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Baseflow Variability Due to Changes in Climate, Basin Characteristics, and Groundwater Withdrawals in the State of Wisconsin, USA

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BASEFLOW VARIABILITY DUE TO CHANGES IN CLIMATE, BASIN CHARACTERISTICS, AND GROUNDWATER WITHDRAWALS IN THE STATE OF WISCONSIN, USA

by

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ABSTRACT

BASEFLOW VARIABILITY DUE TO CHANGES IN CLIMATE, BASIN CHARACTERISTICS, AND GROUNDWATER WITHDRAWALS IN THE STATE OF WISCONSIN, USA

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Under the Supervision of Professor Woonsup Choi

In Wisconsin, the number of high-capacity wells has increased substantially, and concerns have been raised about their impact on both groundwater levels and streamflow. At the same time Wisconsin's climate has been changing, and both the annual precipitation (5%) and temperature (1.5^{o}C) have been trending upward over the last 68 years and both are predicted to increase into the future. This study attempted to demonstrate the simultaneous effects of climate change, physical basin changes and changes to the groundwater withdrawal rate from high-capacity wells by employing both analytic methods and simulation models.

Linear regression was used to determine how variables representing climate, land use, soil characteristics, and groundwater withdrawals would affect baseflow variability. While double-mass curve analysis was used to find that twenty out of the thirty-five basins studied exhibited a deviation in the slope when the cumulative value of precipitation was plotted against the cumulative value of baseflow suggesting an anthropogenic variable was affecting baseflows, most likely groundwater withdrawals. Panel data analysis (PDA) was then used to evaluate the simultaneous effects of climate, withdrawal rate, and physical basin variables on baseflow variability across the state. The PDA found that the climate variables (precipitation and temperature) were significant in explaining the temporal variability of baseflow, whereas land use and the drainage conditions were important in explaining the spatial variability of baseflow as expected. But the groundwater withdrawal was not, which was not expected.

The Soil & Water Assessment Tool (SWAT) and the United States Geological Survey's Modular Hydrologic Model (MODFLOW) were used to simulate changes in hydrology in a single basin in the state that has experienced declining baseflows over the last 30 years but steady population numbers and land use percentages over the same period. Using the variables found to affect baseflow (climate, land use, and soil characteristics), SWAT was used to simulate the change in the recharge rate, and then using the withdrawal rate from high-capacity wells, MODFLOW was used to simulate the change in hydraulic head. The SWAT model predicted that future increases in Wisconsin's annual precipitation of approximately 7.5% will cause increases in both groundwater recharge (16.74%) and streamflow (14.13%). The future increases in temperature of 2.2–3.3°C by the middle of the 21st century, however, are predicted to leave the state with a net reduction in both streamflow (–23.39%) and groundwater recharge (–19.63%). In addition, the MODFLOW model predicted a mean head elevation decrease of over 2 meters due to increased predicted temperatures, this is despite predicted increases in annual precipitation and an additional decrease in groundwater elevation surrounding high-capacity wells due to predicted increases in annual withdrawal rate.

Overall, analytically the most important variable in determining the variability of streamflow is the amount of annual precipitation, but the modeling portion of the study showed that the predicted increases in temperature will ultimately lead to decreases in the available fresh water in the study area. This study also highlights that if the escalating use of irrigation for Wisconsin's agriculture outpaces the increases in annual precipitation, declines in stream baseflow will result. The study also predicted that some of these decreases can be mitigated by abandoning just a select number of high withdrawing wells.

Keywords: Baseflow, Groundwater, High-capacity wells, Double-mass curve analysis, SWAT, MODFLOW, Streamflow, Aquifer, Regression model

To

my husband who didn't tell me

getting my doctorate was a

crazy idea

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LIST OF ABBREVIATIONS

Abbreviation	Definition
AGOL	ArcGIS online
AWR	Annual withdrawal rate
AWS	Available water storage
DEM	Digital Elevation model
ESRI	Environmental Systems Research Institute
ET	Evapotranspiration
GDD	Growing degree days
GIS	Geographic Information System
GWTB	Groundwater toolbox
GWV7	Groundwater Vistas Version 7
HRU	Hydrological Response Units
MAWR	Modified Annual Withdrawal Rate
NCEI	National Centers for Environmental Information
NLCD	National Land Cover Database
PDA	Panel Data Analysis
PET	Potential Evapotranspiration
RCP	Representative Concentration Pathway
SDC	Soil Drainage Class
SSURGO	Soil Survey Geographic Database
SWAT	Soil & Water Assessment Tool
USDA	United States Department of Agriculture
USGS	United States Geological Survey
WDNR	Wisconsin Department of Natural Resources

WGNHS	Wisconsin Geological and Natural History Survey
WICCI	Wisconsin Initiative on Climate Change Impacts
WRB	Wolf River Basin

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CHAPTER 1 INTRODUCTION

1.1 Background

With diminished flows in many of the Wisconsin's gauged streams, concerns have been raised about the impact that climate change (Ficklin et al. 2016) and high-capacity wells (Barlow and Leake 2012) have on both groundwater levels and streamflows. A variety of stake holders from environmentalists to agricultural growers are in search of a better understanding of the groundwater-surface water system and all are seeking a balance between environmental protection and agricultural needs (Bradbury et al. 2017). Both changes in the climate, specifically temperature and precipitation (e.g., Ayers et al. 2021, Price 2011) and increased high-capacity withdrawal rates (e.g., Kraft et al. 2012, Weeks and Stangland 1971, Barlow and Leake 2012) influence streamflow. But these studies have concentrated on the effects, to the hydrological system, from either climate change or the groundwater withdrawals, not both simultaneously. Although stake holders and resource managers generally agree that groundwater withdrawal and climate variables affect both groundwater levels and streamflows, there is disagreement as to the degree each play. Not only is there disagreement on the extent each of the variables play in groundwater level and streamflow variation, but there is also disagreement on how policy managers can assess the effect of regulatory management (Bradbury et al. 2017).

1.2 Baseflow and Climate

When groundwater discharges into surface water, it is defined as the stream baseflow. Baseflow is the portion of streamflow that maintains streamflow between precipitation events. Because baseflow enters the stream from groundwater it has not been warmed by atmospheric temperatures or become turbid from storm flow. Therefore, baseflow is important to Wisconsin streams because of its cooler temperature and better quality (Borchardt 2019). Baseflow decreases and stream temperature increases will lead to decreases in aquatic biodiversity (Brown and Krygier 1970). Both changes in climate and

human activity such as increased groundwater withdrawals, will lead to changes in the rate that groundwater recharges lakes and streams as baseflow. The decline of baseflow due to the irrigation of agriculture from unconfined aquifers connected to surface waters has been well documented (e.g., Kraft et al. 2012, Weeks and Stangland 1971, Weeks et al. 1965). This study investigated how climate, basin characteristics, and groundwater withdrawal from the unconfined aquifers collectively can affect streamflow, baseflow, and groundwater elevation within the state of Wisconsin.

