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Modeling Climate Change Impacts On Water Balance Components Of The Mackinaw River Watershed, Central Illinois

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MODELING CLIMATE CHANGE IMPACTS ON WATER BALANCE COMPONENTS OF THE MACKINAW RIVER WATERSHED, CENTRAL ILLINOIS

JOSEPH HONINGS

55 Pages

Understanding the response of water cycle dynamics to climate change and human activity is essential for best management of water resources. This study used the USDA Soil-Water Assessment Tool (SWAT) to measure and predict major water balance variables including stream discharge, potential aquifer recharge, and surface storage in a small-scale watershed (~2,930 km^2) in Central Illinois. The watershed is predominantly tile-drained agricultural land, which controls the nutrient dynamics and hydrology. Two reservoirs, Evergreen Lake and Lake Bloomington, and the Mahomet Aquifer in the watershed are used for public water supply. The subject watershed has been very sensitive to recent droughts, such that an interim water supply plan has been developed for water management. To assess how the watershed dynamics are affected by future climate change, this study used high-resolution climate projection data (~12 km) in a calibrated and validated SWAT hydrologic model. Using an ensemble of General Circulation Models (GCMs), as well as the GFDL ESM2M and CCSM4.0 individually, four (4) representative concentration pathways (RCPs) developed by the IPCC Coupled Model Intercomparison Project Fifth Assessment Report (CMIP5) were used for prediction of precipitation and temperature for the watershed. Precipitation and temperature are predicted to increase by mid-century for all scenarios. Ensemble, GFDL ESM2M, and CCSM4.0 GCM simulations arrive at similar conclusions for each RCP, and predict an amplification of current watershed dynamics. Periods of drought and flooding are predicted by the models. Results indicate continued nutrient loading of the surficial reservoirs that are used for public water supply and recreation. Nutrient management measures will need to remain in place and be enhanced. This study involving a small-scale watershed can be used to further project behavior of larger watersheds, such as the Illinois River and ultimately the Mississippi River, using similar methods and high-resolution data.

KEYWORDS: Climate Change; Hydrologic Modeling; Soil and Water Assessment Tool; Tile Drainage; Water Balance; Water Resources

MODELING CLIMATE CHANGE IMPACTS ON WATER BALANCE COMPONENTS OF THE MACKINAW RIVER WATERSHED, CENTRAL ILLINOIS

JOSEPH HONINGS

A Thesis Submitted in Partial
Fulfillment of the Requirements
for the Degree of

MASTER OF SCIENCE

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2018

MODELING CLIMATE CHANGE IMPACTS ON WATER BALANCE COMPONENTS OF THE MACKINAW RIVER WATERSHED, CENTRAL ILLINOIS

JOSEPH HONINGS

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ACKNOWLEDGMENTS

The journey to my Masters degree has been both a time to touch base with my roots and to discover how I can grow as my career and life progresses. After being away for many years, I took a chance on myself and left a job to pursue this degree in my hometown. I could not have done this without the love and support from my parents and family along the way. I wish to thank them and everyone else who helped Peoria feel like home again.

I feel that I have gained a new family in the Department of Geography, Geology, and the Environment at Illinois State University. I cannot thank my advisor, Dr. Wondwosen Seyoum, enough for his encouragement, guidance, patience, and enthusiasm along the way. I can say the same of Dr. Seyoum for the rest of the Geology faculty, who share these same virtues. Dr. Seyoum and the other two members of my committee, Dr. Eric Peterson and Dr. Lisa Tranel, have been supportive and posed challenging questions to assure my best work. The department faculty have been exemplary of what I hope to become as an educator and researcher someday.

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J. P. H.

CONTENTS

TABLES

FIGURES

CHAPTER I: INTRODUCTION AND OBJECTIVES

Introduction

Global climate change and its effect on water resources remain a prominent issue in contemporary science. During the 20th Century, the global average surface temperature increased by approximately 0.6°C (Hallett 2002). With these increased temperatures, the global water cycle has intensified (Huntington 2006). The water cycle is a delicate balance of precipitation, evaporation, and all of the processes in between. Warmer temperatures will facilitate increased atmospheric water storage, which will alter the natural balance of hydrologic processes such as evapotranspiration (ET) and precipitation (P). The effects of elevated temperatures will vary spatially across the globe, changing precipitation patterns, runoff, and sea level. These changes are of great concern, as the world's population is increasing and current fresh water demands are already stressed (Vörösmarty et al. 2000). Further understanding of the changes in global water resource availability on all scales will aid the development of management for the demand of human, animal, agricultural, and energy consumption.

On a national scale, temperatures will increase by 2-4 °C (3-12 °F) in the United States by the year 2100 (USEPA 2016). The effects of this rise will vary across the country as evapotranspiration rates increase, with certain areas experiencing more precipitation while others endure drought. The severity of individual precipitation events and drought periods will intensify in the Midwestern United States, changing the dynamics of watershed behavior (Cousino et al. 2015, Stone 2001). Storm events will occur more often during spring and winter months when agricultural cover and vegetation are minimal, facilitating watershed loading of sediment and nutrients from increased runoff. Extreme events will result in decreased infiltration of precipitation to groundwater reservoirs, from which most Central Illinois communities extract their water supply (Brown 2018). Sediment loading of watersheds from the amplified runoff will decrease the total storage volumes of surface water catchment basins that also serve as fresh water supply. The volume decrease will coexist with continued nutrient loading from agricultural practices. The alteration and imbalance of natural processes are expected to diminish surface water storage in regional settings. Generally, most existing climate impact studies focus on these regional scale watersheds (Cousino et al. 2015, Fontaine et al. 2001, Jha et al. 2006, Stone 2001, Vörösmarty et al. 2000), while there is a lack of understanding of local impacts of climate in water resources of watersheds of smaller sizes. Thus, understanding how these smaller watersheds respond to change is imperative.

The Bloomington-Normal metropolitan area and the surrounding communities utilize both ground and surface water reservoirs. The Town of Normal and smaller towns consume water from the Mahomet aquifer, whereas the City of Bloomington pumps water from two surface reservoirs located within the Mackinaw River Watershed, Evergreen Lake and Lake Bloomington, to serve its municipality and adjacent communities. Droughts in 1988 and 2005 demonstrated that these surficial reservoirs were vulnerable (WHPA 2010). Nitrate concentrations continue to be a problem as the US EPA health standard of 10 mg/L NO_3-N (nitrate as nitrogen) (USEPA 2009) is often exceeded in the lakes during the spring (WHPA 2010). Sedimentation has resulted in a decrease of reservoir volume and poor water quality at both locations. Additionally, the land use of the Mackinaw River watershed is predominantly tile-drained agricultural fields. Tile drains promote infiltration of precipitation to the drain system, preventing recharge to the water table. Water within the tile drain is ultimately discharged into a ditch or small stream body, enhancing runoff.

The 2005 drought challenged the routine management practices for the City of Bloomington as it continued to supply water to residents. As a result, the City of Bloomington developed an interim water supply plan in 2010 to address future implications of climate stresses on water supply. Accurate prediction of drought seasons under several scenarios is vital for the City of Bloomington and its residents. As climate continues to warm, increased drought frequency and intensity could diminish water supply to the point of limited service. A switch to the Mahomet Aquifer would not be ideal, as the municipalities of Champaign, Normal, and East Peoria already use the aquifer for water supply and experience decreased water levels locally, and the sustainability of the aquifer is still is not defined (Brown 2018). Portions of the study area overlie the Mahomet Aquifer in Western McLean County and Southern Tazewell County. Quantifying precipitation events and surficial processes could also aid in estimating potential recharge to the Mahomet Aquifer.

A complexity associated with hydrology of watersheds in the Midwestern United States is the practice of tile drainage of agricultural fields. The thick overlying glacial deposits are naturally poorly-drained, and pre-settlement landscapes frequently flooded. Tile drainage was developed to quickly drain fields such that flooding would not cause crop loss. The implementation of tile drains across the landscape has altered natural drainage patterns, as streams typically originate from the outlets of tiles and gain more inputs further downstream. Overall, tile drain contribution to total streamflow can range from 15-60% in subject watersheds (Amado et al. 2017, Culley and Bolton 1983, King et al. 2017, Macrae et al. 2007). In addition, tiles do not filter nutrients that originate from fertilizer, herbicide, and pesticide applications on fields. This results in nutrient loading further downstream in reservoirs and larger stream channels, including Lake Bloomington and

Evergreen Lake. Understanding the physical processes of tile-drained watersheds in the context of climate change will allow better preparation for seasonal loading of nutrients.

Comprehending the effects of climate change on a local watershed scale can serve as the basis for further understanding of the overall global issue. A local approach will enhance an immediate population's understanding of water budget dynamics and predicted water supply. This localized method will allow effective communication of best management practices to governing bodies and the associated urgency of the situation.

The hypothesis of this study is that the water cycle of small-scale watersheds are highly sensitive to climatic stresses, and the current behavior of water balance components will amplify by the continued warming climate trend. This study will use the United States Department of Agriculture (USDA-NRCS) Soil Water Assessment Tool (SWAT) to examine the hydrology of the Mackinaw River watershed and its associated fresh water reservoirs. Under four greenhouse gas emissions scenarios, SWAT simulations will predict discharge totals for the Mackinaw River watershed from 2020-2050. The result from this study will provide information for the City of Bloomington and local decision makers with the best management practices involving water demand, projected changes, and water availability. The results from this research can be used in adjunction with the current interim water supply plan for optimized water supply.

CHAPTER II: STUDY AREA

The study watershed is located within the Wisconsin Episode glacial moraines and till plains (ISGS 2005). Topographically, the area is characterized by relatively flat-lying till plains used for row crop agriculture, and hills associated with glacial moraines. These moraine deposits control the surficial hydrology drainage patterns within the Mackinaw River watershed. The Mackinaw River flows westward from Colfax, Illinois to the Illinois River, which is a tributary of the Mississippi River (Figure 1). The area gets an annual average precipitation of ~ 950 mm (36-38 inches). The average annual minimum, maximum, and mean temperature are 6 °C (43 °F), 17 °C (63 °F), and 11.7 °C (53 °F), respectively (NOAA 2016). Regional recharge estimates showed that the area gets annual groundwater recharge ranging between 10-110 mm (0.35-4.3 inches) (Roadcap 2011). The dominant land cover type in the study area is row crop agriculture; and therefore, evapotranspiration is very high in the growing seasons.

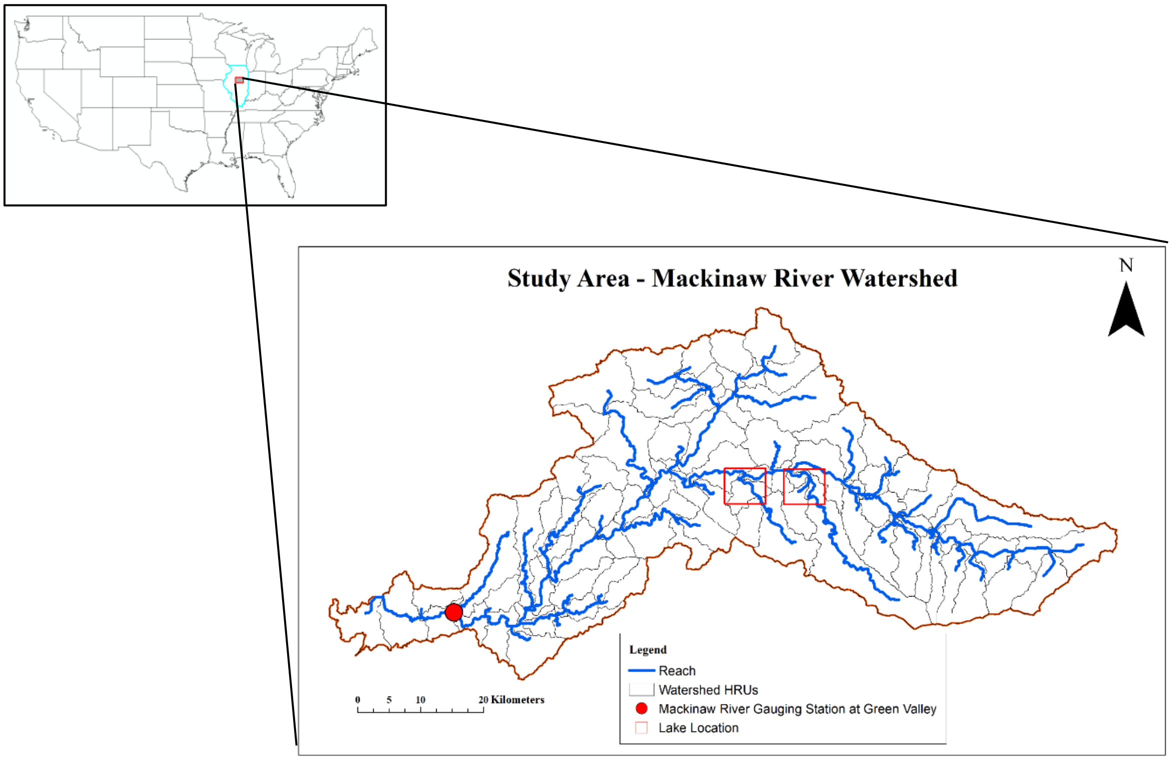


Figure 1. Study area location map.

CHAPTER III: DATA AND METHODS

Data

To model the hydrologic process in the watershed, SWAT integrated weather and climate, spatial/physical land surface, and hydrologic data from 1998-2014. Weather and climate data included precipitation, minimum and maximum temperature, humidity, wind speed, and solar radiation. Weather and climate data were obtained from NOAA's National Climate Data Center (https://www.ncdc.noaa.gov/cdo-web/). These inputs were used to determine some of the water balance components in the watershed, including areal precipitation and evapotranspiration.

Spatial data, describing the land surface characteristics of the watershed, used in the SWAT model consisted of a digital elevation model (Vertenstein et al.), soil data, and land cover type data (Figure 2). The United States National Aeronautics and Space Administration's (NASA) Advanced Spaceborne Thermal Emission and Reflection (ASTER) Global DEM Version 2, which consists of a 30-meter spatial resolution, was used to delineate the sub-watersheds and watershed boundary and to derive watershed characteristics (e.g. slope) of the study area. The United States Department of Agriculture's (USDA-NRCS) Soil Survey Geographic Database (SSURGO) Version 2.2 soil data, obtained via the USDA's Geospatial Data Gateway (https://datagateway.nrcs.usda.gov/GDGOrder.aspx), was used to extract soil characteristics such as Curve Numbers and saturated hydraulic conductivity of the watershed. Land cover data from the National Land Cover Database (NLCD) were obtained from the USDA's Geospatial Data Gateway.

In addition, hydrological data such as streamflow were used to calibrate and to validate the SWAT model. Streamflow data were collected from the United States Geological Survey (USGS) National Water Information System Web Interface. The stream gauging station (USGS 05568000) at the Mackinaw River near Green Valley (Figure 1) was used to calibrate and validate the SWAT model. The calibration and validation simulation periods span from 1998 to 2014.

