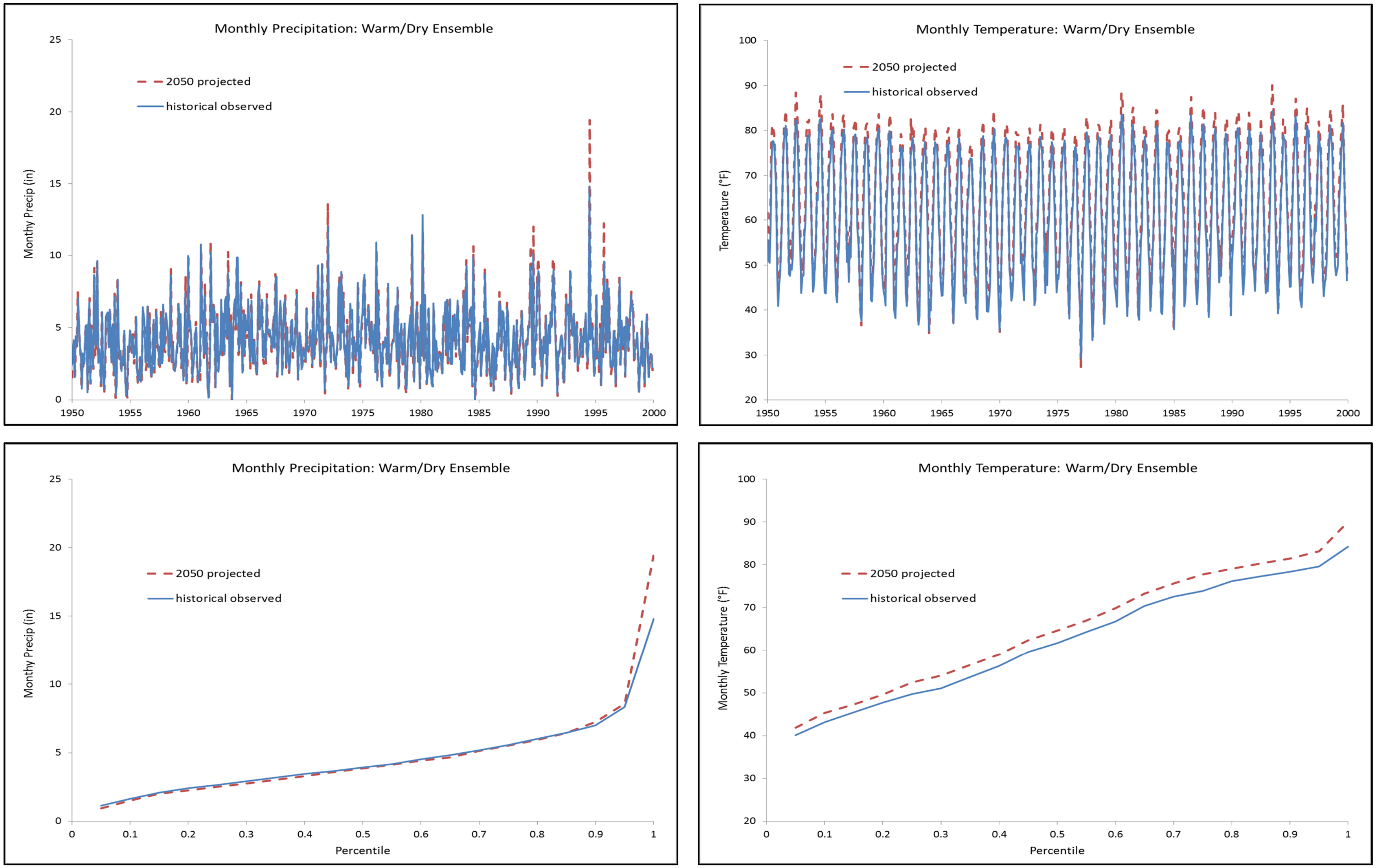

Figure B.5: Warm/Wet Ensemble

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Appendix C

Statistical Water Demand Analysis

Data

To construct the multivariate statistical regression for the water demand model, monthly per capita water use (in gallons per person per day) was used as the dependent variable. Per capita water use was constructed by taking the total surface water withdrawals (reservoir and river) for DeKalb, Fulton, and Gwinnett Counties and dividing it by population for the same three counties. **Figure C-1** presents the water withdrawals and population data, both provided by Metro Water District.