Baseflow is derived from both shallow and deep groundwater storage (Robinson and Ward 1990). Baseflow increases with infiltration and decreases with evapotranspiration (Price 2011). Increases in precipitation can increase storm flow during a single event or increase baseflow over an extended period by increasing the groundwater level. The percent of precipitation that infiltrates the surface to flow vertically to the water table is affected by both soil texture and the soil saturation level. Increased irrigation effectively increases moisture contacting the surface; therefore, irrigation water may also increase baseflow. Since agricultural irrigation is only required when soil moisture is low, the moisture contacting the surface will infiltrate the surface and not increase storm flow. The need to irrigate agricultural fields intensifies as the fields loose moisture to rising air temperatures and/or decreased amounts of precipitation. Therefore, baseflow decreases from increased temperatures and/or decreased precipitation may be offset by the increases in agricultural irrigation sourced from the confined aquifer.

Baseflow increases have been documented in basins in Wisconsin where the primary land use is agriculture between 1970 and 1999 (Gebert et al. 2007), but the mechanism and conditions of such increases are unclear. Two potential explanations are the increased use of soil conservation practices in southwestern Wisconsin (Potter 1991) and increased irrigation from confined aquifers that are not connected to the surface waters. Since the irrigation of agricultural land increases the soil moisture storage and increases in soil moisture storage have been found to be linked to increases in baseflow (Shaw et al. 2013, Price 2011), withdrawals from the confined aquifer may be related to baseflow increases. There are few if any studies on the effects of the withdrawal of groundwater on baseflow from confined aquifers that are disconnected from surface waters (Borchardt 2019). The lack of such

understanding puts environmentalists and agricultural growers across the state at odds with each other on how best to preserve the state's freshwater resources. A better understanding of the factors that affect the groundwater-surface water system will help balance both the needs of the agricultural industry and conservation efforts in Wisconsin and elsewhere.

Preliminary findings for this study suggest declining baseflows in northern Wisconsin, and increasing baseflows in southern portions of the state, between 1984 and 2014. A study found baseflow trends increasing in basins where the primary land use was agriculture, and no trend for those basins located in forested areas between 1970 and 1999 in Wisconsin (Gebert et al. 2007). But declining baseflow trends were found in areas of central Wisconsin, mainly in agricultural areas, between 1977 and 2009 (Kraft et al. 2012). In portions of Pennsylvania strong downward baseflow trends coincided with decreases in precipitation and increases in temperature between 1971 and 2001 (Zhu and Day 2005); and in Wisconsin precipitation and temperature were both found to be statistically significant variables in a regression model created to predict variations in baseflow between 1983 and 2013 (Borchardt et al. 2016). It is crucial to understand the relationship between physical basin properties, such as soil texture and land use, and baseflow; and it is also crucial to understand how both anthropogenic impacts and climate change affect those physical properties (Price 2011). Annual precipitation (7.5%) and temperature (3.9%) have been trending upward over the last 30 years (1983–2013) in Wisconsin (Borchardt et al. 2016). Precipitation and temperature both relate to baseflow, but in opposing directions. This study looked at how these climate factors affect baseflow in areas where there is extensive use of high-capacity irrigation wells.

1.3 Effects of Agricultural Irrigation on Baseflow

Agricultural irrigation was once almost exclusively practiced in the arid western portion of the United States, but in the last few decades, the use of irrigation has accelerated in the humid Great Lakes region of the United States (Kraft et al. 2012). In Wisconsin, the number of high-capacity wells (pumping

capacity of at least 265 liters per minute) increased substantially from less than 4,000 in 1983 to over 16,000 in 2014. Historical trends of baseflow in Wisconsin, and the Great Lakes states in general, have not been broadly studied. A national scale baseflow study (Ficklin et al. 2016) found increasing trends in some parts of the Northeast and decreasing in the Southwest between 1980 and 2010, but there was not sufficient detail at the state level. Baseflow trends in the study were found to be related primarily with precipitation but increases in potential evapotranspiration (PET) were also influencing the trends by either mitigating baseflow increases or accentuating decreases between 1980 and 2010 (Ficklin et al. 2016). With precipitation generally increasing in the second half of the 20th century (5–15%) and projected to increase through the 21st century (5%) in Wisconsin (Wisconsin Initiative on Climate Change Impacts 2011), baseflow would be expected to increase as well. However, there are areas in Wisconsin where baseflow has declined. Baseflow increases and declines need to be studied with respect to the source of the groundwater used to irrigate agricultural lands while considering the effects of high-capacity wells.

High-capacity wells, used to irrigate agriculture, can significantly impact groundwater storage and the associated interaction of surface to groundwater systems (Sophocleous 2002, Wahl and Tororelli 1997). Several studies have explored the relationship between high-capacity irrigation wells and declines in streamflow in areas where the groundwater flows through highly permeable sand and gravel deposits (e.g., Weeks et al. 1965, Kraft et al. 2012, Weeks and Stangland 1971). There is a relationship between declines in both baseflow and groundwater levels and increases in the number of high-capacity wells in the Oklahoma panhandle (Wahl and Tororelli 1997). The decreasing amount of groundwater, which is discharged to streams, is related to the increased rate of groundwater pumped by high-capacity wells (Barlow and Leake 2012). Ambient groundwater that normally would have discharged as baseflow to surface water can be diverted away from discharge points by the gradients created by high-capacity wells (Sophocleous 2002). It has also been found that high-capacity wells outside the surface water basin, but within the groundwater basin, have a significant effect on the baseflow of the stream within the surface water basin (Borchardt et al. 2016). These studies established that high-capacity wells withdrawing

groundwater from an unconfined aquifer that is well connected to the surface waters will lead to declines in the baseflow.