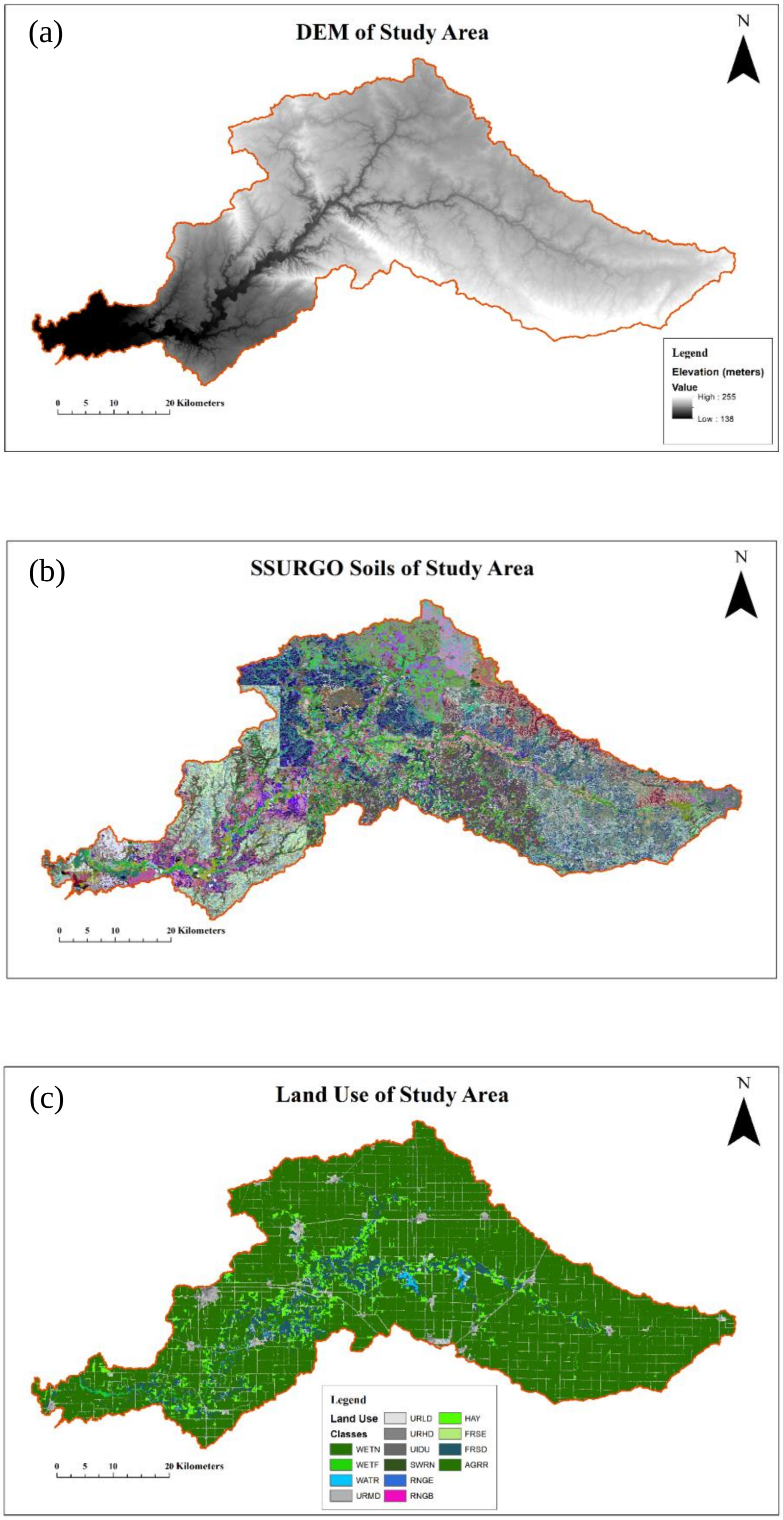


Figure 2. Model input data – land surface characteristics (a) DEM, (b) Soil*, and (c) Land use.

*Soil map legend is included in Appendix A.

Moreover, for the climate impact analysis, downscaled projections of precipitation and temperature data were obtained from Climate Analytics Group Data Portal (http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/dcpInterface.html#Welcome). These climate change data are based on global climate projections from the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project Phase 5 (CMIP5) multi-model dataset that is informing the IPCC Fifth Assessment, discussed in Section 4.2 (ii) below.

Methods

Hydrologic Modeling using SWAT

The SWAT is a semi-distributed, basin-scale water balance model that operates on a daily time step. The model is based on the following equation (Arnold et al. 1998):

$$SW_t = SW + \sum_{t=1}^{t} (P_i - Q_i - ET_i - QR_i) \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (1)$$

In this equation, SW represents soil water content minus the 15-bar water content. The remaining variables are time in days (t), and daily precipitation (P) (mm), runoff (Q) (mm), evapotranspiration (ET) (mm), and percolation & return flow (QR) (mm).

For calculation of runoff, the overall watershed is divided into sub-basins referred to as hydrologic response units (HRUs). These HRUs are determined based on consistencies in soil, landuse, and slope. For each HRU, the water balance is calculated using equation (1) and runoff for daily rainfall is predicted using the USDA Soil Conservation Service (SCS) curve number (CN) equation as follows (Mockus 1972):

$$Q = \frac{(P - 0.2\, s)^2}{P + 0.8s} \quad P > 0.2s$$

$$Q = 0.0 \quad P \leq 0.2s \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (2)$$

In this equation, daily surface runoff (Q) is determined by daily rainfall (P) and a retention parameter (s). The retention parameter, s, is related to the CN by the SCS equation (USDA-NRCS 1986).

$$s = \frac{1000}{CN} - 10 \text{ .... } (3)$$

The higher the CN means the smaller the retention parameter and the higher the runoff it generates. Low CN value produces low runoff. The CN is based on the watershed’s characteristics, such as soil, land use, and slope. The CN relates precipitation and runoff, and is separated into four (4) main hydrologic soil groups (HSGs). The HSGs are classified “A” through “D”, with “A” having low runoff potential (high infiltration), and “D” representing high potential (low infiltration) (USDA-NRCS 1986). The curve numbers range from 30 to 100, with 100 representing the highest runoff (USDA-NRCS 1986).

Tile drainage is a significant component of the hydrology in the area. In some agricultural watersheds such as the Upper Big Walnut Creek Watershed in Ohio, tile drainage contributes up to 47% of watershed discharge (King et al. 2014). Tiles drain water when the perched water table rises above the installation depth of the drains. In SWAT, tile drainage for a given day is calculated by the following equation (Neitsch et al. 2005):

$$tile_{wtr} = \frac{h_{wtbl} - h_{drain}}{h_{wtbl}} \cdot (SW - FC) \cdot \left(1 - exp\left[\frac{-24}{t_{drain}}\right]\right) \ if \ h_{wtbl} > h_{drain} \text{ .... } (4)$$

The amount of water removed by tile drainage for a given day, $tile_{wtr}$ (mm H_2O), is related to the height of the water table, h_{wtbl}, in millimeters above the impervious zone, and the height of the tile drain, h_{drain}, above the impervious zone in millimeters. SW and FC soil water content and field capacity water content of the soil, respectively, in mm H_2O. The time (hours) required to drain the soil to field capacity is t_{drain}. To accommodate the effect of tile drainage in stream flow and recharge, the curve number, tile drain dimensions, and depth to impermeable layer parameters were modified during calibration.

When the SWAT was simulated, each HRU produced a runoff value, and the outlet point was designated as the point of discharge of the Mackinaw River into the Illinois River. Other HRUs ultimately empty into Evergreen Lake or Lake Bloomington. This allowed for prediction of water availability for both reservoirs using the calculated inflow of the respective HRU.

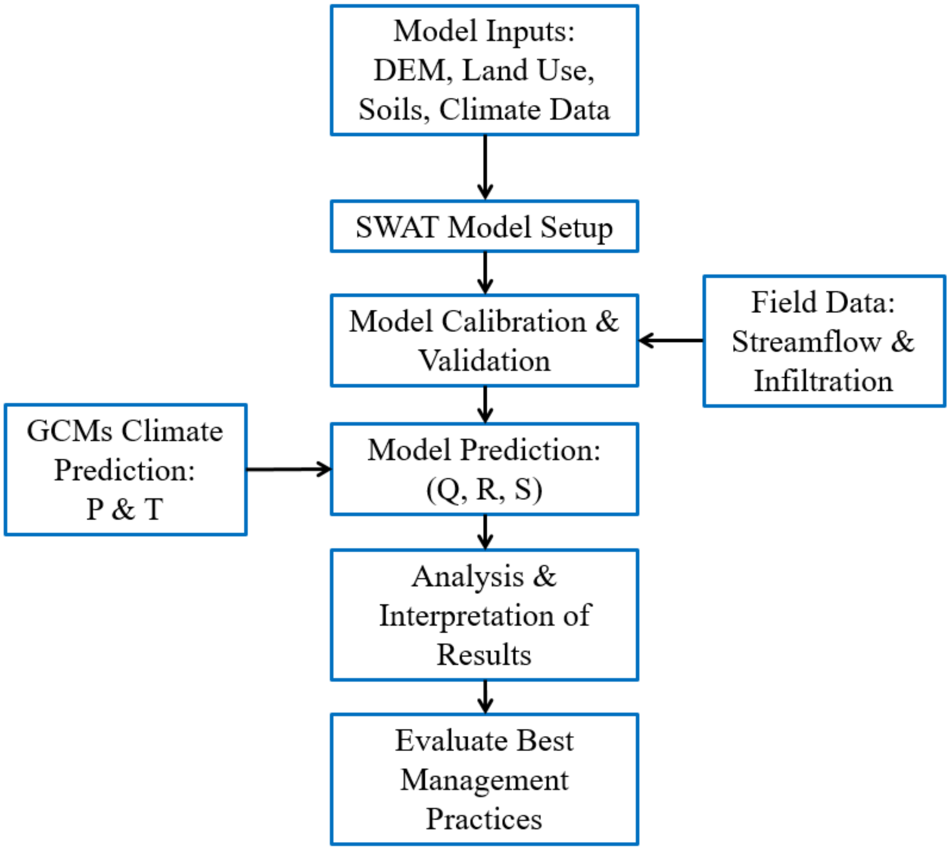


Figure 3. Outline of the methodology.

The geospatial data were imported into an ArcGIS interface. The DEM rasters were mosaicked to cover the entire watershed area and projected to a consistent coordinate system, UTM Zone 16. The SSURGO soil shapefiles contained a map unit key attribute that was not in a readable format for ArcGIS. A new long integer attribute field, “mukey_int,” was created for the map unit key, and the field calculator was used to set the value equal to the "MUKEY" field. This copied the "MUKEY" values into a new column named "mukey_int" that was a readable format for ArcGIS. Once this was completed, the SSURGO polygons were converted to raster format. The SSURGO polygons were selected as the input feature, the value field for the conversion was set to the "mukey_int" with a cell size of 30m resolution. Once the raster was created, the symbology was set to unique values, assigning a color to each individual map unit. The process was repeated for each individual soil shapefile within the watershed. Once all of the soil rasters were created, they were combined into one raster file using the Mosaic to New Raster tool, with pixels 32-bit signed with one band.

Following the soil and DEM setup, weather data for the SWAT were downloaded in a format compatible with SWAT from https://globalweather.tamu.edu/. The weather data consisted of estimates of precipitation, wind, relative humidity, temperature, and solar radiation through 2014. Data from 1998-2014 were collected for ample spin-up, calibration, and validation periods. The weather data were a product of high resolution, coupled atmosphere-ocean-land surface-sea ice system-the National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR). Bounding coordinates were drawn around the watershed on a mapping application, which identified the weather stations within the specified area. The weather data were available since 1979, but to be consistent with the land use and other data, the model was simulated using data from the most recent period, from January 1, 1998 to July 31, 2014.

SWAT was initiated by opening ArcMap and creating a new SWAT project. The first step in ArcSWAT was delineation of the watershed within the "Watershed Delineation" window. This window compiled the necessary functions in a series of steps for the watershed delineation. The mosaicked DEM was loaded from the project data folder and projected to UTM Zone 16. Next, the streams were defined based on the DEM, using a flow direction and accumulation tool. Once the flow directions and accumulation were calculated, the stream network was created. The outlet of the watershed was designated as the gauge location of the Mackinaw River at Green Valley. The “delineate watershed” command was selected, followed by the calculation of the subbasin parameters. When finished, the watershed was divided into subbasins.

The HRU analysis followed the watershed delineation process, beginning with the land use/soils/slope definition window. The land cover raster was loaded from the project folder and clipped to the watershed boundary. The land use values were converted to SWAT categories using the value field and NLCD 2001/2006 lookup table, followed by a reclassification function. This process was repeated for the SSURGO soils data, using the ArcSWAT SSURGO database and reclassified using the “mukey_int” field. The slope classification was divided into 3 classes: 0-3%, 3-7% and greater than 7%. Following the slope reclassification, the land use, soil, and slopes were overlaid. The HRUs were defined by the dominant land use, soils, and slope method in the “HRU Definition” window.

Following the HRU definition, the weather data were defined. This step wrote input tables using the temperature, solar radiation, relative humidity, wind, and precipitation .txt files. The “Write SWAT Database Tables” command opened a window in which all tables were selected to write. The SWAT simulation was initiated from the SWAT toolbar, with a starting date of January 1, 1998 and ending date of July 31, 2014. The rainfall was set to skew normally, and the time step was monthly. A 2-year warm (spin) up period was used to allow the model to equilibrate during this period. The remaining years were divided into two segments: 2000-2008 for calibration and 2009-2014 for the validation period.

Combined manual and automated calibration techniques were used to calibrate and validate the model. An independent SWAT-Cup was used for automated calibration (Abbaspour 2015). Watershed parameters (e.g., curve number, soil antecedent water content, soil hydraulic conductivity, etc.) were adjusted until a satisfactory statistical result was obtained. Statistical measures such as R^2, Nash-Sutcliffe efficiency (Nash and Sutcliffe 1970), and model bias were calculated and used to evaluate model performances. The coefficient of determination (R^2) was calculated by the following equation:

$$R^2 = \frac{\sum(x-\bar{x})(y-\bar{y})}{\sqrt{\sum(x-\bar{x})^2 \sum(y-\bar{y})^2}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

The Nash-Sutcliffe efficiency (E_f) index formula was determined as follows (Nash and Sutcliffe 1970):

$$E_f = 1 - \frac{\sum_{i=0}^{n}(\hat{Y}_i - Y_i)^2}{\Sigma(Y_i - \bar{Y})^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

The efficiency index (E_f) uses the measured (Y_i) and predicted ($\widehat{Y_i}$) values of the dependent variables, the mean of the measured values of Y ($\bar{Y}$), of n sample size to evaluate residual variance compared to measured variance. The result was used understand the current water balance of the watershed. Then, the model was used to perform climate impact prediction studies using climate model output data (for detailed description see the next section).