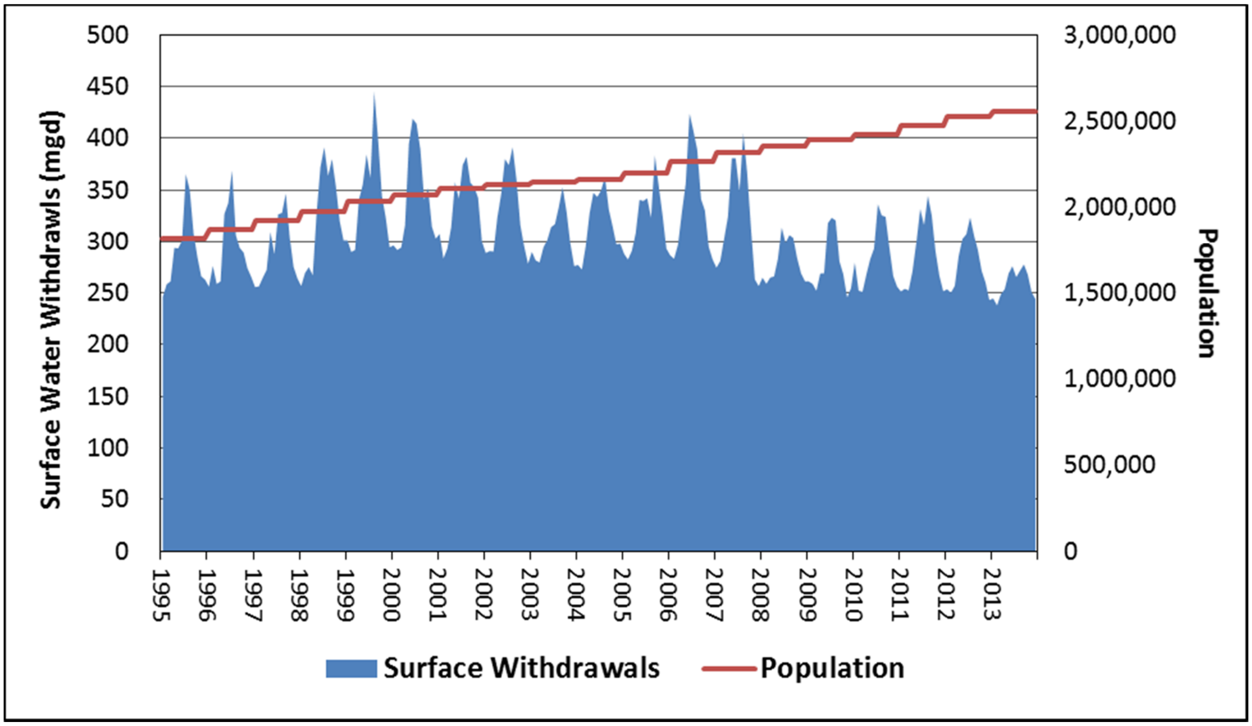

Figure C-1. Monthly Surface Water Withdrawals and Population for DeKalb, Fulton and Gwinnett Counties
(Source: Metro Water District)

Details for the following independent variables are indicated below:

- Average maximum monthly temperature (see **Figure C-2**) and monthly precipitation (see **Figure C-3**), both obtained from Atlanta Airport weather station.
- Constructed average monthly water bill for Gwinnett County (see **Figure C-4**), using GEFA/EFC annual water rate reports.
- Constructed toilet flush volume, as an indicator of plumbing efficiency (see **Figure C-5**), using housing data and plumbing code dates provided by Metro Water District.

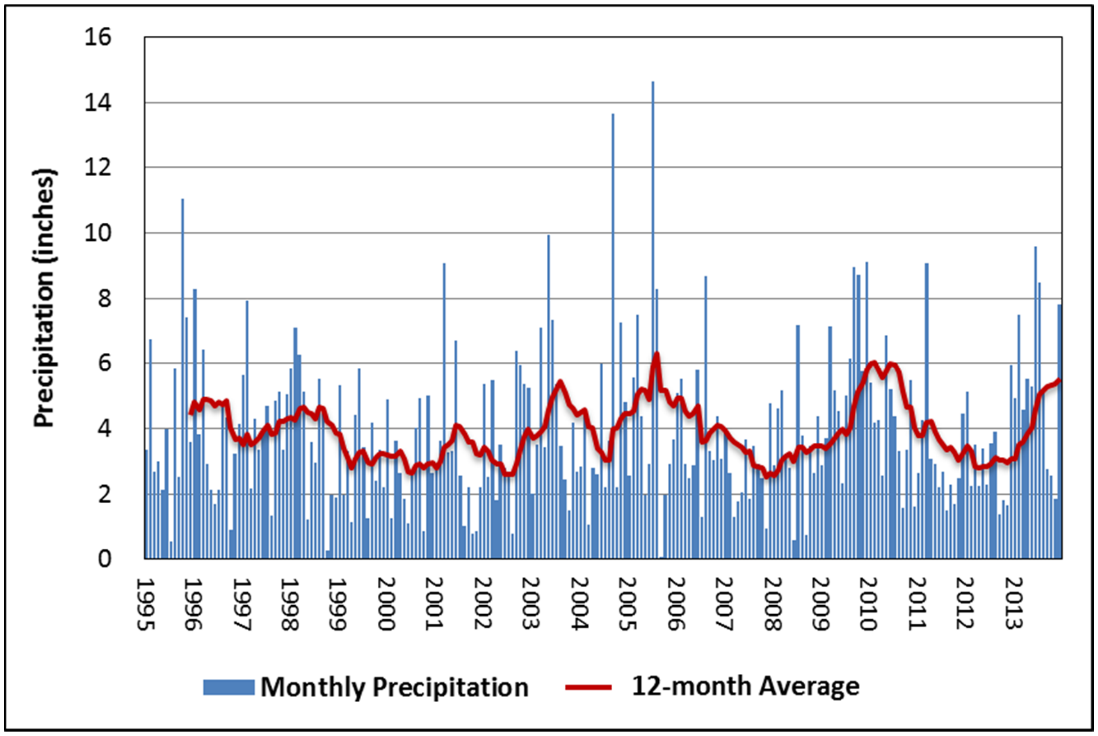

Figure C-2. Monthly Precipitation
(Source: Atlanta Airport weather station)