Environmental stresses have been found to be related to streamflow declines (e.g., Choi et al. 2017, Juckem et al. 2008) and although annual precipitation had the greatest impact on flow rates, if increases in the annual withdrawal rate outpace the increases in annual precipitation, declines in stream baseflow will result across the state of Wisconsin. In Wisconsin, a lot of attention has been paid to the area in the central part of the state called the Central Sands, but despite the attention to the Central Sands region (Figure 5) there is still a lack of knowledge of the combined effect of both climate and anthropogenic stresses. Bradbury et al. (2017) created a flow model for the Little Plover River in the Central Sands. The model was developed to help water managers, users, and citizens visualize the connections between groundwater, surface water, and water use within the Little Plover River basin (Bradbury et al. 2017). The Little Plover River study and others are concentrated on the effects of groundwater pumping in the area, while effects of climate have been secondary at best. The Central Sands region is a contiguous area east of the Wisconsin River. It spans parts of several counties, and it has an unconfined aquifer that is well connected to the area's surface waters. The area has seen both a lowering of the water table and the drying of important trout streams due to excessive use of irrigation sourced from groundwater in the unconfined aquifer. The Wolf River basin (WRB) on the other hand, just to the north of the Central Sands, has not experienced drying of its trout streams yet. The WRB basin has however seen declining baseflows over the last three decades (Borchardt et al. 2016). The WRB in Langlade County has a similar unconfined aquifer as the Central Sands and has experienced an increase in agricultural irrigation although it has been at a slower rate than the Central Sands. Both these areas, along with the rest of the state have seen changes in climate over the last three decades and further changes are expected into the middle of this century.

But there are few if any studies analyzing the effects on baseflow when the high-capacity wells are withdrawing water from a confined aquifer. Aquifers below the confining layer are not connected to the surface waters. Therefore, withdrawals from them may contribute to increases in baseflow rather than

decreases in baseflow. The irrigation of agricultural land increases the soil moisture storage. Increases in soil moisture storage were found to have a moderately strong linkage to increases in baseflow (1982–2011) (Shaw et al. 2013, Price 2011). If groundwater withdrawals for irrigation are from the confined aquifer, then they may be contributing to baseflow increases by increasing the amount of water that infiltrates the surface, thereby adding to the soil moisture storage. But studies which attribute withdrawal rate of high-capacity wells to baseflow change have only analyzed wells withdrawing from above the confining layer (e.g., Borchardt et al. 2016, Kraft et al. 2012, Weeks and Stangland 1971, and Weeks et al. 1965).

1.4 Determining the Factors That Affect the Groundwater-Surface Water System

1.4.1 Statewide annual baseflow trend analysis

Previous studies have found both increasing and decreasing baseflows in Wisconsin (e.g., Gebert et al. 2007, Kraft et al. 2012). Kraft et al. (2012) attributes declining baseflows to the extensive use of irrigated agriculture in the central portion of the state between 1999 and 2008, but irrigation is found throughout the state. Gebert et al. (2007) reported increasing baseflows in agricultural areas of Wisconsin, and no increases in the forested areas of the state between 1970 and 1999. This study calculated baseflow for Wisconsin's streams on an annual basis and determine if the baseflows are trending over time, the direction of the trends, and if there are deviations in any of the baseflow trends over the study period (1984–2014). These finding will determine if baseflow trends over the last decade have changed from previous decades and are the changes related to land use changes and/or increases in agricultural irrigation. The study also mapped spatial patterns related to decreasing/increasing trends and trend deviations. The study determined the natural and human-induced characteristics of basins which show significant baseflow trends.

1.4.2 Regression analysis

Understanding the factors that affect baseflow processes is critical to protecting both water quality and supply, but current literature presents conflicting data. This conflicting data puts environmentalist and agricultural growers across the state at odds with each other on how best to preserve the states freshwater resources. Baseflow declines due to the increased use of groundwater from unconfined aquifers that are well connected to surface waters, for agricultural production, have been well documented. However, there are few if any studies on the effects of the withdrawal of groundwater on baseflow from confined aquifers that are disconnected from surface waters. Furthermore, since the groundwater basin size and shape can be different than the surface water basin, the use of the surface basin to determine which variables including well withdrawal rate will affect baseflow may not be accurate and is further complicated by the variability of groundwater basin divides. This study used the variables determined to be related to baseflow variability from previous studies, and the withdrawal rates of wells located within the study basins to create a regression model. The study found that baseflow changes are significantly affected by the withdrawal rates from high capacity wells when over unconfined aquifers whereas they are significantly affected by precipitation when the basin is over a confined aquifer; that the baseflow variation between basins over unconfined aquifers is significantly affected by the available water storage of the topsoil; and that the use of the surface basin boundaries is more effective in predictions of baseflow than using the groundwater basin boundaries. Wisconsin's annual precipitation has been trending upward over the last 30 years and is predicted to increase into the future (Borchardt 2019, WICCI 2011). But, if the escalating use of irrigation for Wisconsin's agriculture outpaces the increases in annual precipitation, declines in stream baseflow will result and a balance of this resource will need to be found.

It is crucial to understand how both climate change and anthropogenic impacts affect the relationship between physical basin properties, such as soil texture and land use, and baseflow (Price 2011), but few studies (Malekinezhad and Banadkooki 2018) address both climate and anthropogenic impacts. The Malekinezhad and Banadkooki (2018) study found declining hydraulic head in an aquifer in Central Iran due to both climate change and anthropogenic stresses Currently, numerical models (e.g.,

MODFLOW) can simulate the impacts of multiple variables on baseflow, but they are site specific and require significant effort, time, and knowledge for calibration and validation (Li et al. 2020). Some studies examined how either anthropogenic (e.g., Borchardt 2019; Sophocleous 2002, Wahl and Tororelli 1997) or climate factors (e.g., Borchardt et al. 2016) affect baseflow. Some other studies have used analytical depletion functions to quite accurately predict which streams in a given basin would be affected by the groundwater withdrawal of an individual well (e.g., Zipper et al. 2019, Li et al. 2020), but climate factors were not considered. Ayers et al. (2021) combined the effects of climate factors, physical basin properties, and land-use factors to find the main drivers in baseflow variability using regression analysis, but the groundwater withdrawal variable was not included. Previous studies have used regression analysis to determine stream baseflow (e.g., Scanlon et al. 2002, Santhi et al. 2008, Lorenz and Delin 2007, Cherkauer and Ansari 2005, Borchardt et al. 2016, and others). The Borchardt et al. (2016) study was the only study that used groundwater withdrawal rate in a regression analysis, and no studies were found that analyzed the relationship between increasing stream baseflows and the groundwater withdrawal rates of high-capacity wells used to irrigate agriculture. The regression model in this study used both variables found to be related to baseflow from the first part of the study and the recorded withdrawal rates from high-capacity wells to predict baseflow.

1.4.3 Hydrologic modeling software

Groundwater models offer a tool for resource managers to quantify the effects of withdrawal rate and climate changes on groundwater levels and streamflow rates. This proposed research used modeling to investigate how climate variables and human activity affect both streamflow and groundwater elevations. Groundwater flow models are used to quantify the complex relationship between basin variables and streamflow, but there is not a universally accepted method used by water resource planners to determine the relationship between land use, climate, irrigation, groundwater withdrawals, and streamflow (Bradbury et al. 2017). The use of computer modeling is particularly useful in the assessment

of the groundwater-surface water interaction (Bailey et al. 2016). The goal of this study was to create two hydraulic models to predict and visualize the relationship between climate and water management variations, and the effect both have on surface and groundwater resources.