Climate Model

The Intergovernmental Panel on Climate Change (IPCC) is an international organization with the purpose of communicating the contemporary state of knowledge and science of climate change, as well as its environmental and social implications. The IPCC provides a scientific framework for climate studies, identified in published assessment reports. Following the most recent meeting, the IPCC prepared its Fifth Assessment Report (AR5) that established four (4)

Representative Concentration Pathways (RCPs) of greenhouse gas emission scenarios to be used as standards for climate projection studies.

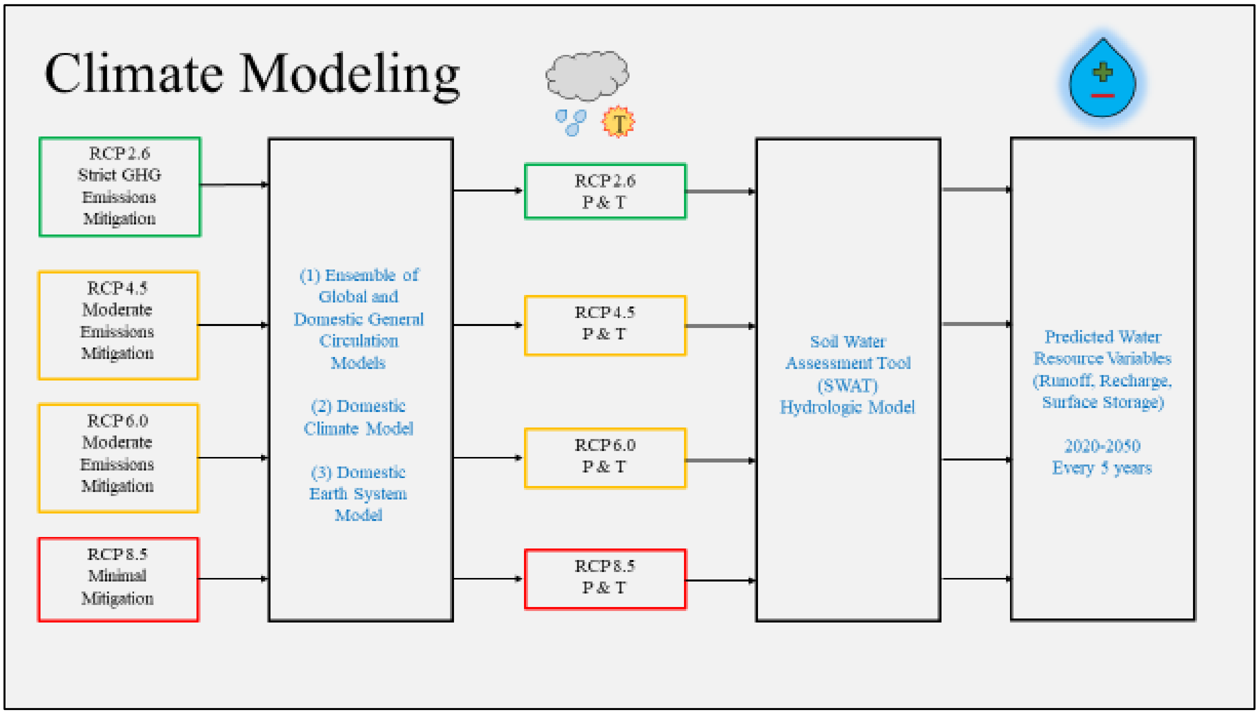


Figure 4. Overview of the climate modeling process.

The first scenario, RCP2.6, represents a strict mitigation scenario, whereas RCP4.5 and RCP6.0 represent intermediate mitigation, and RCP8.5 involves severe greenhouse gas emissions. These RCPs serve as input data for general circulation models (GCMs), which are numerical models that represent physical processes of the atmosphere, ocean, cryosphere and land surface. These GCMs are identified by the Coupled Model Intercomparison Project 5 (CMIP5), which is a set of coordinated climate models established by the World Climate Research Programme (WCRP). The GCMs use the four (4) RCPs as inputs to produce precipitation and temperature predictions up to the year 2050. This study used three different sources for precipitation and temperature outputs from the average of an ensemble of all GCMs (an average of nearly 42 climate and earth system models), as well as outputs from an individual earth system model and individual climate model, as inputs into the SWAT model.

The earth system model used in this study was the Geophysical Fluid Dynamics Laboratory (GFDL) Earth System Model (ESM) version 2M (GFDL ESM2M). Developed for NOAA, GFDL-ESM2M couples an atmospheric circulation model with an oceanic circulation model while integrating biogeochemical elements (Dunne et al. 2012, Dunne et al. 2013). The climate model chosen for this study was the Community Climate System Model version 4.0 (CCSM4.0). The CCSM4.0 includes atmospheric, sea-ice, land, ocean, and land-ice geophysical models with a coupler to share information amongst them as the simulation progresses (Vertenstein et al.). The simulations were run from 2015-2050 in the SWAT.

CHAPTER IV: RESULTS

Calibration & Validation

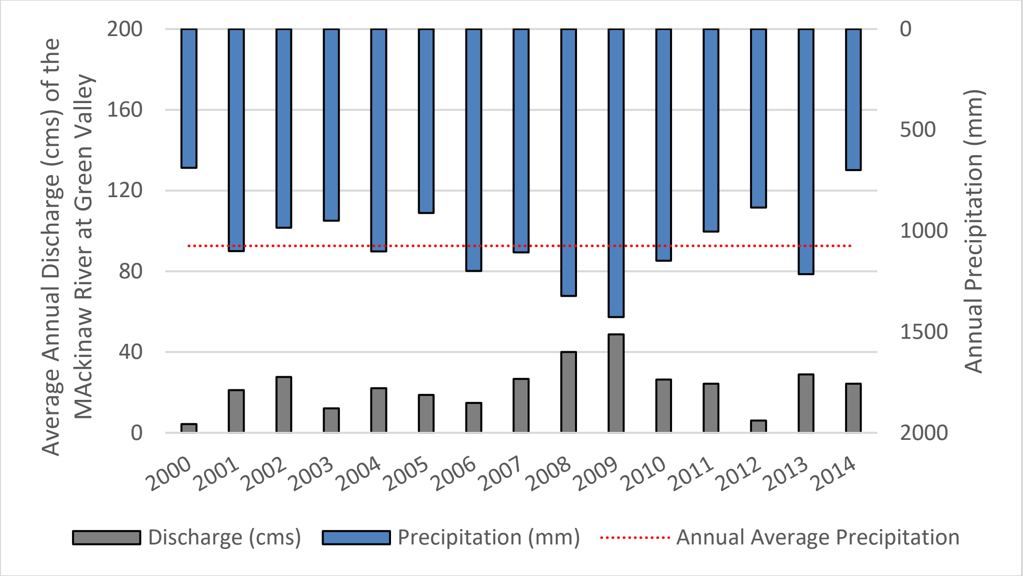


Figure 5. Current watershed precipitation and discharge, 2000-2014.

Prior to model calibration and validation, the field measured precipitation and average annual discharge were evaluated for patterns of significance (Figure 5). The average annual precipitation from 2000-2014 was slightly over 1,000 mm. Years that were lower than this average exhibited lower average discharge of the Mackinaw River at Green Valley, such as in 2000, 2003, and 2012. The 2005 drought mentioned in the Interim Water Supply Plan for the City of Bloomington is evident, and more severe events in 2000, 2003, and 2012. Wetter years exceeding the average precipitation resulted higher discharge, such as in 2008 and 2009. Current watershed behavior indicates that droughts occur multiple times within a decade, with flooding or high discharge on a decadal frequency.

The SWAT model was calibrated using data from January 1, 1998 to July 31, 2008. The first two years, 1998 and 1999, were used as a warm-up period for the model. The model discharge calculation of the Mackinaw River at Green Valley was compared to actual discharge from the gaging station. Model calibration results included an R^2 of 0.68, and a Nash-Sutcliffe Efficiency (NSE) of 0.39. Table 1 indicates parameter adjustments within the model calibration. Overall, the simulated hydrograph behavior matched well with the observed values, and baseflow was captured sufficiently, except the peak discharge values where the model underestimated peak flows (e.g., in 2002, 2005, see Figure 6). Once the model was calibrated, the model was validated using data independent of calibration data, ranging from January 1, 2008 to July 31, 2014. Model validation results included an R^2 of 0.64, and a NSE of 0.10. At the beginning of the validation period, the model underestimated peak flow and slightly overestimated baseflow. Later, in the validation period, the model simulated both peak flow and baseflow well (Figure 6). Generally, the model was calibrated and validated satisfactorily.

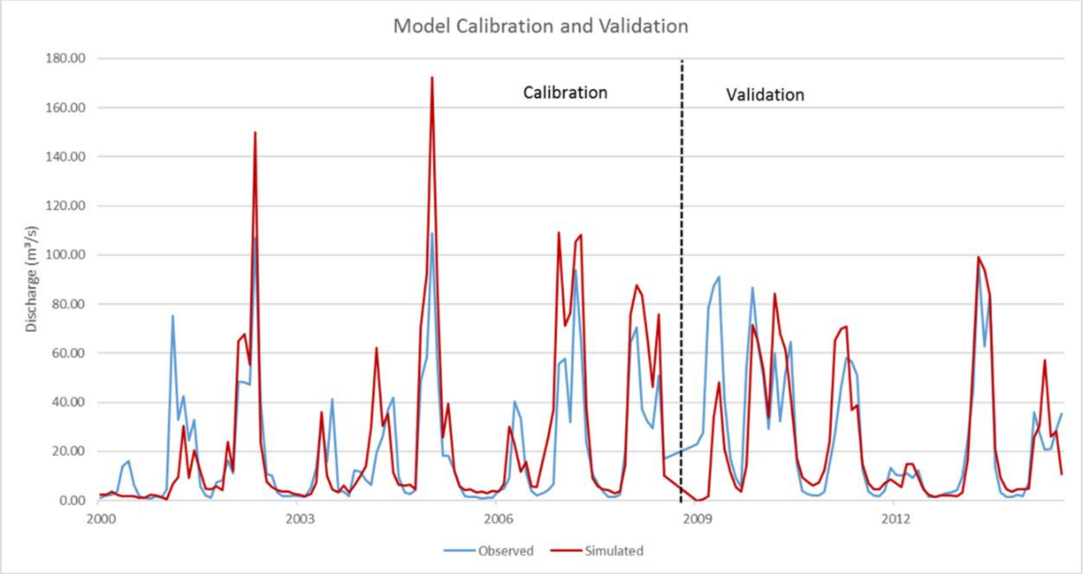


Figure 6. Model calibration and validation hydrograph. Blue and red indicate the observed and simulated discharge (m^3/s), respectively, at the Green Valley gauge location.

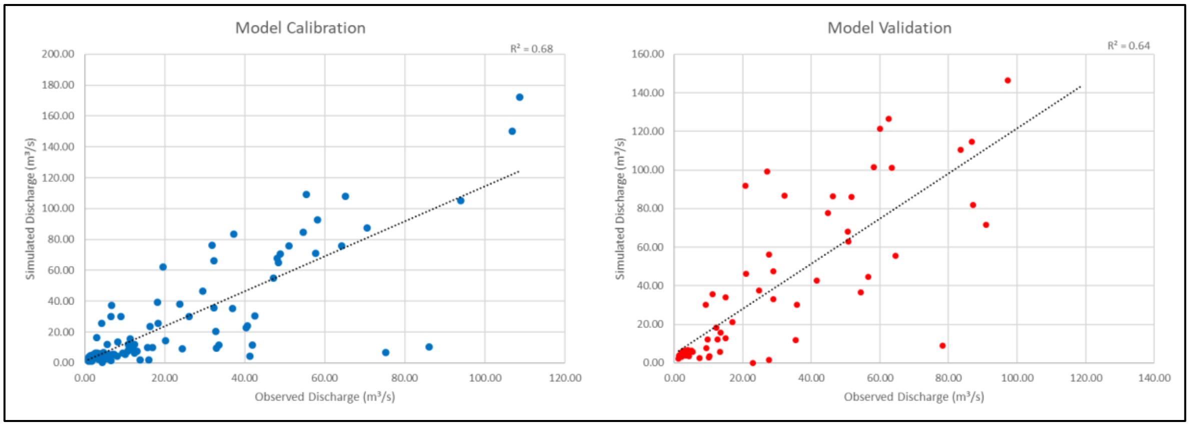


Figure 7. Scatter plots of simulated vs. observed monthly discharge for the calibration and validation period.

Table 1

Calibration Parameter Adjustments

Parameter	*Description*	*Calibrated Min*	*Calibrated Max*
r__CN2.mgt	SCS runoff Curve Number	-20.00%	20%
v__ALPHA_BF.gw	Baseflow alpha factor (days)	0-1	1
v__GW_DELAY.gw	Groundwater delay (days)	250	--
v__GWQMN.gw	Threshold depth of water in shallow aquifer for return flow to occur (mm)	1	--
v__GW_REVAP.gw	Groundwater "revap" coefficient	0.1	--
v__ESCO.hru	Soilevaporation compensation factor	0.95-1.00	1
v__CH_N2.rte	Manning's "n" value for the main channel	0-0.3	0.3
v__CH_K2.rte	Effective hydraulic conductivity for main channel alluvium	5	130
v__ALPHA_BNK.rte	Baseflow alpha factor for bank storage	0	1
r__SOL_AWC().sol	Available water capacity of the soil layer (mm/mm)	-0.2	0.4
r__SOL_K().sol	Saturated hydrauic conductivity (mm/hr)	-0.8	0.8
v__SFTMP.bsn	Snowfall temperature (°C)	-5	5
v__REVAPMN.gw	Threshold depth of water in shallow aquifer for "revap" to occur	750	--
v__RCHRG_DP.gw	Deep aquifer percolation fraction	0-1	--
v__EPCO.hru	Plant uptake compensation factor	1	--
v__DEP_IMP.hru	Depth to impervious layer for modeling perched water tables (mm)	2500	--
v__CH_K1.sub	Effective hydraulic in tributary channel alluvium	0	300
v__CH_N1.sub	Manning's "n" value for the tributary channels	0.01	30
v__SURLAG.bsn	Surface runoff lag time (hr)	0.05	24
v__SHALLST.gw	Initial depth of water in the shallow aquifer (mm)	1000	--
v__DEEPST.gw	Initial depth of water in the deep aquifer (mm)	2000	--

Table 2

Calibration and Validation Statistical Analysis

Variable	*Calibration*	*Validation*
r	0.82	0.8
R^2	0.68	0.64
NSE	0.39	0.1

Climate Projections - Ensemble

The baseline for this prediction is based on the GCM ensemble approach. The ensemble under-predicted precipitation compared to in-situ measurements. Climate projections of all RCP scenarios from ensemble GCMs outputs predicted an increase from the baseline in both precipitation and average temperature in the watershed by the year 2050 (Figures 7 and 8). RCP 2.6 predicts an increase in total annual precipitation from 798.60 mm in 2010 to 815.76 mm (+17.16 mm) in 2050, and an increase in average temperature from 11.65°C in 2010 to 12.81°C (+1.16℃) in 2050. RCP 4.5 predicts an increase in total annual precipitation from 779.68 mm in 2010 to 823.64 mm (+43.96 mm) in 2050, and an increase in average temperature from 11.81°C in 2010 to 13.17°C (+1.36℃) in 2050. RCP 6.0 predicts an increase in total annual precipitation from 776.95 mm in 2010 to 815.08 mm (+38.13 mm) in 2050, and an increase in average temperature from 11.68°C in 2010 to 12.64°C (+0.96℃) in 2050. RCP 8.5 predicts an increase in total annual precipitation from 790.36 mm in 2010 to 827.99 mm (+37.63 mm) in 2050, and an increase in average temperature from 11.60°C in 2010 to 13.85°C (+2.25℃) in 2050.