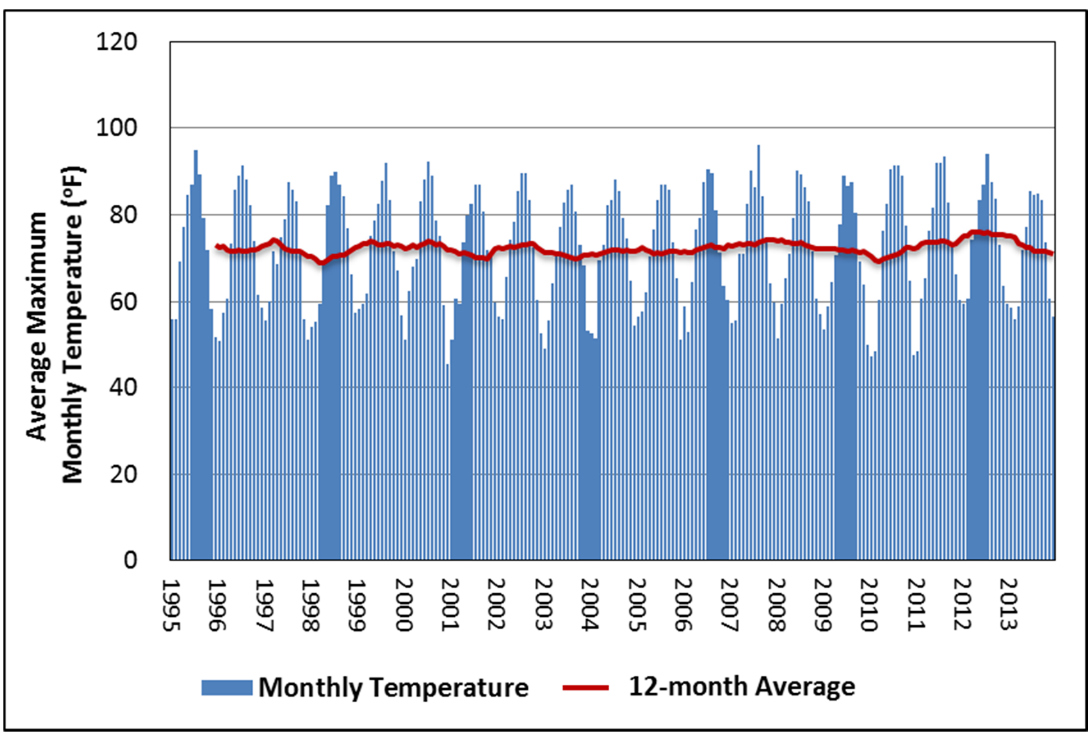

Figure C-3. Average Maximum Monthly Temperature
(Source: Atlanta Airport weather station)

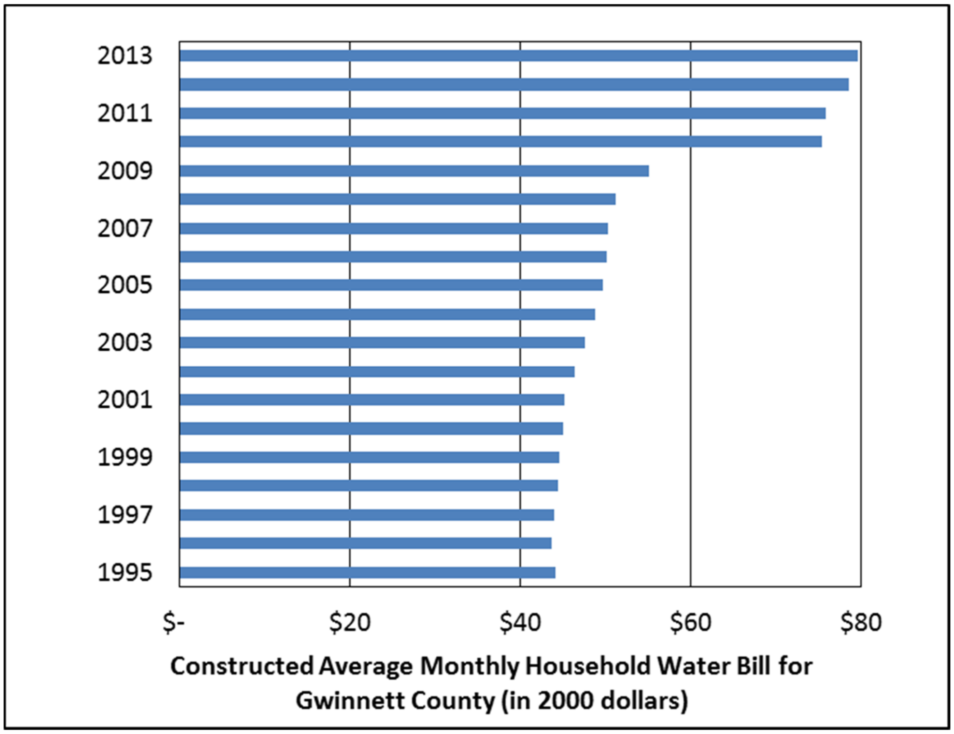

Figure C-4. Average Monthly Household Water Bill
(Source: GEFA/EFC annual water rates reports)