The study used two computer programs: SWAT (Soil & Water Assessment Tool) and MODFLOW (Modular Groundwater Flow); both are public domain models which are freely downloadable. The Soil & Water Assessment Tool (SWAT) was developed by the United States Department of Agriculture (USDA) Research Service. The program analyzes surface water processes by dividing the sub basins into unique Hydrological Response Units (HRU). HRU's are delineated based on land use, soil, and slope. The program is capable of rapidly running simulations of basin responses over long time periods. The SWAT model is available as an ArcGIS extension–ArcSWAT 2012.10.19 from Texas A&M University as a free downloadable program (https://swat.tamu.edu/software/arcswat/, last accessed 19 April 2018). The United States Geological Survey (USGS) Modular Hydrologic Model (MODFLOW) is open-sourced and distributed by the US Geological Survey. The program has been used for over 30 years due to its accuracy and reliability. The MODFLOW model is a groundwater model capable of modeling groundwater recharge, vadose zone percolation, evapotranspiration, high capacity well withdrawal, and river to aquifer interactions. But since MODFLOW does not simulate surface process it is not capable of investigating climate effect on groundwater or the groundwater-surface water interaction (Baily et al. 2016). This study used the output from the SWAT model as input for the MODFLOW model to investigate the effects of climate on hydrologic head. The MODFLOW program is available for free download from the USGS (https://water.usgs.gov/ogw/modflow/MODFLOW.html, last accessed 19 April 2018).

This three-part study investigated how climate variables and human activity affect surface water and groundwater in Wisconsin at different spatial and temporal scales. The first two parts of the study concentrated on baseflow and the variables that are related to its variability. The first part used analytic methods to determine if baseflow trends over the last decade have changed from previous decades and are the changes related to land use changes and/or increases in agricultural irrigation. In the second part of the

study, precipitation, temperature, drainage class, available storage, land cover, slope, and the recorded well withdrawal rates were used to predict baseflow variability across basins. These variables were found to be related to baseflow in the first part of this study and other literature (e.g., Santhi et al. 2008, Lorenz and Delin 2007). The third and final part of the study used both surface and subsurface characteristics to investigate how climate variables and human activity together, affect surface water and groundwater in Wisconsin through modeling.

CHAPTER 2 EFFECTS OF HIGH-CAPACITY WELLS ON STREAM BASEFLOW IN WISCONSIN DURING 1984–2014[1]

2.1 Introduction

When groundwater is pumped from a confined aquifer for irrigation, it effectively increases the amount of water that can infiltrate and flow to the unconfined aquifer and increases the groundwater available to recharge the surface waters. Several studies point to land use changes as the only anthropogenic cause of baseflow increases (e.g., Juckem et al. 2008, Schilling et al. 2008, Zhang and Schilling 2006). But, when baseflow increases are attributed to land use change alone, without considering the presence of agricultural irrigation or its source aquifer type, the potential large effect of increased infiltration of the irrigation water to the unconfined aquifer is neglected. Baseflow increases can have a positive effect on aquatic ecosystems, but the losses to the freshwater resource of groundwater stored in the confined aquifer may not be replaceable. The current knowledge gap is a hindrance to not only the science but also to policy makers who determine how the permitting of additional high-capacity irrigation wells will affect the baseflow in the basin.

2.2 Background

2.2.1 Study area

This study was conducted for the state of Wisconsin. Wisconsin was chosen in large part because irrigation in the state has grown tremendously over the last few decades, providing an opportunity for trend analysis. Wisconsin also has unique geography with both shallow unconfined aquifers well connected to surface waters in the northern portion of the state and deep confined aquifers in the southern portion of the state. Preliminary findings for this study report increasing baseflow trends in the southern

[1]Borchardt, S. (2019). Are high-capacity wells mitigating or intensifying climate change effects on stream baseflow in the state of Wisconsin (USA)? A case study 1984–2014. *Environmental Earth Sciences*, *78*(18), 1-25.

portion of the state over the period 1984–2014, whereas those in northern Wisconsin show a declining trend over the same time.

2.2.2 Climate

The climate in Wisconsin is considered continental but with modifications from the two bordering Great Lakes, Michigan and Superior. Wisconsin's average annual temperature varies from 4.4^{o}C in the northern regions to 8.9^{o}C in the southern regions. Average monthly temperatures range from a low of −14^{o}C to a high of 28^{o}C (Netstate 2016). The median date of last spring freeze ranges from early May in southern regions and along the Lake Michigan coast to early June in the Northern portion of the state. Average annual precipitation varies between 76 and 86 cm across the higher elevations to the west and north. Average precipitation is less, approximately 71 cm, in the lower elevations in the south and along the Lake Michigan shore (Atmospheric and Oceanic Sciences University of Wisconsin-Madison 2003).

2.2.3 High-capacity wells

Per the Wisconsin Department of Natural Resources (WDNR), a high-capacity well is defined as a well capable of pumping 100,000 gallons (378,541 liters) per day, or a well that, together with all the other wells on the property, is capable of pumping 100,000 gallons (378,541 liters) per day (WDNR 2017). The use of high-capacity wells has increased by almost 400% over the period 1984–2014 with only 3,928 wells approved prior to 1984 to over 14,200 approved as of 2014 (Figure 1) (Smail 2015). In Wisconsin, groundwater sourced irrigation is used to supplement precipitation, allowing high water demand crops to be grown in soils with low water holding capacity (Kraft et al. 2012).