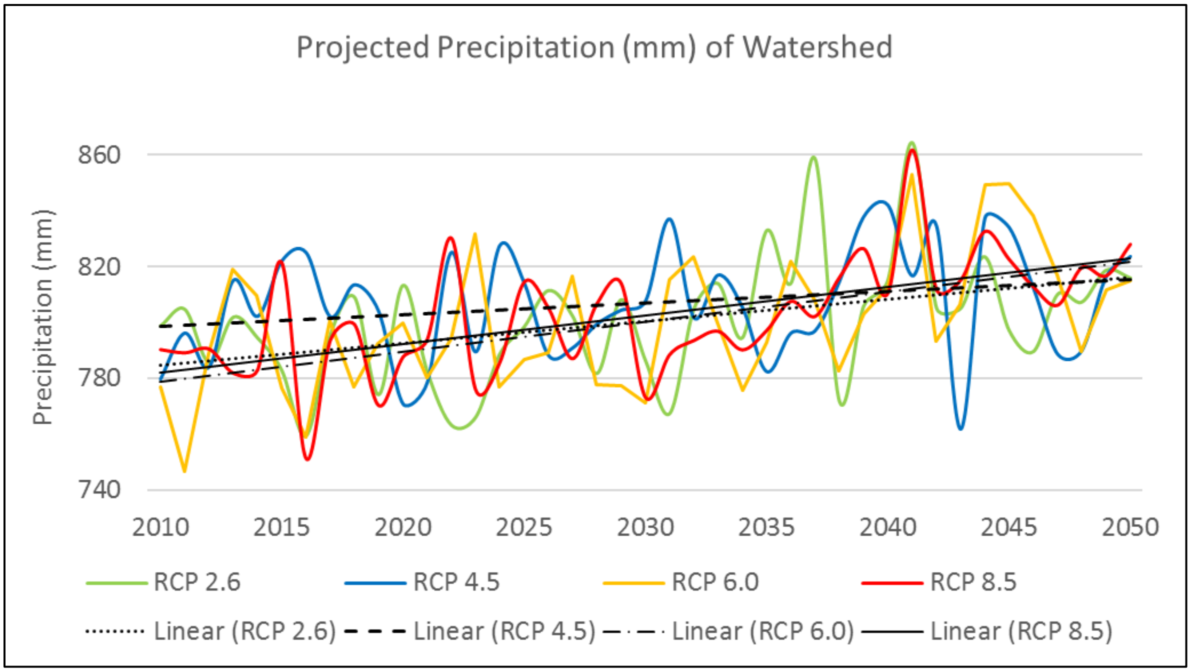


Figure 8. Projected annual precipitation (mm) predicted by the Ensemble of GCMs.

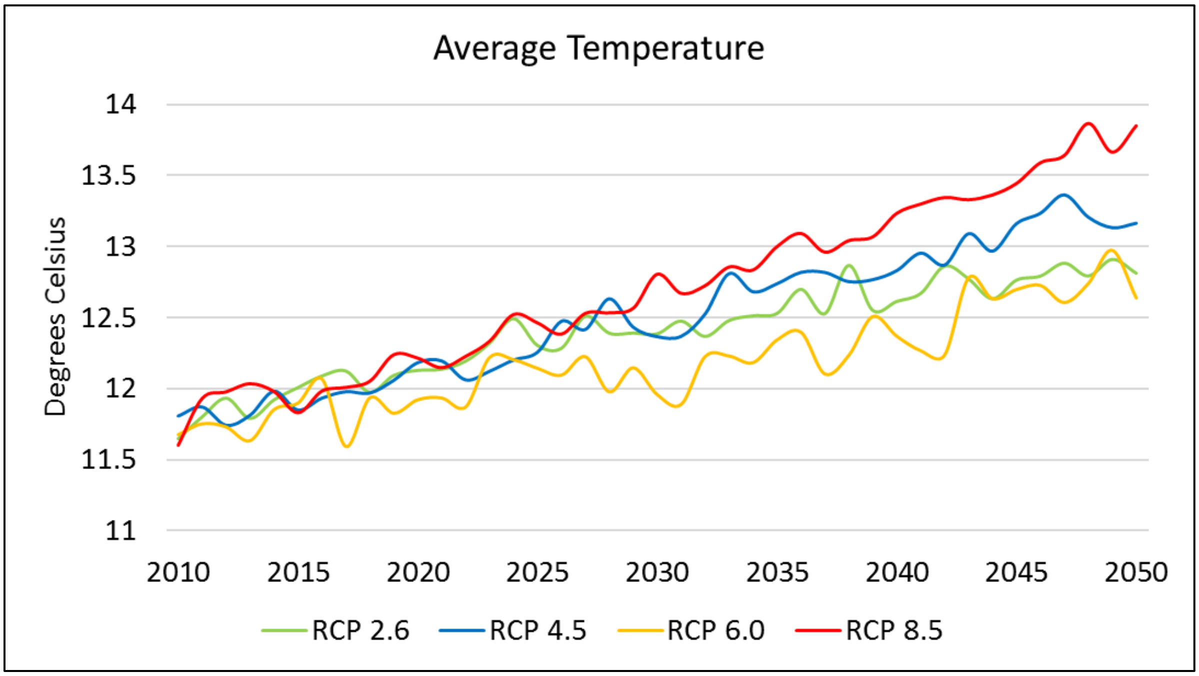


Figure 9. Projected annual average temperature (℃) predicted by the Ensemble of GCMs.

Water Balance

Current

The baseline simulation from 2000-2014 results indicate an average total precipitation of 1,031.9 mm and a total water yield of 281.33 mm for the watershed. Tile drainage comprises 127.03 mm (~45%) of the total water yield. Total aquifer recharge and surface runoff are 8.41 and 48.74 mm. Average annual evapotranspiration is 726 mm, 57% of precipitation.

Table 3

Baseline Simulation Water Balance

Water Balance Component	*Average Annual Basin Value (mm)*
Precipitation	1031.9
Snowfall	128.25
Snowmelt	117.68
Sublimation	0.54
Surface Runoff Discharge	48.74
Lateral Soil Discharge	97.62
Tile Discharge	127.03
Shallow Groundwater Discharge	7.99
Deep Groundwater Aquifer Discharge	0.42
Revap (Shallow Aquifer Discharge to Soil and Plants)	1.66
Deep Aquifer Recharge	0.42
Total Aquifer Recharge	8.41
Total Water Yield	281.33
Percolation Out of Soil	8.5
Evapotranspiration	726.1
Potential Evapotranspiration	1275.4

Projected

RCP 2.6.

GCM ensemble. Under this scenario, an increase in all water balance components was observed (Table 4). For example, the total evapotranspiration increases from 706.2 mm in 2010 to 729.7 mm in 2050 (+23.5 mm) (+3%). As a percentage of precipitation, evapotranspiration fluctuates between 58.6-63.3%. The scenario indicates an approximately 21 mm (+37%) increase in surface runoff from 2010-2050. The maximum surface runoff projection was 88.62 mm (+55%) in 2020, and the minimum of 57.13 mm in 2010, with an average of 74.56 mm (+31%). Total aquifer recharge remained relatively constant over the 40-year span, ranging between 8.85 (2010) and 10.11mm (+14%) (2035), with an average of 9.43 mm (+7%) per year. Total water yield of the watershed increased from 368.18 mm in 2010 to 438.91 mm (+70.73 mm) (+19%) in 2050. The maximum, minimum, and average total water yield were 469.66 mm (+28%) (2035), 368.18 mm (2010), and 424.43 mm (+15%), respectively. Tile drainage, which is a portion of the total water yield, increased from 176.15 mm in 2010 to 210.11 mm (+33.96 mm) (+19%) in 2050. The maximum, minimum, and average tile drainage were 225.46 mm (2035) (+28%), 176.15 mm (2010), and 202.81 mm (+15%), respectively. Tile drainage as a portion of total water yield ranges between 47 and 48% (Table 4).

Table 4

Summary of the Ensemble Results for RCP 2.6

Water Balance Component	*Total Change from Baseline*	*Percent Change from Baseline*
Precipitation (mm)	23.5	3%
Surface Runoff (mm)	21	37%
Tile (mm)	33.96	19%
Total Aquifer Recharge (mm)	0.79	9%
Total Water Yield (mm)	70.73	19%
Evapotranspiration (mm)	23.5	3%

To assess the estimated water availability to Lake Bloomington and Evergreen Lake reservoirs, the inflow (m^3/s) predicted by the model at the outlets of Money Creek and Sixmile Creek were used, respectively. The model predicts Lake Bloomington to receive an average inflow (m^3/s) increase of 14% from the 2010 baseline, with a minimum of +3% (2030) and maximum of +21% (2035). Evergreen Lake is predicted to receive an average inflow increase of +11%, with a minimum of 2% (2030) and maximum of +17% (2035).

Climate model and earth system model prediction. The climate model RCP 2.6 projection predicts a total evapotranspiration increase from 706.2 mm in 2010 to 754.50 mm in 2050 (+48.3 mm) (+7%). Evapotranspiration as a percentage of precipitation (891 mm) is 85%. The scenario indicates an approximately 47 mm decrease (-82%) in surface runoff from 2010-2050. Total aquifer recharge decreased by 2.02 mm (-23%) from 2010-2050. Total water yield of the watershed decreased from 368.18 mm in 2010 to 132.99 mm (-235.19 mm) (-64%) in 2050. Tile drainage decreased from 176.15 mm in 2010 to 49.96 mm (-126.19 mm) (-72%) in 2050, and was 38% of total water yield.

The earth system model RCP 2.6 projection predicts a total evapotranspiration decrease from 706.2 mm in 2010 to 503.60 mm in 2050 (-202.60 mm) (-29%). Evapotranspiration as a percentage of precipitation (962.90 mm) is 52%. The scenario indicates an approximately 2 mm decrease (-3.3%) in surface runoff from 2010-2050. Total aquifer recharge increased by 4.26 mm (+48%) from 2010-2050. Total water yield of the watershed increased from 368.18 mm in 2010 to 451.99 mm (+83.81 mm) (+23%) in 2050. Tile drainage increased from 176.15 mm in 2010 to 215.05 mm (+38.90 mm) (+22%) in 2050, and was 48% of total water yield.

By 2050, the climate model predicts Lake Bloomington to receive an average annual inflow of 0.79 m^3/s, a minimum of 0.01 m^3/s, and a maximum of 2.18 m^3/s. Evergreen Lake is predicted to receive an average annual inflow of 0.69 m^3/s, with a minimum of 0.20 m^3/s, and a maximum of 1.38 m^3/s. The earth system model predicts Lake Bloomington to receive an average annual inflow of 2.66 m^3/s, with a minimum of 1.15 m^3/s, and maximum of 4.85 m^3/s. Evergreen Lake is predicted to receive an average annual inflow of 1.64 m^3/s, with a minimum of 0.76 m^3/s, and a maximum of 3.02 m^3/s.

RCP 4.5.

GCM ensemble. The RCP 4.5 projection predicts a total evapotranspiration increase from 703 mm in 2010 to 737.6 mm in 2050 (+34.6 mm) (+5%). As a percentage of precipitation, evapotranspiration fluctuates between 57-63%. The scenario indicates an approximately 21.65 mm (+36%) increase in surface runoff from 2010-2050. The maximum surface runoff projection was 95.03 mm in 2015 (+57%), and the minimum of 60.35 mm in 2010, with an average of 81.6 mm (+35%). Total aquifer recharge remained relatively constant over the 40-year span, ranging between 8.73 (2010) and 10.18 mm (+17%) (2040), with an average of 9.72 mm (+11%) per year. Total water yield of the watershed increased from 364.91 mm in 2010 to 468.44 mm (+103.53 mm) (+28%) in 2050. The maximum, minimum, and average total water yield were 489.09 mm (+34%) (2040), 364.91 mm (2010), and 451.62 mm (+24%), respectively. Tile drainage increased from 171.54 mm in 2010 to 227.76 mm (+33%) (+56.22 mm) in 2050. The maximum, minimum, and average tile drainage were 235.75 mm (+38%) (2040), 171.54 mm (2010), and 216.93 mm (+26%), respectively. Tile drainage as a portion of total water yield ranges between 47 and 48% (Table 5).

Table 5

Summary of the Ensemble Results for RCP 4.5

Water Balance Component	*Total Change from Baseline*	*Percent Change from Baseline*
Precipitation (mm)	142.7	13%
Surface Runoff (mm)	21.65	36%
Tile (mm)	56.22	33%
Total Aquifer Recharge (mm)	1.25	14%
Total Water Yield (mm)	103.53	28%
Evapotranspiration (mm)	34.6	5%

The model predicts Lake Bloomington to receive an average inflow (m^3/s) increase of 22% from the 2010 baseline, with a minimum of +10% (2020) and maximum of +28% (2025).

Evergreen Lake is predicted to receive an average inflow increase of +18%, with a minimum of 8% (2020) and maximum of +23% (2025).

Climate model and earth system model prediction. The climate model RCP 4.5 projection predicts a total evapotranspiration increase from 706.2 mm in 2010 to 750.8 mm in 2050 (+47.8 mm) (+7%). Evapotranspiration as a percentage of precipitation (907.2 mm) is 83%. The scenario indicates an approximately 49 mm decrease (-81%) in surface runoff from 2010-2050. Total aquifer recharge decreased by 1.28 mm (-15%) from 2010-2050. Total water yield of the watershed decreased from 368.18 mm in 2010 to 148.59 mm (-216.32 mm) (-59%) in 2050. Tile drainage decreased from 176.15 mm in 2010 to 56.58 mm (-114.86 mm) (-67%) in 2050, and was 38% of total water yield.