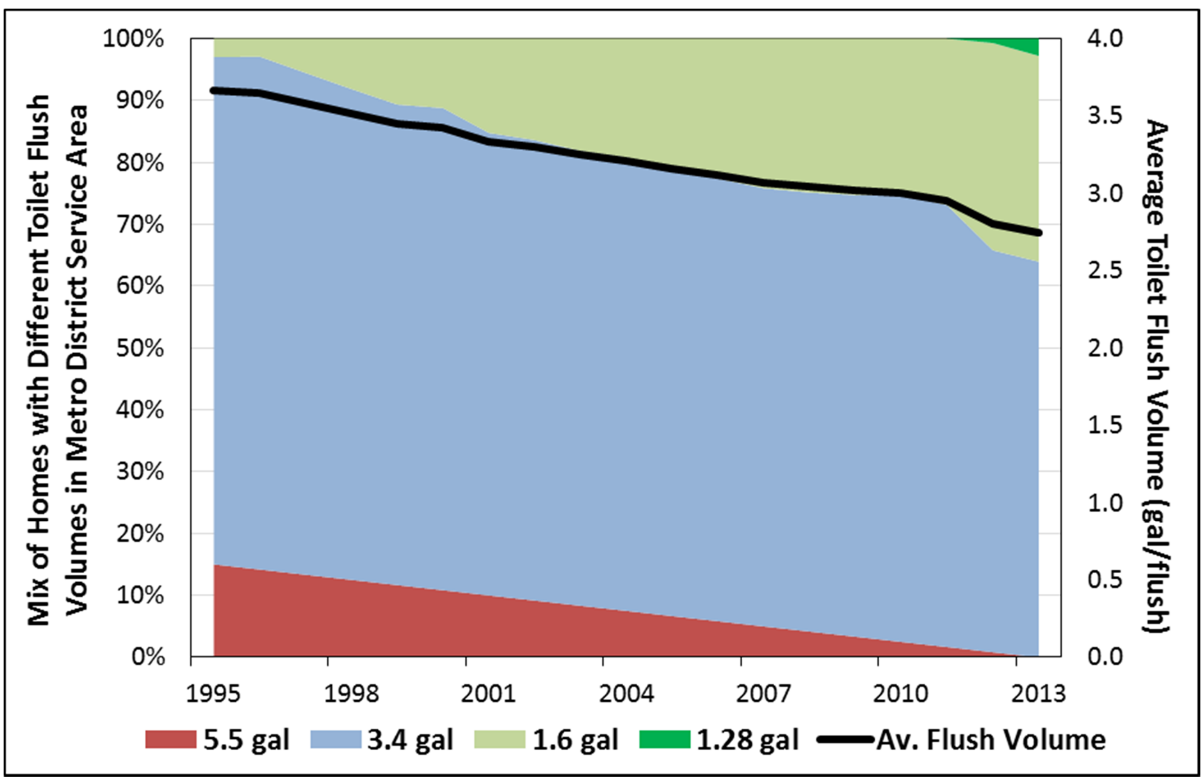

Figure C-5. Toilet Flush Volume
(Source: constructed from annual housing data and plumbing code dates provided by Metro Water District)

Statistical Model

The output from the statistical demand model is shown below.

Regression Statistics	
Multiple R	0.957
R Square	0.916
Adjusted R Square	0.909
Standard Error	0.056
Significance F	<0.0001
Observations	228

	Coeff.	*St. Error*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	4.512	0.353	<0.0001	3.815	5.209
Unemployment	-0.202	0.025	<0.0001	-0.251	-0.152
Rainfall	-0.028	0.006	<0.0001	-0.040	-0.016
Temperature	0.346	0.048	<0.0001	0.250	0.441
Drought Restrictions	-0.033	0.005	<0.0001	-0.042	-0.024
Plumbing Efficiency	0.080	0.113	0.480	-0.143	0.302
Water Price	-0.192	0.060	0.002	-0.310	-0.073
Stewardship Act	-0.054	0.009	<0.0001	-0.072	-0.036
Jan	0.009	0.016	0.590	-0.023	0.040
Mar	-0.050	0.015	0.001	-0.080	-0.019
Apr	-0.032	0.017	0.061	-0.066	0.001
May	0.030	0.020	0.128	-0.009	0.070
Jun	0.059	0.023	0.010	0.014	0.103
Jul	0.068	0.024	0.004	0.022	0.115
Aug	0.074	0.023	0.002	0.028	0.120
Sep	0.055	0.021	0.009	0.014	0.095
Nov	-0.004	0.015	0.805	-0.033	0.026

Model Parameters:

Dependent Variable	Per Capita Demand (gpcd), monthly, natural log value
Independent Variables	Unemployment Rate (%), annual, natural log value
	Rainfall (inches), monthly, natural log value
	Average Max Temperature, monthly, natural log value
	Drought Restrictions (binary), monthly
	Pluming Code Average Flush Capacity (gal/flush), annual, natural log value
	Water Price (household water bill, $2000), annual, natural log value
	GA Stewardship Act (binary), monthly
	January Binary, monthly
	March Binary, monthly
	April Binary, monthly
	May Binary, monthly
	June Binary, monthly
	July Binary, monthly
	August Binary, monthly
	September Binary, monthly
	November Binary, monthly

Appendix D

Adaptive Strategies

This appendix provides a full list of adaptive strategies developed during the literature review (**Table D.1**) and the review of the 2009 Management Plans (**Table D.2 through D.4**).