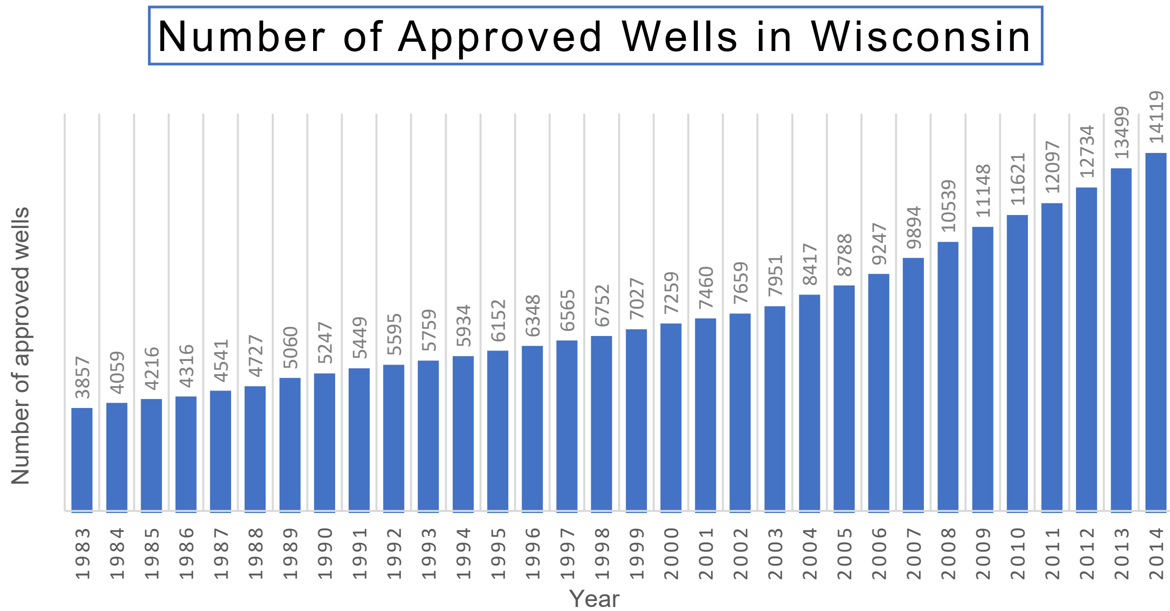


Figure 1 Number of high-capacity wells approved to operate in the state of Wisconsin per WDNR

2.3 Materials and Methods

2.3.1 Research question

Additional state-wide analysis needs to be completed to determine the spatial distribution of baseflow trends. The proposed research investigated how climate variables and human activity affect baseflow. Specifically, the study aimed to answer the following research questions:

1. What are the geographical and temporal trends of baseflow in Wisconsin in the last several decades (1984–2014) and which basins have a significant increase or decrease?
2. What are the characteristics of basins showing significant trends such as land cover, precipitation, basin size, soil characteristics, and topography, and has human activity influenced stream baseflows across the state?

2.3.2 Baseflow determination

Annual mean baseflow was calculated from streamflow data collected for the period 1984–2014 at 36 gauging stations located in Wisconsin by the US Geological Survey (USGS). The RORA method in the USGS computer program, Groundwater Toolbox (USGS 2017) was used to derive baseflow from streamflow. Only gauges that have been continuously recording daily streamflow during the study period were be used. The RORA method creates estimates of net recharge using the recession-curve displacement method for baseflow separation (Barlow et al. 2015). The RORA method was chosen over the hydrograph separation methods because it is a measure of the groundwater that drains from storage to the surface water versus a measure of the low flow in the stream (Barlow et al. 2015). Baseflow was plotted against time over the study period and a regression line calculated. The equation for the regression line was used to calculate the percent change in baseflow between 1984 and 2014.

2.3.3 Testing for significance in baseflow trend over time

The significance of the baseflow trends were tested with a nonparametric statistical measure of correlation (Kendall Tau method). The Kendall Tau statistic (Kendall 1938) is used by the USGS in the Groundwater Toolbox program to test the significance of both streamflow and baseflow trend over time (Barlow et al. 2015). Kendall (1938) developed an equation to measure the correlation of ranked pairs of data (equation 1). The Tau equation measured the correlation between the ranked values of time and the calculated baseflow values from Groundwater Toolbox on a scale from –1 to 1, where a value of –1 would indicate a perfect negative relationship, +1 would indicate a perfect positive relationship, and 0 would indicate no ordinal relationship (Kendall 1938). Kendall’s Tau is a measure of the strength of the association between two variables, and it is a ratio between the number of concordant pairs and the total number of possible pairs that can be created between the two variables (Hauke and Kossowski 2011). Kendall’s Tau is more reliable and more interpretable because it is less sensitive to error and discrepancies in the data than Spearman’s r_s (Kendall and Gibbons 1990). Both the Kendal Tau statistic and the p-level are available calculations within the Groundwater Toolbox program.

$$\tau = \frac{4P}{n(n-1)} - 1 \qquad \text{Equation 1}$$

where P = the number of concordant pairs

n = the number of pairs

The total number of possible pairs is calculated as [n(n–1)] and is in the denominator. The number of concordant pairs (pairs where the second data point is chronologically greater than the first data point) is in the numerator. The number of concordant pairs that can be created can be obtained by comparing each number with each of its succeeding numbers to calculate the totals that are in chronological order (Kendall 1938). Consider two sets of data, the first is put in chronological order from 1 to 10, the second set is random (4,7,2,10,3,6,8,1,5,9), the two sets make up 10 pairs (n = 10). To find the number of concordant pairs (P) we find the quantity of numbers to the right of each data point that is greater than the data point and add them together. There are 6 numbers greater than 4 to its right, and 3 numbers greater than 7 to its right and so on. The total number of concordant pairs in this example is 25 (P = 25). Substituting 10 and 25 for n and P in equation 1 will give us +0.11 ($\tau = 0.11$).

2.3.4 Divergence detection

A double-mass curve analysis was used to detect divergences in the graphed slope of the cumulative annual totals for precipitation versus the cumulative annual total for the baseflow. The double-mass curve technique is useful for detecting hydrological changes that may occur due to anthropogenic influence (Choi et al. 2016). The slope of the straight line formed by this proportional relationship represents the relationship between the quantities (Searcy and Hardison 1960), annual precipitation and annual baseflow in this study. A divergence, or a break in the slope, will suggest another variable, potentially the high-capacity well withdrawal rate, is affecting the baseflow rate.

2.3.5 Testing significance of divergence

The data was split at the point of the divergence and the two separate sets of data, and their regression slope lines were graphed. Levene's test (Levene 1960) available in SPSS Software (IBM) tested for the homogeneity of the regression slopes. The Levene test tested the null hypothesis that the variance of the two sets of data are equal. If the two slopes are different, then a covariant (anthropogenic stress) is significantly affecting the independent variable (cumulative baseflow).

H_o: $\sigma_1^2 = \sigma_2^2 = \ldots = \sigma_k^2$

H_a: $\sigma_i^2 \neq$

σ_j^2 for at least one pair (i,j).

The Levene test rejects the null hypothesis if the test statistic is greater than the critical value at a given significance level.

2.3.6 Spatial analysis

Stream gauging station locations and their baseflow trend over time (percent declining or increasing) was mapped using Arc GIS desktop 10.4 from Environmental Systems Research Institute (ESRI). A second map was created with the stream gauge locations that exhibited a divergence in the regression slope and showed the direction of the divergence. The maps examined the spatial distribution of trend direction and divergence direction.