The earth system model RCP 4.5 projection predicts a total evapotranspiration increase from 706.2 mm in 2010 to 745.60 mm in 2050 (+42.60 mm) (+6%). Evapotranspiration as a percentage of precipitation (984.60 mm) is 76%. The scenario indicates an approximately 36.5 mm decrease (-61%) in surface runoff from 2010-2050. Total aquifer recharge increased by 0.4 mm (+4.7%) from 2010-2050. Total water yield of the watershed decreased from 368.18 mm in 2010 to 234.63 mm (-130.28 mm) (-36%) in 2050. Tile drainage decreased from 176.15 mm in 2010 to 99.11 mm (-72.43 mm) (-42%) in 2050, and was 42% of total water yield.

By 2050, the climate model predicts Lake Bloomington to receive an average annual inflow of 0.86 m^3/s, with a minimum of 0.02 m^3/s, and a maximum of 2.34 m^3/s. Evergreen Lake is predicted to receive an average annual inflow of 0.73 m^3/s, with a minimum of 0.23 m^3/s, and a maximum of 1.61 m^3/s. The earth system model predicts Lake Bloomington to receive an average annual inflow of 1.37 m^3/s, with a minimum of 0.06 m^3/s, and a maximum of 3.11 m^3/s. Evergreen

Lake is predicted to receive an average annual inflow of 1.01 m^3/s, with a minimum of 0.29 m^3/s, and a maximum of 2.01 m^3/s.

RCP 6.0.

GCM ensemble. The RCP 6.0 projection predicts a total evapotranspiration increase from 699.2 mm in 2010 to 730.5 mm in 2050 (+31.3 mm) (+4%). As a percentage of precipitation, evapotranspiration fluctuates between 56.2-62.7%. The scenario indicates an approximately 31.6 mm increase in surface runoff from 2010-2050 (+54%). The maximum surface runoff projection was 98.94 mm (+70%) in 2045, and the minimum of 58.37 mm in 2010, with an average of 82.64 mm (+42%). Total aquifer recharge remained relatively constant over the 40-year span, ranging between 8.92 mm (2010) and 10.64mm (+19%) (2045), with an average of 10 mm (+12%) per year. Total water yield of the watershed increased from 376.69 mm in 2010 to 484.14 mm (+29%) (+107.45 mm) in 2050. The maximum, minimum, and average total water yield were 525.6 mm (+40%) (2045), 376.69 mm (2010), and 457.59 mm (+21%), respectively. Tile drainage increased from 181.12 mm in 2010 to 232.72 mm (+28%) (+51.6 mm) in 2050. The maximum, minimum, and average tile drainage were 256.23 mm (+41%) (2050), 181.12 mm (2010), and 218.92 mm (+21%), respectively. Tile drainage as a portion of total water yield ranges between 47 and 49% (Table 6).

Table 6

Summary of the Ensemble Results for RCP 6.0

Water Balance Component	*Total Change from Baseline*	*Percent Change from Baseline*
Precipitation (mm)	146.9	13%
Surface Runoff (mm)	31.62	54%
Tile (mm)	51.6	29%
Total Aquifer Recharge (mm)	1.37	15%
Total Water Yield (mm)	107.45	29%
Evapotranspiration (mm)	31.3	5%

The model predicts Lake Bloomington to receive an average inflow (m^3/s) increase of 15% from the 2010 baseline, with a minimum of +9% (2035) and maximum of +27% (2045). Evergreen Lake is predicted to receive an average inflow increase of +13%, with a minimum of 9% (2025) and maximum of +25% (2045).

Climate model and earth system model prediction. The climate model RCP 6.0 projection predicts a total evapotranspiration increase from 706.2 mm in 2010 to 743.30 mm in 2050 (+44.1 mm) (+6%). Evapotranspiration as a percentage of precipitation (915.20 mm) is 81%. The scenario indicates an approximately 44 mm decrease (-60%) in surface runoff from 2010-2050. Total aquifer recharge decreased by 0.87 mm (-10%) from 2010-2050. Total water yield of the watershed decreased from 368.18 mm in 2010 to 167.27 mm (-209.42 mm) (-56%) in 2050. Tile drainage decreased from 176.15 mm in 2010 to 63.71 mm (-117.41 mm) (-65%) in 2050, and was 38% of total water yield.

The earth system model RCP 6.0 projection predicts a total evapotranspiration increase from 706.2 mm in 2010 to 745.20 mm in 2050 (+46.0 mm) (+7%). Evapotranspiration as a percentage of precipitation (978.20 mm) is 76%. The scenario indicates an approximately 35 mm decrease (-60%) in surface runoff from 2010-2050. Total aquifer recharge increased by 0.16 mm (+2%) from 2010-2050. Total water yield of the watershed decreased from 368.18 mm in 2010 to 229.03 mm (-147.66 mm) (-39%) in 2050. Tile drainage decreased from 176.15 mm in 2010 to 97.65 mm (-83.47 mm) (-46%) in 2050, and was 43% of total water yield.

By 2050, the climate model predicts Lake Bloomington to receive an average annual inflow of 0.93 m^3/s, with a minimum of 0.10 m^3/s, and a maximum of 2.39 m^3/s. Evergreen Lake is predicted to receive an average annual inflow of 0.78 m^3/s, with a minimum of 0.31 m^3/s, and a maximum of 1.73 m^3/s. The earth system model predicts Lake Bloomington to receive an average annual inflow of 1.33 m^3/s, with a minimum of 0.19 m^3/s, and a maximum of 2.77 m^3/s. Evergreen Lake is predicted to receive an average annual inflow of 1.01 m^3/s, with a minimum of 0.34 m^3/s, maximum of 1.73 m^3/s.

RCP 8.5.

GCM ensemble. The RCP 8.5 projection predicts a total evapotranspiration increase from 701.7 mm in 2010 to 748.3 mm in 2050 (+6%) (+46.6 mm). As a percentage of precipitation, evapotranspiration fluctuates between 59.4-62.3%. The scenario indicates an approximately 2.3 mm (+3%) increase in surface runoff from 2010-2050. The maximum surface runoff projection was 77.01 mm (+3%) in 2050, and the minimum of 58.87 mm (-21%) in 2020, with an average of 69.31 mm (-7%). Total aquifer recharge remained relatively constant over the 40-year span, ranging between 9.18 mm (-3%) (2030) and 9.72 mm (+3%) (2015), with an average of 9.45 mm (+ < 1%) per year. Total water yield of the watershed increased from 409.86 mm in 2010 to 452.17 mm (+10%) (+42.31 mm) in 2050. The maximum, minimum, and average total water yield were 452.17 mm (+10%) (2050), 397.50 mm (-3%) (2020), and 423.31 mm (+3%), respectively. Tile drainage increased from 190.49 mm in 2010 to 221.55 mm (+16%) (+31.06 mm) in 2050. The average annual tile drainage was 206.17 mm (+8%), and ranged between 46.5 and 49% of total water yield (Table 7).

Table 7

Summary of the Ensemble Results for RCP 8.5

Water Balance Component	*Total Change from Baseline*	*Percent Change from Baseline*
Precipitation (mm)	92.2	8%
Surface Runoff (mm)	2.3	3%
Tile (mm)	31.06	16%
Total Aquifer Recharge (mm)	0.29	3%
Total Water Yield (mm)	42.31	10%
Evapotranspiration (mm)	46.6	7%

To assess the estimated water availability to Lake Bloomington and Evergreen Lake reservoirs, the inflow (m^3/s) predicted by the model at the outlets of Money Creek and Sixmile Creek were used, respectively. The model predicts Lake Bloomington to receive an average inflow (m^3/s) increase of 8% from the 2010 baseline, with a minimum of +3% (2030) and maximum of +11% (2045). Evergreen Lake is predicted to receive an average inflow increase of +8%, with a minimum of 4% (2020) and maximum of +11% (2045).

Climate model and earth system model prediction. The climate model RCP 8.5 projection predicts a total evapotranspiration increase from 706.2 mm in 2010 to 749.70 mm in 2050 (+48 mm) (+7%). Evapotranspiration as a percentage of precipitation (909.90 mm) is 82%. The scenario indicates an approximately 62 mm decrease (-83%) in surface runoff from 2010-2050. Total aquifer recharge decreased by 1.80 mm (-19%) from 2010-2050. Total water yield of the watershed decreased from 368.18 mm in 2010 to 155.94 mm (-253.92 mm) (-62%) in 2050. Tile drainage decreased from 176.15 mm in 2010 to 59.44 mm (-131.05 mm) (-69%) in 2050, and was 38% of total water yield.

The earth system model RCP 8.5 projection predicts a total evapotranspiration increase from 706.2 mm in 2010 to 746.70 mm in 2050 (+45.0 mm) (+6%). Evapotranspiration as a percentage of precipitation (994.50 mm) is 75%. The scenario indicates an approximately 50 mm decrease (-67%) in surface runoff from 2010-2050. Total aquifer recharge decreased by 0.13 mm (-1.4%) from 2010-2050. Total water yield of the watershed decreased from 368.18 mm in 2010 to 241.57 mm (-168.29 mm) (-41%) in 2050. Tile drainage decreased from 176.15 mm in 2010 to 102.93 mm (-87.56 mm) (-46%) in 2050, and was 43% of total water yield.

By 2050, the climate model predicts Lake Bloomington to receive an average annual inflow of 0.92 m^3/s, with a minimum of 0.02 m^3/s and a maximum of 2.62 m^3/s. Evergreen Lake is predicted to receive an average annual inflow of 0.76 m^3/s, with a minimum of 0.20 m^3/s, and a maximum of 1.79 m^3/s. The earth system model predicts Lake Bloomington to receive an average annual inflow of 1.38 m^3/s, with a minimum of 0.05 m^3/s, and a maximum of 2.57 m^3/s. Evergreen Lake is predicted to receive an average annual inflow of 0.99 m^3/s, with a minimum of 0.28 m^3/s, and a maximum of 1.81 m^3/s.

CHAPTER V: DISCUSSION

Calibration and Validation

The calibration output of the model agreeably matched base flow behavior when compared to the observed field data of discharge at the Mackinaw River at Green Valley USGS stream gauge. The R^2 value of 0.68 is deemed acceptable according to similar publications (Wang, 2018; Guo, 2017; Abbaspour, 2015; Moriasi, 2012). Calibration over-predictions of peak flow are likely due to errors in precipitation gauge measurements, spatial variability, and availability of precipitation data. The model validation performed sufficiently, with an R^2 value of 0.64, and baseflow matched well with the observed measurements. Moving forward, the calibration and validation performance of the SWAT was determined as adequate for the further prediction of water balance components of the watershed under the various climate change scenarios.

Ensemble, Climate, and Earth System Model Predictions

Model simulations using the ensemble of all GCMs predicted an intensification or amplification of the current watershed balance behavior. This is similar to the findings of previous studies completed in larger Midwestern United States watersheds (Cousino et al. 2015, Jha et al. 2006), as well as global trends (Huntington 2006, Vörösmarty et al. 2000). The ensemble of GCMs predicted an increase in both precipitation and temperature for the watershed. The average increase in precipitation for all RCPs was approximately 40mm by mid-century. As for temperature, RCP 8.5 predicts an approximately 2.25℃ from 2010-2050, whereas RCP 6.0 projects an approximate increase of 0.96℃. The average increase in temperature for all RCPs is 1.4℃. Results indicate that shallow aquifer recharge remains consistent over time. Surface runoff values fluctuate over time, but generally increase by mid-Century. Evapotranspiration as a percentage of precipitation decreased by mid-Century, but total evapotranspiration increased. This is due to the increase in precipitation as a whole, allowing for more water to be lost as evapotranspiration with increasing temperature.

As the ensemble GCMs predict an increase in precipitation over time, there are a few seasonal patterns worth noting. The analysis using the two extreme projection scenarios: RCP 2.6 (stringent emission scenario) and RCP 8.5 (extreme emission scenario) show the frequency of wet (daily precipitation event ≥2.5mm) precipitation events increase by mid-century, see Figure 10 and Figure 13, respectively. The number of extreme events per decade increase slightly by mid-century and continues the trend continues until the end of the century (2099). In addition to an increase in the frequency of extreme precipitation events (≥95th Percentile = 4.5mm), the total precipitation delivered during the extreme events increases (Figure 10 & 13). Considering the seasonal pattern, the frequency of extreme precipitation events increases by mid-century in the spring and summer months (Figures 11 & 14), whereas autumn and winter months do not change (Figure 15 & 16). Around mid-century (2040s decade), there is a shift (significant increase) in the occurrence and magnitude of the extreme precipitation (≥95th percentile) events that occur in the spring for both RCP 2.6 and 8.5 projection scenarios (Figure 10a and 13a). Generally, the annual frequency of extreme wet conditions (precipitation ≥95th percentile) increases from the current decade ~17 to 24 events and ~18 to 28 events by the end of the century (Figure 11). Therefore, it can be concluded that this projection scenario results in an amplification of the current watershed behavior, in which spring and summer seasons become wetter in the watershed. This, in turn, affects the hydrologic (e.g., runoff and evapotranspiration) processes in the watershed.

As a result of the increased frequency of extreme events and total precipitation delivered during those extreme events, the discharge of the Mackinaw River into the Illinois River reaches extreme highs more frequently (Figure 14). The modification of the watershed by tile drainage does not have the capacity to drain the increased volumes of water from heavier rains, and the soils are very clayey which favor runoff when saturated, ultimately favoring more frequent and extreme flooding events. This is of major concern for agriculture near streams, as well as communities further downstream in the watershed that may lie within a floodplain. If the intense spring storm events occur before vegetation is established in the soil, sediment washouts could occur and diminish the quality of plots through soil loss. Depending on their origin, these washed soils could be deposited in either Lake Bloomington or Evergreen Lake, causing sedimentation and therefore a decrease in volume of the reservoirs over time.