Table D.1: Adaptive Strategy List

Adaptive Strategy	Climate Trend						System Impacted							
	Central Tendency	Hot/Dry	Hot/Wet	Warm/Dry	Warm/Wet	Historical Trend	Water Treatment Plants	Wastewater Treatment Plants	Stormwater Conveyance Systems	Dams & Levees	Wastewater Collection System	Streams & Ecosystems	Reservoir	Policy
Elevate facilities to avoid flooding from increased storm depth	X	X			X		X	X		X				
Floodproof facilities to avoid flooding from increased storm depth	X	X			X		X	X		X				
Relocate facilities to higher ground to avoid flooding from increased storm depth	X	X			X		X	X		X				
Build levees to avoid flooding from increased storm depth	X	X			X		X	X		X				
Change drinking water treatment processes to address water quality concerns from source water bodies from increased non-point source pollutant loads and other potential future climate conditions	X	X	X	X	X	X	X							
Add additional chlorine boosters to address increased temperatures	X	X	X	X	X	X	X							
Develop models to understand water quality changes and costs of resultant changes in treatment due to changes in non-point source pollutant loads and other potential future climate conditions	X	X	X	X	X	X	X	X	X		X	X	X	
Retrofit water treatment plant intakes to accommodate lower water levels in reservoirs and decreased late season flows as a result of increased drought	X	X	X	X			X							
Monitor and inspect the integrity of existing infrastructure to handle existing and potential future climate scenarios	X	X	X	X	X	X	X	X	X	X	X	X	X	
Establish alternative power supplies, potentially through on-site generation, to support operations in case of loss of power	X	X	X	X	X	X	X	X	X		X		X	
Improve pumps to avoid backflow prevention from receiving and source water bodies with increased water levels as a result of increased storm depths	X	X			X		X	X						

Table D.1: Adaptive Strategy List

Adaptive Strategy	Climate Trend						System Impacted							
	Central Tendency	Hot/Dry	Hot/Wet	Warm/Dry	Warm/Wet	Historical Trend	Water Treatment Plants	Wastewater Treatment Plants	Stormwater Conveyance Systems	Dams & Levees	Wastewater Collection System	Streams & Ecosystems	Reservoir	Policy
Design extra re-aeration to account for the reduced DO in the effluent and receiving water bodies to address potential increased temperatures and pollutant loading.	X	X	X	X	X			X						
Land use planning changes to address increases in non-point source pollutant loads	X	X	X	X	X	X	X	X				X		
Design plant outfalls, structures, and equipment at higher elevation to address increases in storm depth	X	X			X			X						
Design water reuse systems to address water supply shortages during times of increased drought	X	X	X	X								X	X	X
Anticipate reduced flows from increased water conservation during times of increased drought	X	X	X	X				X						
Anticipate changes in TMDLs and more stringent permits to offset reduced stream flows due to increased drought	X	X	X	X			X	X				X		X
Anticipate permits to require cooling wastewater before discharging to receiving water bodies and design temperature treatment processes due to increased temperatures	X	X	X	X	X	X		X						X
Anticipate needs for revisiting NPDES permitting process for water quality due to increased temperatures impacting water bodies	X	X	X	X	X	X		X						X
Identify weakness in the processes that would be stressed by sudden shifts between extreme operating conditions due to increased storm depths.	X	X	X	X	X	X								
Increase capacity to hedge against infrastructure losses, overflows, and disruptions due to increased storm depths	X	X			X			X	X		X			
Monitor systems to understand the impact of higher groundwater infiltration due to increased storm depths	X	X			X			X	X		X	X		
Conduct stress testing on wastewater treatment biological systems to assess tolerance to increased heat	X	X	X	X	X	X		X						
Design green infrastructure with appropriate vegetation to address increased non-point source pollutant loadings, increased storm depth, and increased temperatures	X	X	X	X	X	X	X	X	X			X		
Anticipate increased maintenance and inspection costs due to increased drought, increased storm depth, and associated sediment transport	X	X			X		X	X	X	X	X	X	X	
Anticipate damage due to tree root migration due to increased drought	X	X	X	X					X		X			
Develop models to predict future runoff conditions due to increased storm depth	X	X			X				X			X		

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Table D.1: Adaptive Strategy List