2.3.7 Surface basin delineation

Basins that exhibited a divergence were analyzed for soil and topographic characteristics, landcover, and the aquifer type that high-capacity wells in the basin are withdrawing from. Since gauging stations are often situated in the center of WDNR watersheds, the hydrology tools in Arc GIS were used to delineate only the surface area that contributes water to each gauging station. For the surface basin

delineation, the digital elevation model (DEM) was obtained from the USGS web site (USGS n.d.). The DEM was filled to eliminate pits, and both flow direction and accumulation were calculated using the Arc GIS tools. Once the flow accumulation has been calculated, the area contributing to the gauging station can then be delineated using the location of the gauging station as the pour point. The delineated basin raster file was converted to a poly file to be used to clip landcover and topography data. The surface area contributing to each gauging station can contain more than one WDNR watershed, therefore the area affecting baseflow may encompass a different area than the WDNR watershed the gauge is in.

2.3.8 Soil characteristics

This study analyzed available water storage (AWS) and soil drainage class (SDC). Previous studies have correlated the percentage of sand in the soil (Santhi et al. 2007) and specific yield (Lorenze and Delin 2007) to variations in stream baseflow. Sand is a texture class of soil that is defined as well drained soil. This study used the percent of well drained or very well drained soil the basin contains. Specific yield is a ratio or percent between the volume of water that will drain by gravity from a saturated soil to the total volume of the soil. This study used AWS which is a measure of the amount of water the soil can hold measured in cm.

Available Water Storage (AWS) was downloaded from the Soil Survey Geographic Database (SSURGO) Downloader (ESRI 2018). AWS is a calculation of the difference between soil water content at field capacity and the permanent wilting point. AWS is then adjusted for salinity and fragments at 4 different depths, the top 25cm, 50cm, 100cm, and 150cm of soil. This study uses the calculation for the top 150 cm of soil, the AWS is measured in cm of water (ESRI. n.d.a). The AWS mean value was calculated in ArcGIS for each delineated basin.

Soil drainage class (SDC) was also downloaded from the Soil Survey Geographic Database (SSURGO) Downloader (ESRI 2018). SDC is a classification of the drainage condition of the soil in the dominant soil component of the map unit (ESRI, n.d.b). The drainage classes are divided into 7 conditions: excessively drained, somewhat excessively drained, well drained, moderately drained,

somewhat well drained, somewhat poorly drained, poorly drained, and very poorly drained. The percent of well-drained soil for each clipped area was calculated in ArcGIS.

2.3.9 Landcover and topography

Topographical characteristics of the basin were analyzed by calculating the average slope over the basin. Landcover type was also analyzed. Previous studies have found correlations between increasing baseflows and the clearcutting of forested regions (e.g., Harr et al. 1982, Hicks et al. 1991, Smith 1991). These studies did not take into consideration what landcover replaced the forested land. Baseflow increases have also been attributed to the conversion of perennial grasslands to agriculture row crops (e.g., Juckem et al. 2008, Schilling et al. 2008, Zhang and Schilling 2006). The effect of irrigation required to grow the row crops was not taken into consideration in these studies. This study looked at landcover change over the last decade to determine if there is a correlation between landcover change and baseflow variation.

The National Land Cover Database (NLCD) was downloaded from the USGS web site (USGS n.d.) for years 2001 and 2011. The data was then clipped to the area of each delineated basin. Landcover and landcover change over the last decade was analyzed in ArcGIS desktop 10.4 from ESRI for each basin. Percent slope across each basin was calculated using a digital elevation model (DEM) that was obtained from the USGS web site (USGS n.d.). The DEM file was also clipped to each basin. Each DEM basin file was analyzed using the slope tool in the spatial analyst tool set in ArcGIS desk 10.4. The slope tool calculates the maximum rate of elevation change between each raster cell and its neighboring cells (ESRI n.d.c). The mean value of all the raster cells in the basin were used as the basin slope value.

2.3.10 Aquifer determination

The correlation between the withdrawal of groundwater, from the unconfined aquifer, to irrigate agriculture crops and baseflow variation has been well documented (e.g., Weeks et al. 1965, Kraft et al. 2012, Weeks and Stangland 1971). However, the effect groundwater withdrawal from confined aquifers

has on surface waters has not been studied. This study determined if there is a relationship between the number of high-capacity wells, withdrawing groundwater from either the confined or the unconfined aquifer, in each study basin and the variation of baseflow in that basin. The study also determined if there is a difference in the relationship direction between the wells pumping from the confined versus the unconfined aquifer.

A geographic information system layer containing high-capacity well data from the WDNR was used to locate the wells within each basin. The number of high-capacity wells in each basin was then calculated in Arc GIS. Well construction reports filed with the WDNR after the completion of a well installation record both the well depth and the depth of the confining layer. By comparing the two depth records a determination can be made which wells are drawing from the confined aquifer and which are drawing from the unconfined aquifer. Well construction report data compiled by the Wisconsin Geological and Natural History Survey (WGNHS) was received from the University of Wisconsin-Extension via email correspondence from Stephen Mavel, 10 March 2018. The well ID included in the data was used to perform a join operation between the construction report data and the well withdrawal data. The join was performed on each of the 19 basins that contained the well data that had previously been clipped with the basin poly shape file.

2.4 Results

2.4.1 Baseflow separation

The RORA method of baseflow separation was used to calculate the annual baseflow from stream records available from the USGS. Thirty-six stations across the state of Wisconsin were found to have continuous data over the study period (1984–2014). Trend was calculated using Microsoft Excel. Annual baseflow from the RORA method was plotted in Excel (Appendix A). The percent decline was determined using the equation for the trend line. The calculated baseflow for 1984 and 2014 from the trend line were used in lieu of the calculated values from the RORA method. The trend over the study

period ranged from approximately 202% to −28%, and a mean of approximately 18%. The 202% baseflow increase (station 05427948) appears to be an outlier. If data for this gauge is removed the results of the study range from approximately 67% to −28% and a mean of approximately 16 percent (Table 1). Increasing stream baseflows were found mainly in the southern half of the state, while declining stream baseflows were found in the northern half of the state (Figure 2).