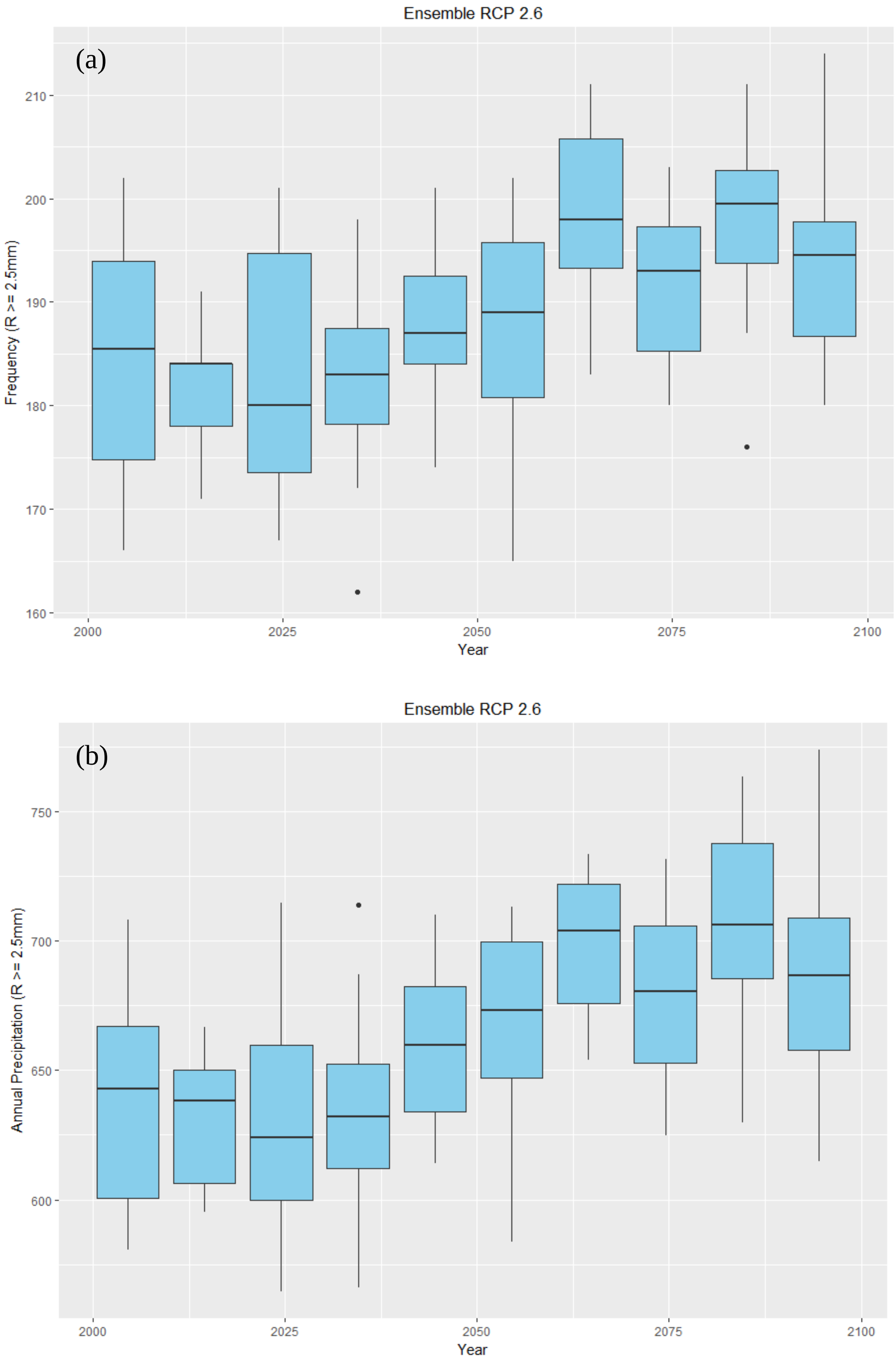


Figure 10. RCP 2.6 ensemble (a) Frequency of precipitation events exceeding 2.5mm per decade; (b) Total precipitation delivered by extreme events by decade

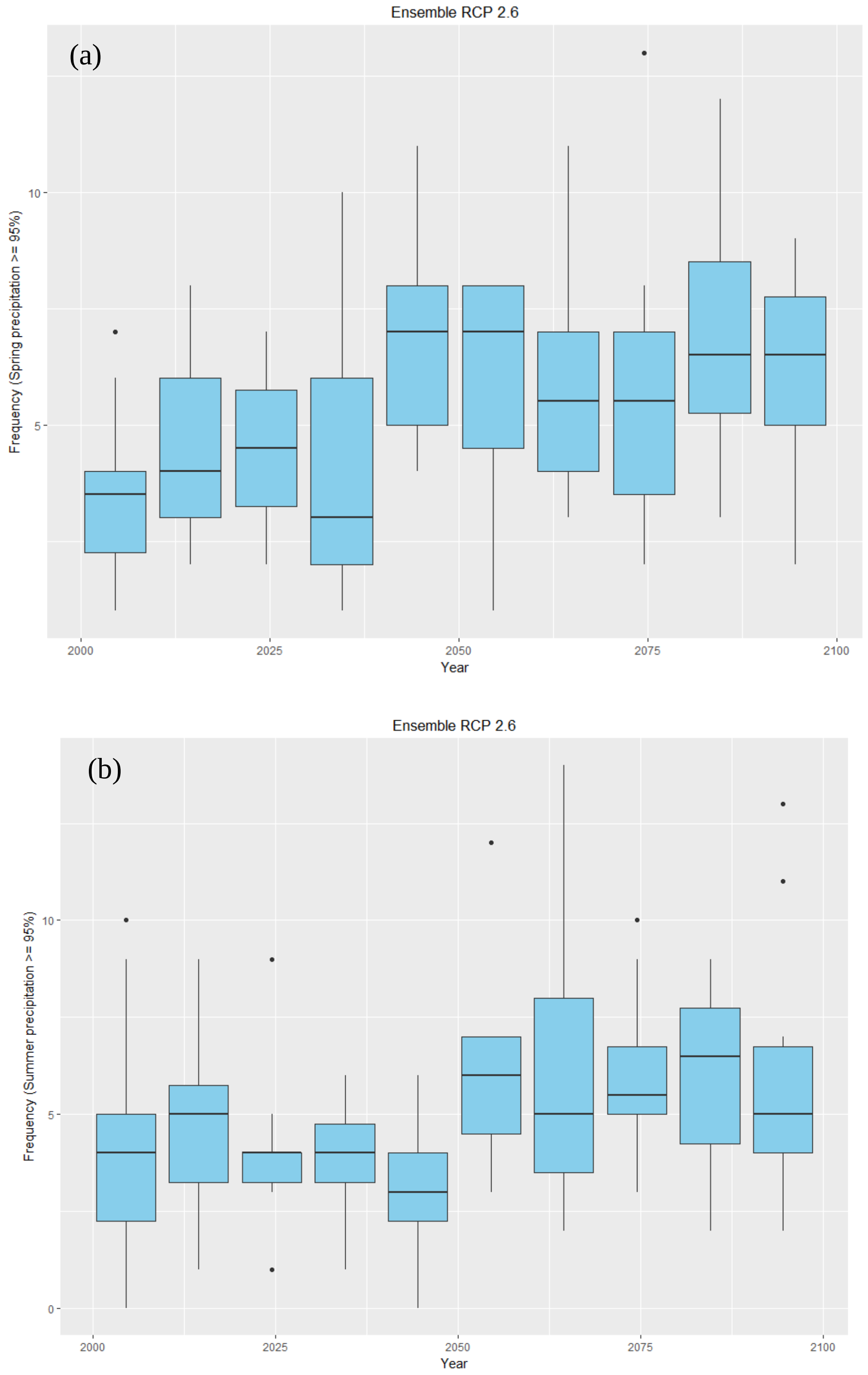


Figure 11. RCP 2.6 ensemble (a) Spring precipitation events exceeding 95th percentile by decade; (b) Summer precipitation events exceeding 95th percentile by decade

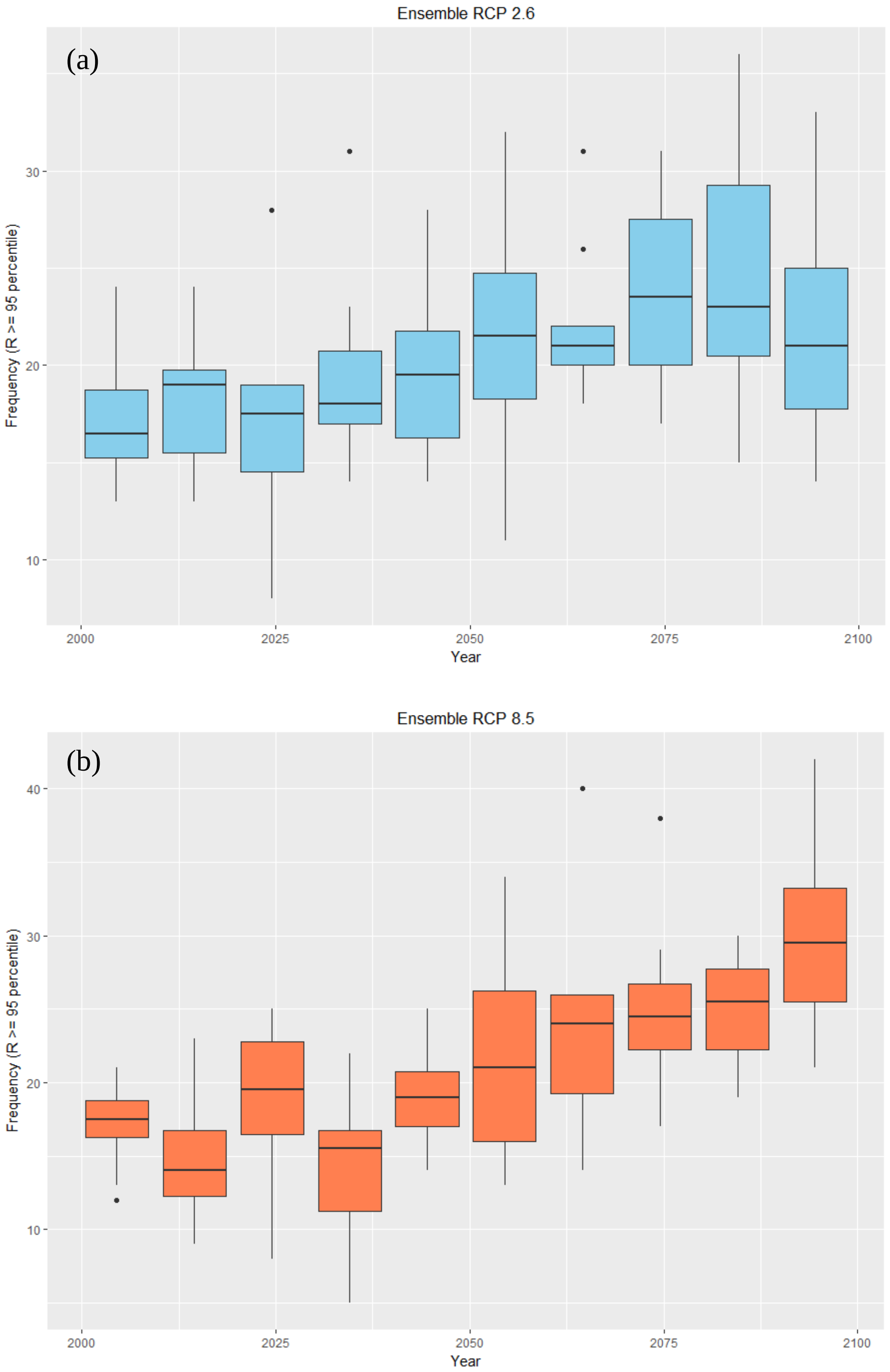


Figure 12. Frequency of extreme precipitation (precipitation ≥95th percentile): (a) RCP 2.6 ensemble (b) RCP 8.5 ensemble

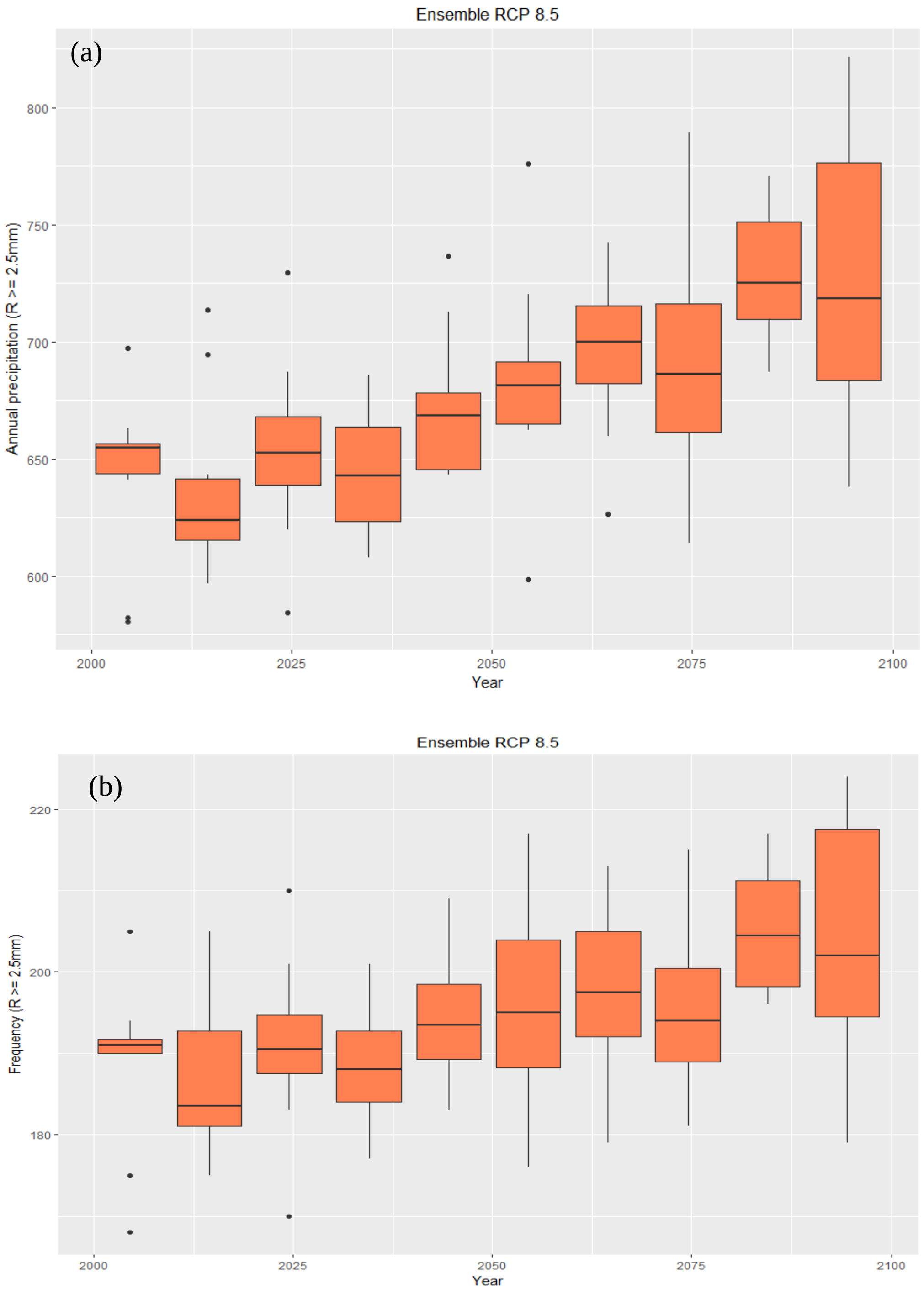


Figure 13. (a) Annual precipitation totals from extreme events by decade, RCP 8.5 ensemble; (b) Frequency of precipitation events exceeding 2.5mm per decade, RCP 8.5 ensemble