Adaptive Strategy	Climate Trend						System Impacted							
	Central Tendency	Hot/Dry	Hot/Wet	Warm/Dry	Warm/Wet	Historical Trend	Water Treatment Plants	Wastewater Treatment Plants	Stormwater Conveyance Systems	Dams & Levees	Wastewater Collection System	Streams & Ecosystems	Reservoir	Policy
Conduct analyses on extreme precipitation to understand the risks of impacts on the system	X	X	X	X	X	X	X	X	X	X	X	X	X	
Model systems to understand inflow and filtration, and reduce system inflow and infiltration by preventing illegal connections and leaks, as well as other prevention measures, to reduce flow volumes during increased storm depths	X	X			X				X		X			
Design systems for water reuse to address increased drought	X	X	X	X			X	X	X		X		X	
Regulate point source and non-point source pollutant loads	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Acquire and manage ecosystems to regulate runoff from increased storm depths	X	X			X			X	X			X	X	
Monitor surface water conditions, including river discharge, streamflow, and water quality to understand impacts of climate conditions	X	X	X	X	X	X						X	X	
Monitor vegetation changes in watersheds to understand impacts of climate conditions	X	X	X	X	X	X						X		
Practice fire management strategies, such as mechanical thinning, weed control, selective harvesting, controlled burns, and creation of fire breaks to address increased drought	X	X	X	X								X		
Modify fill and withdrawal procedures for reservoirs to address changes in drought, water supply and increased storm depths	X	X	X	X	X								X	X
Control reservoirs to limit flooding to address increased storm depths	X	X			X								X	
Work with irrigators to install advanced equipment to address increased drought conditions	X	X	X	X									X	
Practice water conservation and demand management through water metering, rebates for water conservation appliances, and/or rainwater harvesting tanks to address water supply concerns during times of increased drought and increased water demand	X	X	X	X	X	X							X	
Build infrastructure needed for aquifer storage and recovery to address water supply concerns during times of increased drought and increased water demand	X	X	X	X	X	X							X	
Diversify options to complement current water supply, including recycled water, to address water supply concerns during times of increased drought and increased water demand	X	X	X	X	X	X							X	
Expand current resources by developing regional water connections to allow for water trading in times of service disruption or shortage	X	X	X	X	X	X							X	

Table D.1: Adaptive Strategy List

Adaptive Strategy	Climate Trend						System Impacted								
	Central Tendency	Hot/Dry	Hot/Wet	Warm/Dry	Warm/Wet	Historical Trend	Water Treatment Plants	Wastewater Treatment Plants	Stormwater Conveyance Systems	Dams & Levees	Wastewater Collection System	Streams & Ecosystems	Reservoir	Policy
Increase reservoir storage capacity, including silt removal to expand capacity at existing reservoirs and by constructing new reservoirs and/or dams to address increased water demands and increased drought conditions	X	X	X	X	X	X				X			X	
Manage reservoir water quality by investing in practices such as lake aeration to minimize algal blooms due to higher temperatures	X	X	X	X	X	X						X	X	
Conduct climate impacts and adaptation training for staff	X	X	X	X	X	X								X
Participate in community planning and regional collaboration related to climate adaptation	X	X	X	X	X	X								X
Monitor current weather conditions including precipitation and temperature	X	X	X	X	X	X								X
Establish mutual aid agreements with neighboring utilities	X	X	X	X	X	X								X
Adopt insurance mechanisms and other financial instruments, such as catastrophe bonds, to protect against financial losses associated with infrastructure losses	X	X	X	X	X	X								X
Update drought contingency plans	X	X	X	X	X	X								X
Implement adaptive water rates to correspond with water supply	X	X	X	X	X	X								X
Develop communications package for customers promoting incentives and available equipment for rainwater collection and water conservation practices	X	X	X	X	X	X								X

Table D.2: Relevant Action Items from the 2009 Water Supply and Water Conservation Plan

2009 Water Supply Management Plan Action Items			Identified Potential Climate Impacts						
Category	#	Description	Water Demand ↑	24-hr Storm ↑	DO ↓	River Low Flow ↓	Peak Stream Flow ↑	Nonpoint Source Pollutant Loads ↑	Comment
Water Conservation Program	5.1	Conservation Pricing	X			X			All conservation measures can help mitigate rising water demand and stress during low flow/drought periods.
	5.2	Replace Older, Inefficient Plumbing Fixtures	X			X			
	5.3	Require Pre-Rinse Spray Valve Retrofit Education Program	X			X			
	5.4	Rain Sensor Shut-Off Switches on New Irrigation Systems	X			X			
	5.5	Require Sub-Meters in New Multi-Family Building	X			X			
	5.6	Assess and Reduce Water System Leakage	X			X			
	5.7	Conduct Residential Water Audits	X			X			
	5.8	Distribute Low-Flow Retrofit Kits to Residential Users	X			X			
	5.9	Conduct Commercial Water Audits	X			X			
	5.10	Implement Education and Public Awareness Plan	X			X			
	5.11	Install High Efficiency Toilets and High Efficiency Urinals in Government Buildings	X			X			
	5.12	Require New Car Washes to Recycle Water	X			X			
	5.13	Expedited Water Loss Reduction	X			X			
	5.14	Multi-Family High-Efficiency Toilets Rebates	X			X			
	5.15	Install Meters with Point of Use Leak Detection	X			X			