Table 1 2011 land cover percent per delineated basin

Station ID	Station Name	Trend %	Forest	Agriculture	Wetlands	Developed
04074950	Wolf River at Langlade, WI	−28.47	54.6	4.18	28.96	3.74
04060993	Brule River at US Hwy 2 Near Florence, WI	−27.54	59.99	2.18	31.51	2.63
04024430	Nemadji River Near South Superior, WI	−24.53	59.96	7.92	17.93	3.3
05394500	Prairie River Near Merrill, WI	−18.14	57.34	8.57	27.14	3.69
05397500	Eau Claire River at Kelly, WI	−15.48	45.01	30.86	15.69	5.81
04087088	Underwood Creek at Wauwatosa, WI	−11.1	3.57	0.81	2.29	91.24
05393500	Spirit River at Spirit Falls, WI	−11.07	66.46	8.15	17.45	3.28
04063700	Popple River Near Fence, WI	−0.79	45.77	1.24	47.67	1.81
05370000	Eau Galle River at Spring Valley, WI	1.09	20.59	69.48	1.35	6.2
05406500	Black Earth Creek at Black Earth, WI	26.46	32.87	54.68	0.7	9.27
05436500	Sugar River Near Brodhead, WI	27.97	13.11	73.68	2.39	8.59
05432500	Pecatonica River at Darlington, WI	29.02	8.34	84.76	0.28	5.69
05543830	Fox River at Waukesha, WI	30.27	12.22	24.69	7.8	49.58
05430150	Badfish Creek Near Cooksville, WI	32.33	7.06	77.43	3.5	9.5
05426250	Bark River Near Rome, WI	41.34	15.98	38.5	18.26	21.08
05414000	Platte River Near Rockville, WI	43.23	14.88	79.59	0.28	4.76
05431486	Turtle Creek at Carvers Rock Road, Clinton, WI	43.86	7.03	76.85	0.88	10.93
05413500	Grant River at Burton, WI	54.48	14.78	78.59	0.27	5.98
05429500	Yahara River at Mc Farland, WI	59.04	5.35	52.41	3.91	29.1
05430175	Yahara River Near Fulton, WI	66.68	6.1	58.6	4.53	22.92
	max	66.68	66.46	84.76	47.67	91.24
	min	−28.47	3.57	0.81	0.27	1.81
	mean	15.93	27.5505	41.6585	11.6395	14.955

2.4.2 Testing for significance

The Kendall Tau method was used to test if the baseflow trends are significant. Half the study basins had a significance level greater than 80%. One basin (04074950) had a declining trend that was

highly significant ($p \leq 0.01$) and a Tau of –0.355. One basin (04060993) had a declining trend that was moderately significant ($p \leq 0.05$) and a Tau of –0.306. Three basins (05427948, 05430150, and 05430175) had increasing trends that were highly significant with Tau of 0.463, 0.342 and 0.342 respectively. One basin (05429500) that had an increasing trend that was moderately significant ($p \leq 0.05$) with a Tau score of 0.258. Five additional basins (04063700, 05394500, 04024430, 05368000 and 05397500) had declining baseflow trends with a significance score of < –0.200. There were also seven basins with increasing trends (05406500, 05425912, 05431486, 05543830, 05413500, 05426250, and 05414000) that had a Tau significance score of < 0.200. The remaining 18 basins exhibited baseflow trends that were either constant or not significant (Appendix B).

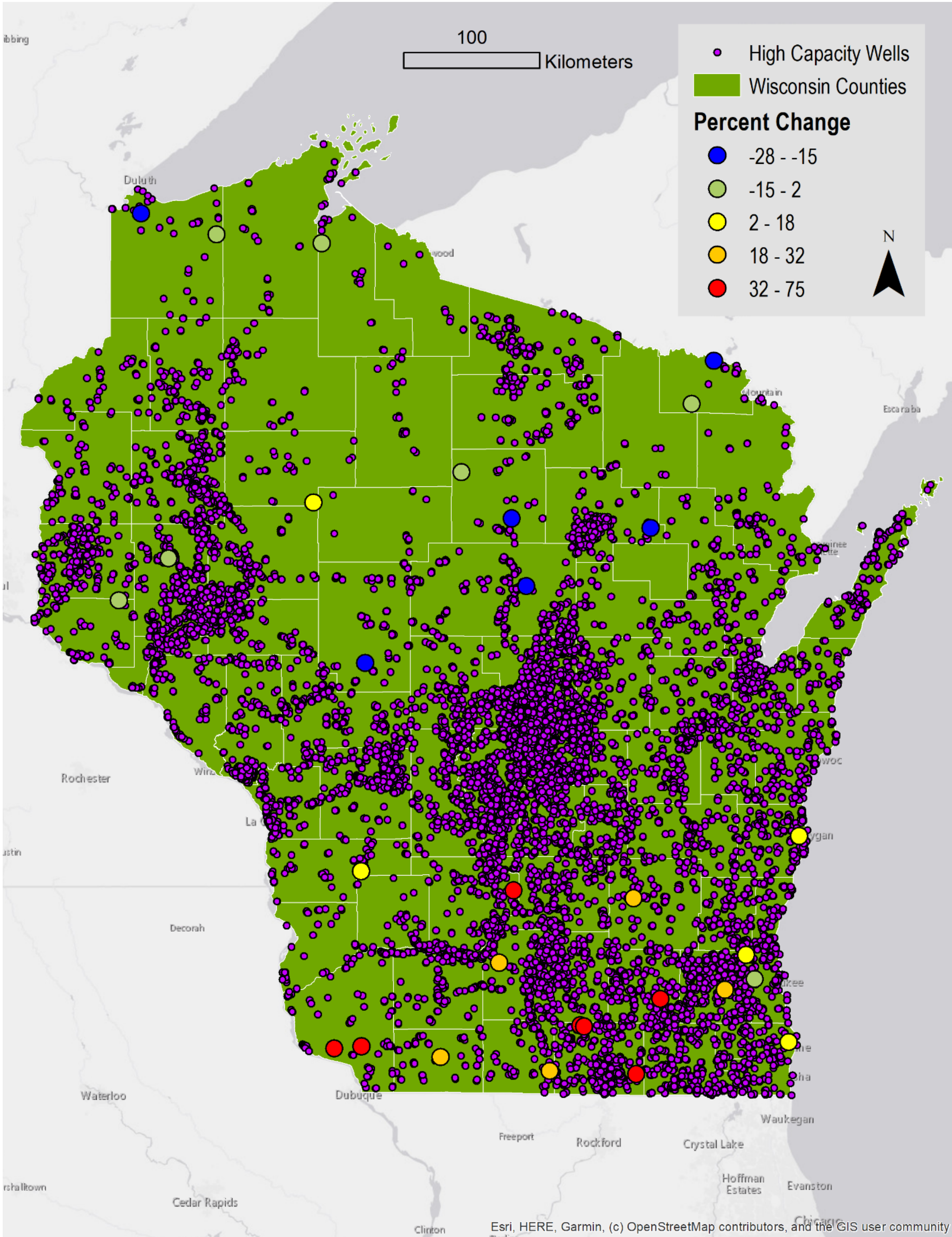


Figure 2 Percent change in baseflow at gauging stations with 30 years of continuous data (1984–2014) in Wisconsin. Streamflow data obtained from USGS and baseflow calculated with USGS computer program RORA in the groundwater toolbox.