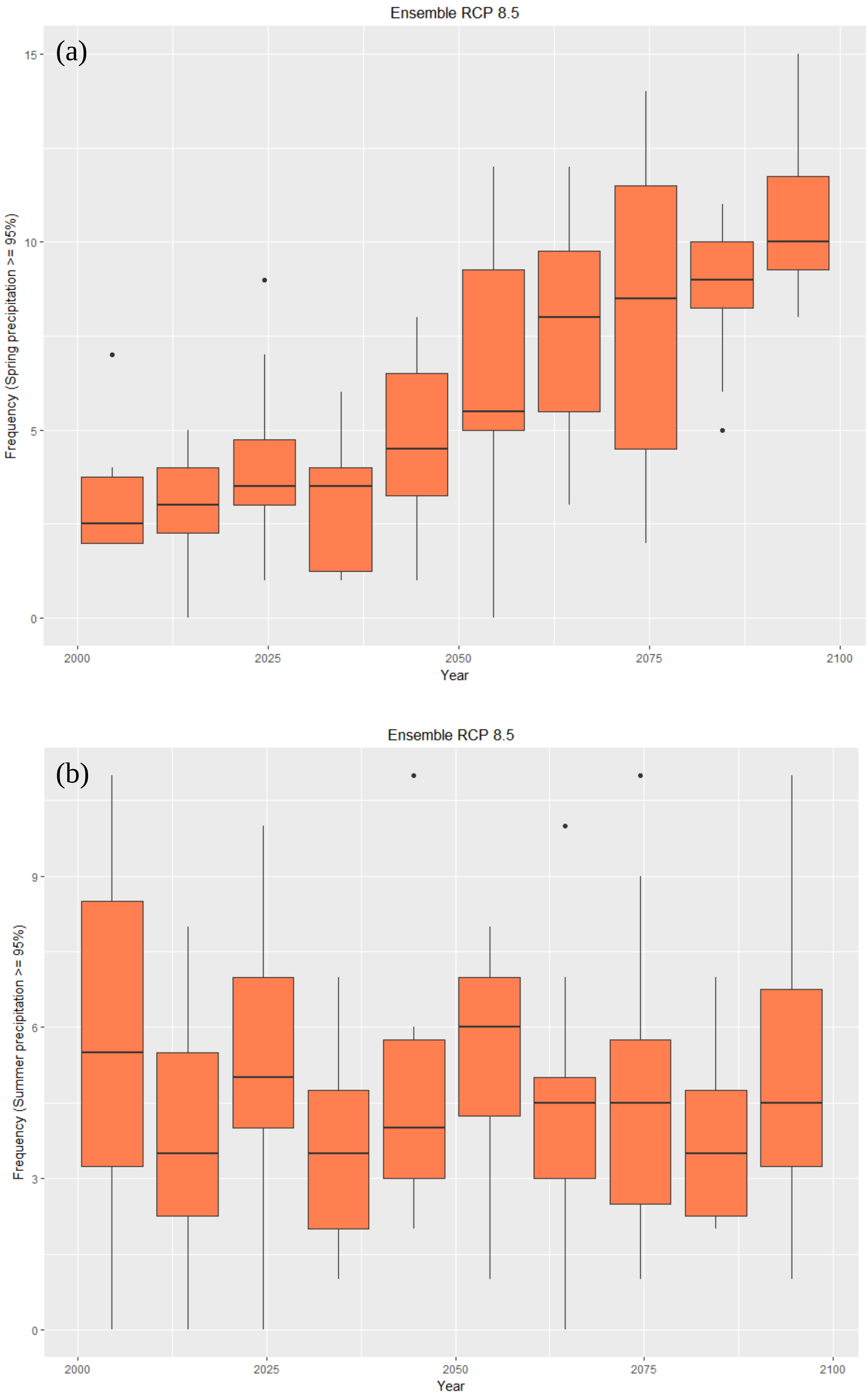


Figure 14. RCP 8.5 ensemble (a) Frequency of extreme precipitation events during the Spring by decade; (b) Frequency of extreme precipitation events during the Summer by decade

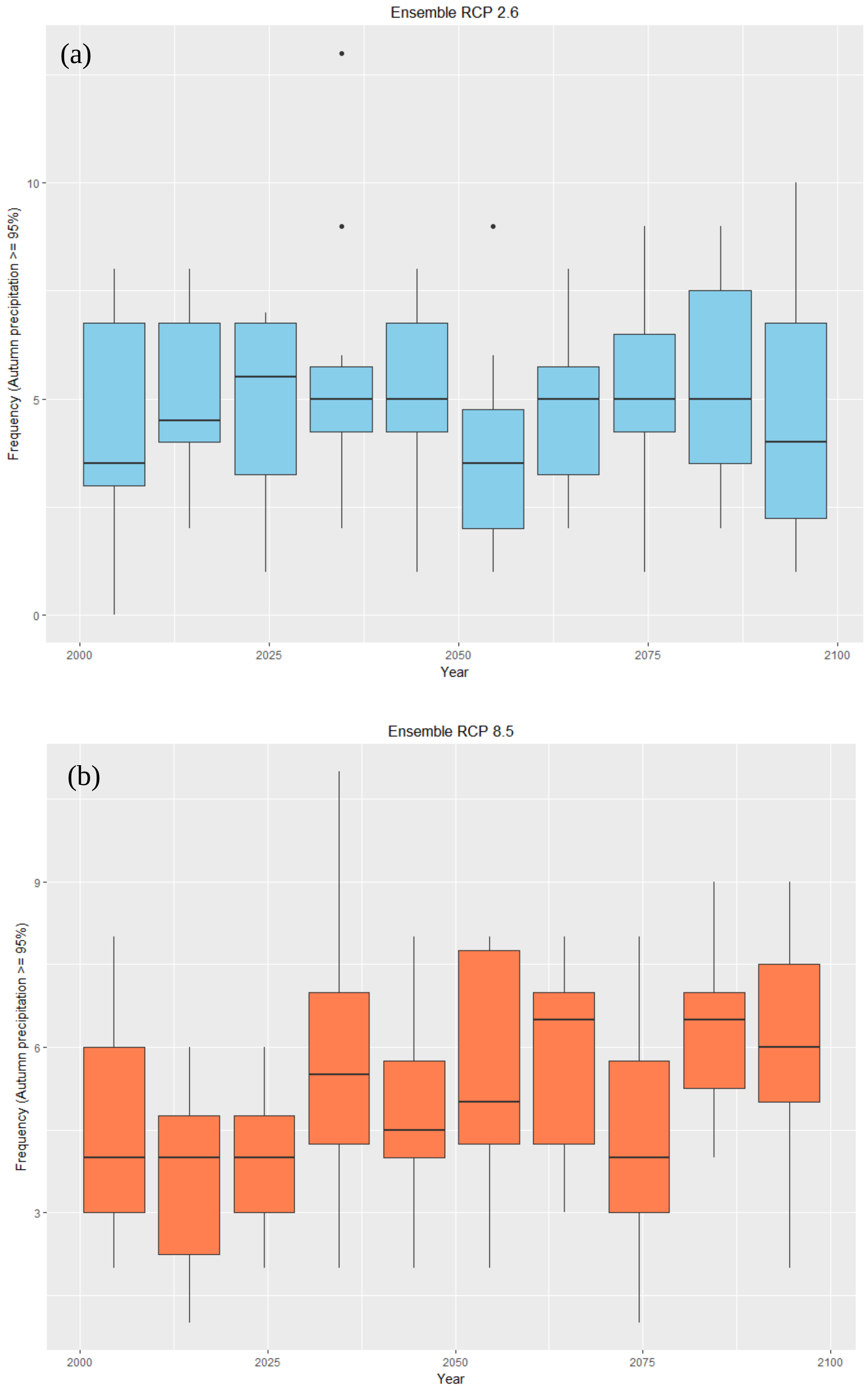


Figure 15. (a) Frequency of extreme precipitation events during Autumn by decade, RCP 2.6; (b) Frequency of extreme precipitation events during the Autumn by decade, RCP 8.5

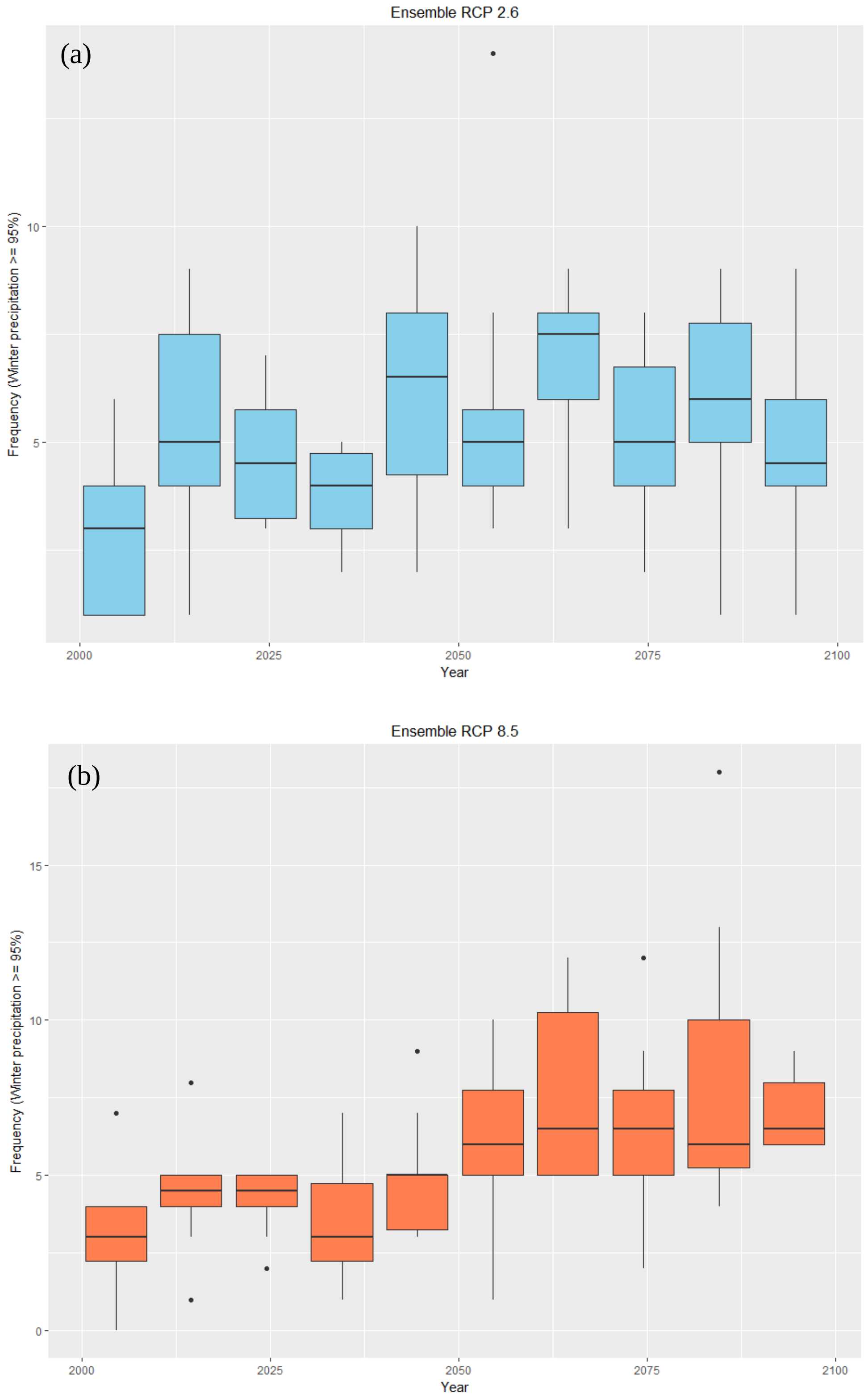
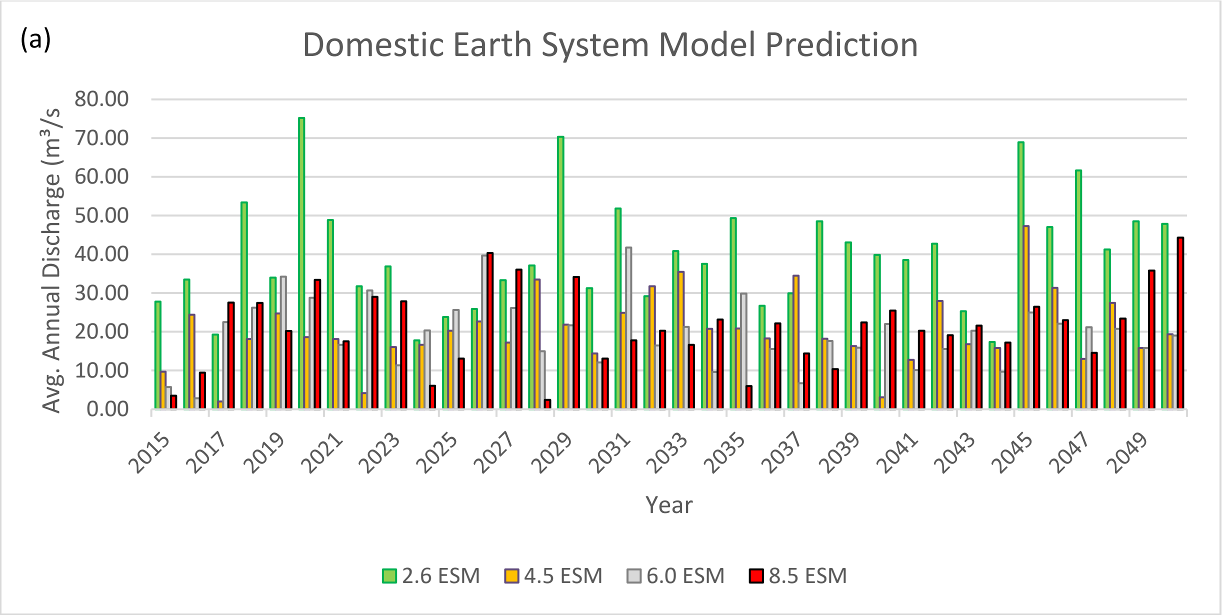


Figure 16. (a) Frequency of extreme precipitation events during Winter by decade, RCP 2.6; (b) (b) Frequency of extreme precipitation events during the Winter by decade, RCP 8.5

The GFDL ESM2M and CCSM4.0 projected precipitations have decreased when compared to the ensemble results, but the overall trends were consistent with the ensemble GCMs projection. Discharge at the Mackinaw River increases by mid-century, but low-flow conditions are anticipated over several years. The ESM predicts notable low-flow periods for the Mackinaw River in 2015, 2017, 2024, 2030, and 2044 under all RCPs. Model simulation using the CM data predicts less water than the ESM, but with similar low-flow patterns, spanning 2023-2028, 2035-2044, and 2048-2049. Patterns in the discharge projection data (Figure 17) show a cyclicity in drought patterns on a somewhat decadal frequency.

Previous studies have concluded that an ensemble approach is more accurate and feasible than the use of a singular GCM (Yuan et al. 2015). The main conclusion from the comparison of the ensemble approach with the GFDL ESM2M and CCSM4.0 is the importance of similar predictions of watershed behavior and droughts for each RCP, regardless of the total precipitation.