Table D.2: Relevant Action Items from the 2009 Water Supply and Water Conservation Plan

2009 Water Supply Management Plan Action Items			Identified Potential Climate Impacts						Comment
Category	#	Description	Water Demand ↑	24-hr Storm ↑	DO ↓	River Low Flow ↓	Peak Stream Flow ↑	Nonpoint Source Pollutant Loads ↑	
Water Conservation Program Cont.	5.16	Require Private Fire Lines to Be Metered	X			X			All conservation measures can help mitigate rising water demand and stress during low flow/drought periods.
	5.17	Maintain a Water Conservation Program	X			X			
	5.18	Water Waste Policy	X			X			
	5.19	Require High Efficiency Plumbing Fixtures Consistent with State Legislation	X			X			
Reuse	7.1	Return Reclaimed Water to Lake Lanier and Allatoona Lake for Future Indirect Potable Reuse	X			X			Return of reclaimed water can help supplement these important water supply sources.
Planned Water Supply Facilities	8.1	Support Construction of 6 Planned Water Supply Reservoirs	X			X			More water supply reservoirs can help meet increasing water demands and provide increased storage for droughts.
	8.2	Construct 6 New Water Treatment Plants	X					X	New and expanded water treatment plants will help meet water demands. The effects of increased pollutant loads on water chemistry and required treatment should also be considered.
	8.3	Expand 28 Existing Water Treatment Plants	X					X	
Local Water Planning	9.1	Develop Local Water Master Plans	X	X		X		X	During planning efforts consider potential climate impacts to water demand, drought, water quality, and increased flooding risks of key infrastructure.
	9.2	Develop or Update Local Emergency Water Plans		X		X			Although droughts are the main concern for emergency water plans, also consider planning for instances of flooding of key infrastructure.
	9.3	Source Water Supply Watershed Protection						X	Protect water supply from increased nonpoint pollution sources.
	9.4	Water System Asset Management	X	X					Ensure infrastructure is well understood and maintained.

Table D.3: Relevant Action Items from the 2009 Wastewater Plan

2009 Wastewater Management Plan Action Items			Identified Potential Climate Impacts						Comment
Category	#	Description	Water Demand ↑	24-hr Storm ↑	DO ↓	River Low Flow ↓	Peak Stream Flow ↑	Nonpoint Source Pollutant Loads ↑	
Planned Wastewater Treatment Facilities	6.1	Construct 19 New Wastewater Treatment Plants	X	X					New and expanded WWTPs will increase available capacity to treat higher system flows related to increased baseflow and increased peak wet weather events
	6.2	Expand 48 Existing Wastewater Treatment Plants to Meet Capacity Needs	X	X					
	6.3	Upgrade Wastewater Treatment Plants to Protect Water Quality			X	X		X	Planned treatment upgrades can help protect receiving waters from effects of lower DO, lower flow events and increased nonpoint source pollution
	6.4	Retire 24 Existing Wastewater Treatment Facilities			X			X	Retiring the oldest and worst performing plants can help protect water quality
	6.5	Enhance Reliability of Wastewater Treatment Plants and Pumping Stations		X					Ensuring adequate firm capacity at plants and pump stations will help handle increased storm events without overflows
	6.6	Reclaim Water for Lake Lanier and Lake Allatoona	X						Reclaimed water planned to augment these important water supply sources to ensure demand can continue to be met
Wastewater Collection System Inspection and Maintenance	7.1	Sewer System Inventory and Mapping	X	X			X		All these measures lead to a better understood and maintained collection system. This will be of greater importance if increased baseflows, wet weather events, and potential flooding is seen.
	7.2	Sewer System Asset Management	X	X			X		
	7.3	Sewer System Inspection Program	X	X			X		
	7.4	Sewer System Maintenance Program	X	X			X		
	7.5	Sewer System Rehabilitation Program	X	X			X		
	7.6	Capacity Certification Program	X	X					Ensure adequate capacity available before authorizing new connections
	7.7	Grease Management Program		X					Help reduce clogging to keep as much capacity available for peak flow events
	7.8	Sewer System Overflow Emergency Response Program		X			X		Have plans in place for when overflows do occur. These may occur more as peak storm events increase.
	7.9	Sewer System Inspection and Maintenance Training	X	X			X		Ensure other planned actions are as effective as possible

Table D.3: Relevant Action Items from the 2009 Wastewater Plan

2009 Wastewater Management Plan Action Items			Identified Potential Climate Impacts						Comment
Category	#	Description	Water Demand ↑	24-hr Storm ↑	DO ↓	River Low Flow ↓	Peak Stream Flow ↑	Nonpoint Source Pollutant Loads ↑	
Septic Systems and Decentralized Systems	8.1	Septic System Planning			X	X		X	Protect water quality through better maintenance and planning of septic systems
	8.2	Septic System Critical Area Management			X	X		X	
	8.3	Septic System Maintenance Education			X	X		X	
	8.4	Septic Tank Septage Disposal			X	X		X	
	8.5	Private Decentralized Wastewater System Ordinance	X	X	X	X	X	X	Ensure decentralized systems are prepared to handle potential climate impacts and protect water quality
	8.6	Septic System Coordination			X	X		X	Protect water quality through better maintenance and planning of septic systems
Local Wastewater Master Plans	9.1	Develop Local Wastewater Master Plans	X	X	X	X	X	X	Incorporate potential climate impacts into local wastewater master plans
	9.2	Establish Policies for Connections to Public Sewer	X	X					Ensure adequate capacity available before authorizing new connections

Table D.4: Relevant Action Items from the 2009 Watershed Plan

2009 Watershed Management Plan Action Items			Identified Potential Climate Impacts						
Category	#	Description	Water Demand ↑	24-hr Storm ↑	DO ↓	River Low Flow ↓	Peak Stream Flow ↑	Nonpoint Source Pollutant Loads ↑	Comment
Legal Authority	5.A.1	Post-Development Stormwater Management		X			X	X	Ensure developments manage their stormwater quality and quantity impacts to limit downstream flooding and nonpoint source pollution.
	5.A.2	Floodplain Management / Flood Damage Prevention		X			X		Minimize future flooding impacts
	5.A.3	Stream Buffer Protection		X			X		More intense storms and higher water levels can lead to increased erosion.
	5.A.4	Illicit Discharge and Illegal Connection			X			X	Protect water quality from unauthorized discharges to the stormwater system
	5.A.5	Litter Control		X				X	Litter can cause blockages within the stormwater system during storm events as well as potentially increase pollutant loads
Watershed Planning	5.B.1	Comprehensive Land Use Planning		X			X	X	Ensure development includes watershed protection measures and does not escalate flooding risks.
	5.B.2	Future-Conditions Floodplain Delineation		X			X		Consider future climate impacts while updating floodplain maps.
	5.B.3	Sewer and Septic Planning			X	X		X	Protect water quality through coordination with sanitary sewer and septic system programs and projects
	5.B.4	Greenspace and Green Infrastructure Tools for Watershed Protection		X	X	X	X	X	Green infrastructure can have a variety of benefits depending on the types implemented including improved water quality, storing water during storm events, or replenishing groundwater to help counteract river low flows.

Table D.4: Relevant Action Items from the 2009 Watershed Plan

2009 Watershed Management Plan Action Items			Identified Potential Climate Impacts						
Category	#	Description	Water Demand ↑	24-hr Storm ↑	DO ↓	River Low Flow ↓	Peak Stream Flow ↑	Nonpoint Source Pollutant Loads ↑	Comment
Land Development	5.C.1	Integrated Development Review Process							Provides coordination to support other stormwater and watershed management action items but limited direct effect on mitigating climate impacts.
	5.C.2	Stormwater Design Criteria & Standards (Georgia Stormwater Management Manual)		X				X	Ensure best practices in place for stormwater design
	5.C.3	Construction Erosion and Sediment Control		X				X	Limit erosion from construction sites
Asset Management	5.D.1	Stormwater Infrastructure Inventory		X					Asset management of the stormwater infrastructure will lead to better understanding, maintenance, and improvements providing a better level of service and limiting effects of increased storm events.
	5.D.2	Extent and Level of Service Policy		X					
	5.D.3	Inspections (public and private systems)		X					
	5.D.4	Maintenance		X					
	5.D.5	Capital Improvement Program		X					
Pollution Prevention	5.E.1	Pollution Prevention / Good Housekeeping for Local Operations			X			X	Improve water quality through reductions in nonpoint source pollution and illicit discharges
	5.E.2	Illicit Discharge Detection and Elimination Program			X			X	
Watershed Conditions Assessment	5.F.1	Long-term Ambient Trend Monitoring			X	X	X	X	Monitor water quality and quantity so strategies can be adjusted as trends arise.
	5.F.2	Habitat and Biological Monitoring							Important monitoring for general watershed health, but limited direct effect on mitigating specific climate impacts
Education and Public Awareness	5.G.1	Local Education and Public Awareness Program							Education to build support for other measures and build awareness of personal behaviors effecting watershed health

Table D.4: Relevant Action Items from the 2009 Watershed Plan

2009 Watershed Management Plan Action Items			Identified Potential Climate Impacts						
Category	#	Description	Water Demand ↑	24-hr Storm ↑	DO ↓	River Low Flow ↓	Peak Stream Flow ↑	Nonpoint Source Pollutant Loads ↑	Comment
Watershed-Specific Measures	5.H.1	Source Water Watershed Protection						X	Protect water supply from nonpoint source pollution
	5.H.2	Total Maximum Daily Load (TMDL) Management			X	X		X	Address water quality issues when waterbodies are not meeting designated standards. Monitor and change strategies as changing conditions seen.
	5.H.3	Endangered Species Protection							Limited direct relationship to identified climate impacts, although changing climate conditions can put additional pressure on endangered species
	5.H.4	Watershed Improvement Projects		X	X	X	X	X	Project to address specifically identified watershed needs across a variety of categories.

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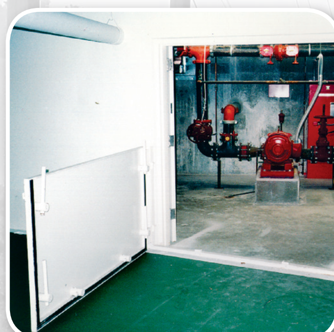

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