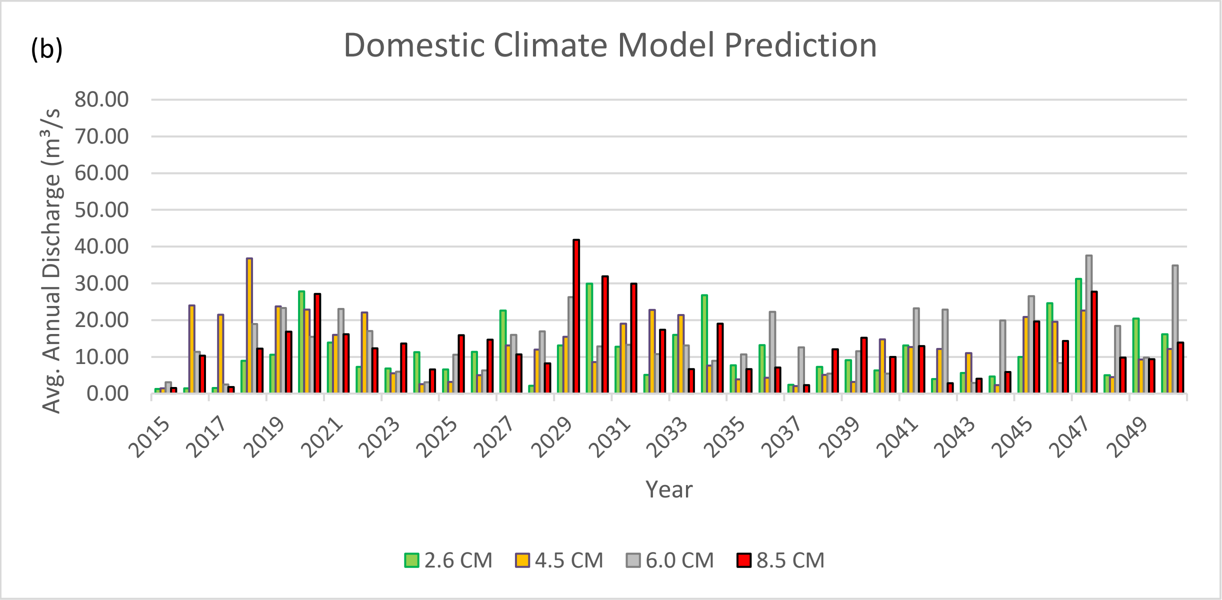


Figure 17. Model-predicted discharge for the watershed at the outlet: (a) GFDL ESM2M; (b) CCSM4.0

Tile Drainage Predictions & Water Resource Implications

Tile drainage remains a strong component of total watershed discharge across all ensemble and individual simulations. Results from simulations using the ensemble climate projection data indicate a contribution ranging between 46-49%, whereas the climate and earth system model predictions indicate a contribution of 38-48%. These contributions agree with previous findings in Midwestern US agricultural watersheds (Arenas Amado et al. 2017, Culley and Bolton 1983, King et al. 2014, Macrae et al. 2007). As a result, non-point source loading of nitrate from tile drainage is expected to continue based on all scenarios. This suggests that the Bloomington Water Department should be prepared for treatment of reservoir waters that will be in exceedance of the 10 mg/L nitrate as nitrogen EPA maximum contaminant level (MCL) every spring following agricultural chemical applications. This should be of particular concern in the context of the results of the individual GCM simulations, in which water balance is predicted to decrease for the watershed as a whole.

Model-predicted surface inflow to the lakes (Lake Bloomington and Evergreen Lake) is anticipated to increase for all RCPs scenarios predicted by the ensemble, GDFL ESM2M, and CCSM4.0 GCM scenarios. Model-simulated times series inflow data to the lakes showed that surface inflow varies annually, with several years showing droughts. Further, an amplification or decrease in precipitation or discharge patterns relative to seasonal norms can be observed. All RCPs under each GCM method arrive at similar predictions of drought in terms of both individual years and multi-year spans. As mid-century approaches (~2035-2045), a drought event is predicted by each simulation. This prediction should be addressed when developing best management practices for public water supply. The aforementioned drought is a consequence of both past and modern global emissions practices, as it is predicted by RCP 2.6, the most stringent emissions scenario. The RCPs represent varying degrees of mitigation of current emissions practices, therefore the RCP 8.5 prediction can be viewed as the trajectory of current watershed behavior. The sooner that more stringent emissions practices are adapted, the likelihood of system recovery to the RCP 2.6-4.5 prediction increases. If emissions practices continue as they have in the past and present, it is likely that the watershed will undergo extreme events (drought and flooding) similar to the RCP 6.0 & 8.5 predictions (See Figure 14 and Figure 15).

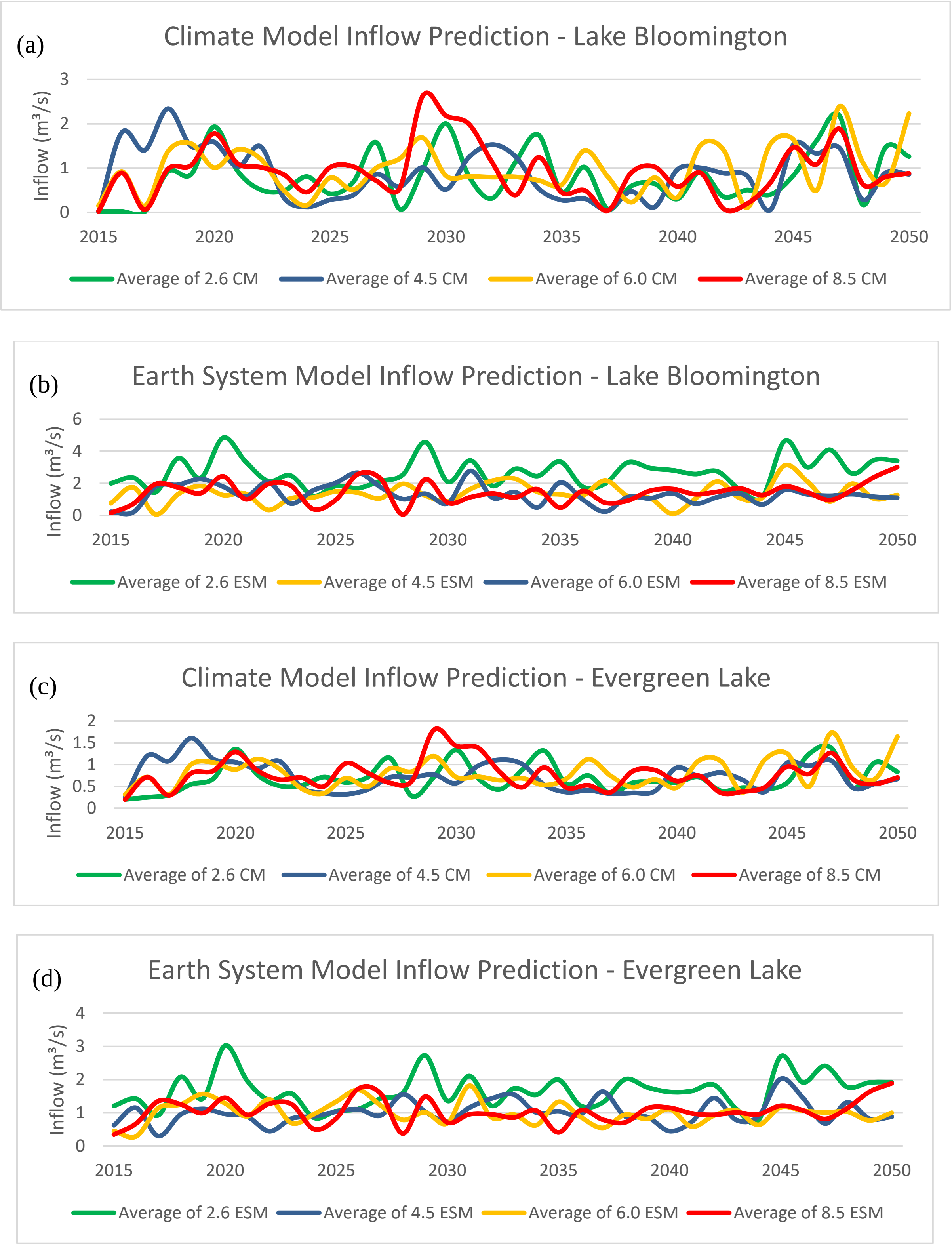


Figure 18. (a-d) Inflow predictions for public water supply reservoirs

CHAPTER VI: CONCLUSIONS

Climate change impacts on the water resources of the Mackinaw River watershed and its fresh water reservoirs was conducted. A USDA SWAT hydrologic model was set up using high-resolution elevation, soil, and land cover data. The SWAT was calibrated and validated using measured streamflow of the Mackinaw River at the outlet into the Illinois River. Once the model was calibrated and validated, precipitation and temperature outputs from a GCM ensemble as well as individually from GFDL ESM2M and CCSM4.0 under each RCP were used as inputs into the SWAT model for water balance projections until 2050. The major findings of this study are as follows:

- The ensemble, GFDL ESM2M, and CCSM4.0 GCM simulations arrive at similar conclusions for watershed behavior under each RCP. All scenarios predict an amplification of current watershed dynamics by mid-century.
- Droughts are predicted similarly for each GCM approach and RCP due to the high-resolution capabilities of the model and methods. The analogous projections of drought will be advantageous in preparation for water supply management.
- Tile drainage will remain a strong component of watershed runoff. This ultimately means that nutrient loading will continue into the Lake Bloomington and Evergreen Lake reservoirs, affecting water quality and recreational use of the lakes.
- Surface reservoir inflow is expected to increase by mid-century. However, as mentioned above, nutrient loading will remain a problem due to dominance of tile-drained agricultural land use within the watershed. Water quantity will vary with drought events.

- Flooding events can be predicted using the model. The timing of intense precipitation could induce high discharge events could cause washouts of soils if vegetation is not established enough to hold soils together. Future studies should aim to include sediment dynamics within the watershed for soil conservation and reservoir sedimentation.
- This study involving a small-scale watershed can be used to further project behavior of larger watersheds, such as the Illinois River and ultimately the Mississippi River, using similar methods and high-resolution data.

Overall, GCM approaches predict that the average discharge of the Mackinaw River watershed will increase by 2050 from the 2010 baseline. Inflow to the Lake Bloomington and Evergreen Lake surface reservoirs will continue to originate from tile drainage, meaning that nutrient loading will be a challenge to water quality and reservoir recreation regardless of total water influx. As the Bloomington-Normal area population continues to grow, water supply service demand will increase. RCPs 2.6 and 4.5, the more stringent emissions practices, typically tend to predict a greater abundance of water available than the more extreme scenarios, but are not lacking in droughts. Droughts will continue to occur, followed by wetter years. These dry periods are more extreme and frequent under the RCPs 6.0 and 8.5. Current warming trends and watershed response from decades of previous emissions practices will take time to reverse, thus aiming for a future similar to the RCP 2.6 and 4.5 projections. Therefore, it is in the best interest of policymakers and populations to assume stricter emissions rule as soon as possible.

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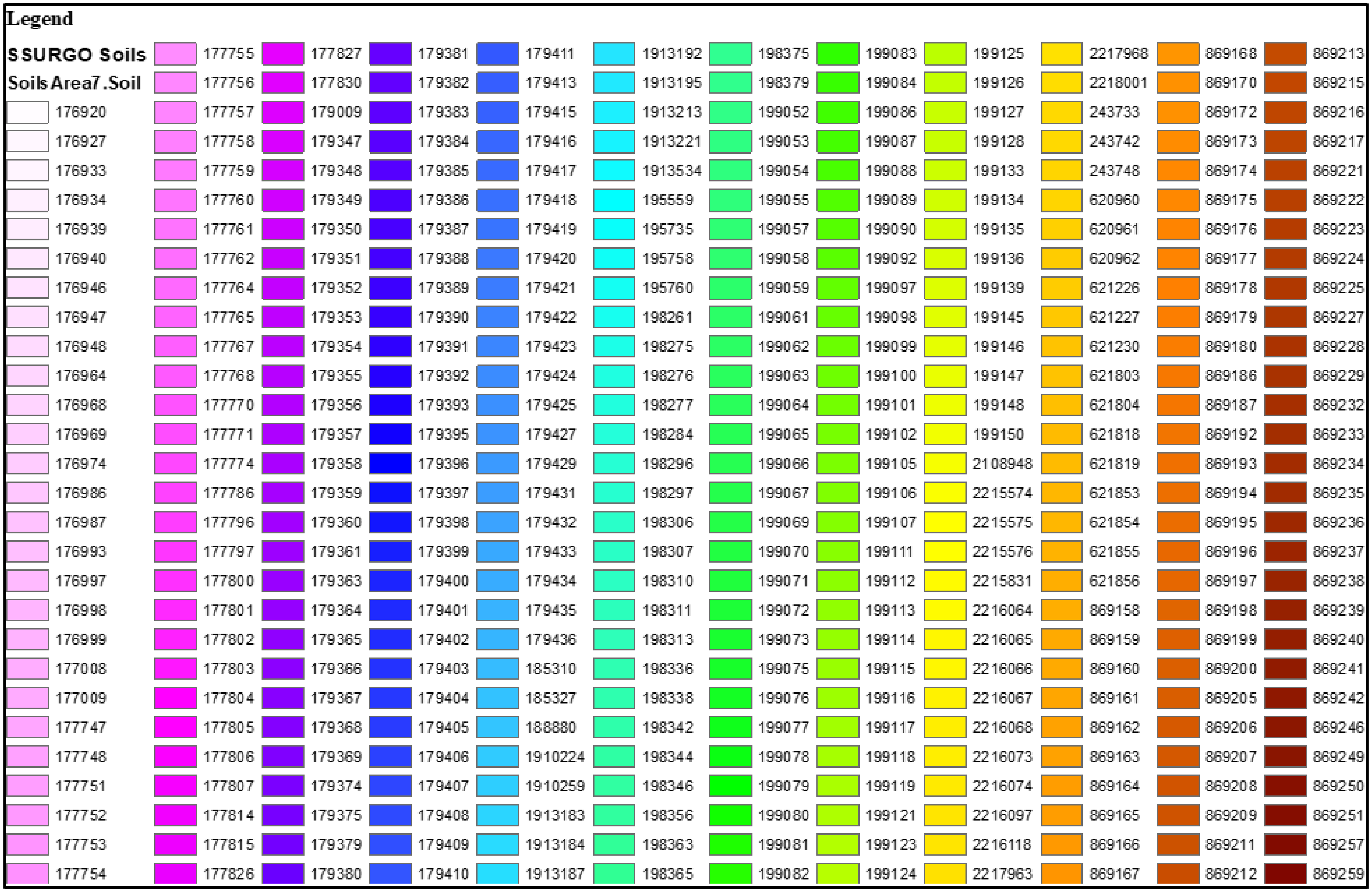
APPENDIX A: SSURGO SOILS LEGEND



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