2.4.3 Relationship between precipitation and baseflow

It is generally accepted that increases in annual precipitation will lead to increases in annual baseflow and that there is a proportional relationship between the two variables. Therefore, if the cumulative value of precipitation is plotted against the cumulative value of baseflow, a slope line will form that represents the relationship between precipitation and baseflow (Choi et al. 2016, Searcy and Hardison 1960). The theory of double-mass curves states that if there is a deviation in the slope line, then there is a change in the relationship between the two variables. Double-mass curve analysis is useful in determining if anthropogenic influences are affecting annual baseflow rate. Deviations in the slope were recorded in 20 of the 35 basins from visual inspection of the graph created in Microsoft Excel. 18 of the 20 basins that exhibited a deviation in the double-mass curve slope also exhibited a significant trend over time. There were also an additional 4 basins that did exhibit a deviation in the double-mass curve that did not show a significant trend over time. Deviations were evenly split between increases and decreases in slope with 9 basins exhibiting a decrease in slope, and 11 basins exhibiting an increase in slope. 15 basins showed no significant change in the slope line (per visual inspection) representing the relationship between precipitation and baseflow. Declines in the slope were found beginning in approximately 1999 but increases in the slope were not detected until approximately 2007 (Appendix C). All the basins that exhibited an increasing deviation are in the southern half of the state. All except 1 of the basins exhibiting a decreasing deviation are in the northern half of the state (Figure 3).

2.4.4 Testing for significance in slope deviation

The Leven test was performed on the 20 basins that exhibited a deviation in the regression slope from visual inspection of the Microsoft Excel graph. All except one (basin 05432500) had p values $\leq$ 0.05, therefore the deviations were significant. A visual inspection of the Excel graph from basin 05432500 verifies that the deviation was only marginally deviated and likely not statistically significant.

Since the two regression lines in the other 19 basins have slopes that are statistically different, then it is highly probable that an anthropogenic variable is affecting stream baseflow in the 19 basins (Table 4).

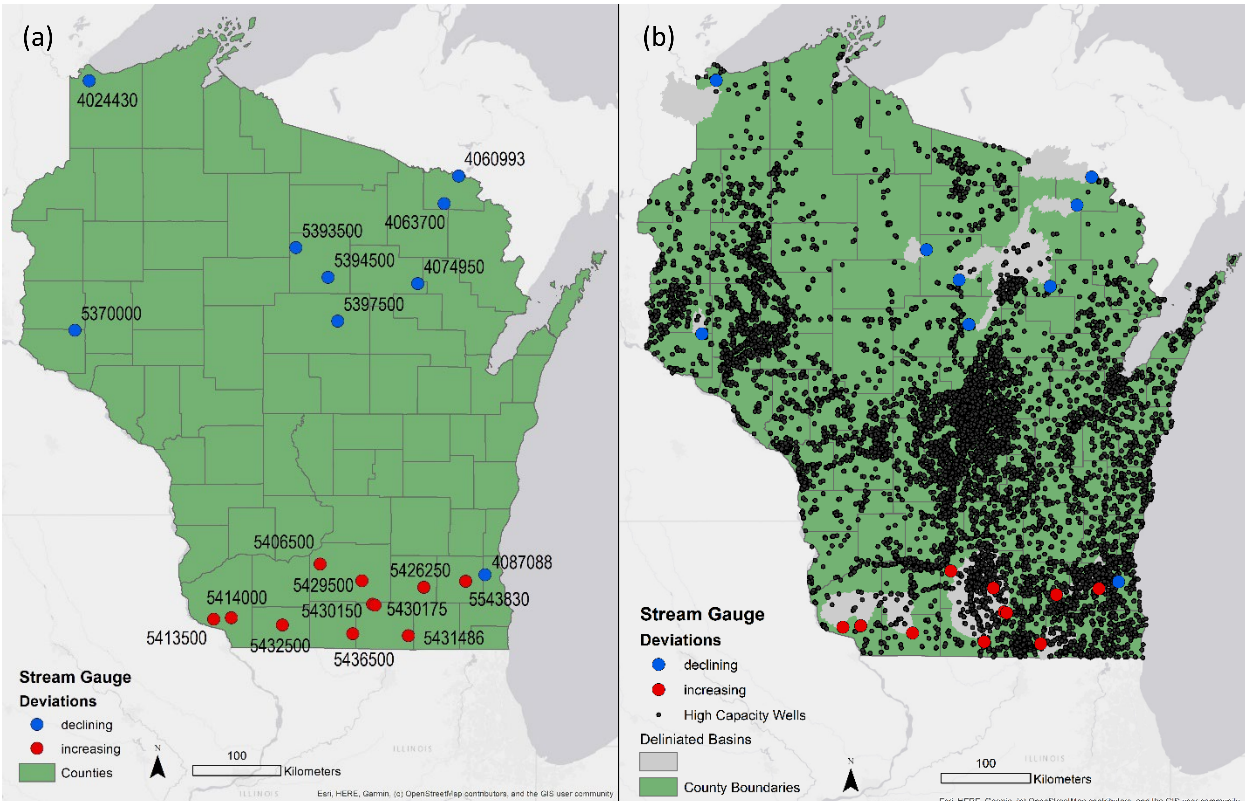


Figure 3 (a) Direction of deviation from regression slope from the double-mass curve analysis between cumulative precipitation and cumulative baseflow in Wisconsin streams between 1984–2014. **(b)** High capacity well locations from a shape file received from the WDNR, basins delineated using ArcGIS 10.4 esri hydrology tool set.

2.4.5 Land cover and topography

The 4 principle landcovers found in the 20 delineated basins are listed in Table 1 below. The landcovers were calculated as percent of total landcover in each basin in 2011. Agriculture was the most prevalent landcover ranging from ≈ 85% to ≈ 1% with a mean value of ≈ 42%. The next highest landcover is forested ranging from ≈ 66% to ≈ 4% and a mean value of ≈ 28%. The 2 following landcover are Wetlands and Developed land having mean values of ≈ 12% and 15% respectively. Increasing baseflow trends are more likely to be found in basins with a lower percent of forested landcover, and a higher percentage of agricultural land cover with a r^2 of 0.6499 and 0.5851, respectively. Percent land

cover of wetland and developed land had less significant effect on baseflow trend with a r^2 of 0.394 and 0.0114 respectively (Figure 4).

Mean slope and basin area of each basin is recorded in Table 2. Mean slope for the 20 basins ranges between ≈ 13 and ≈ 2 with a mean of ≈ 5. Mean slope was calculated as percent rise, which is the rise divided by the run and the result multiplied by 100. This translates to a mean slope of 5, which would be equivalent to a 5 cm rise per 1 meter of run or a relatively gentle slope across all 20 basins. The area of the basins varies between 1,350 square kilometers to 48 square kilometers. The mean area of the basins is ≈ 573 square kilometers. Neither the mean slope nor the basin area has a significant relationship with the baseflow trend with an r^2 of 0.0215 and 0.0076 respectively (Figure 5)

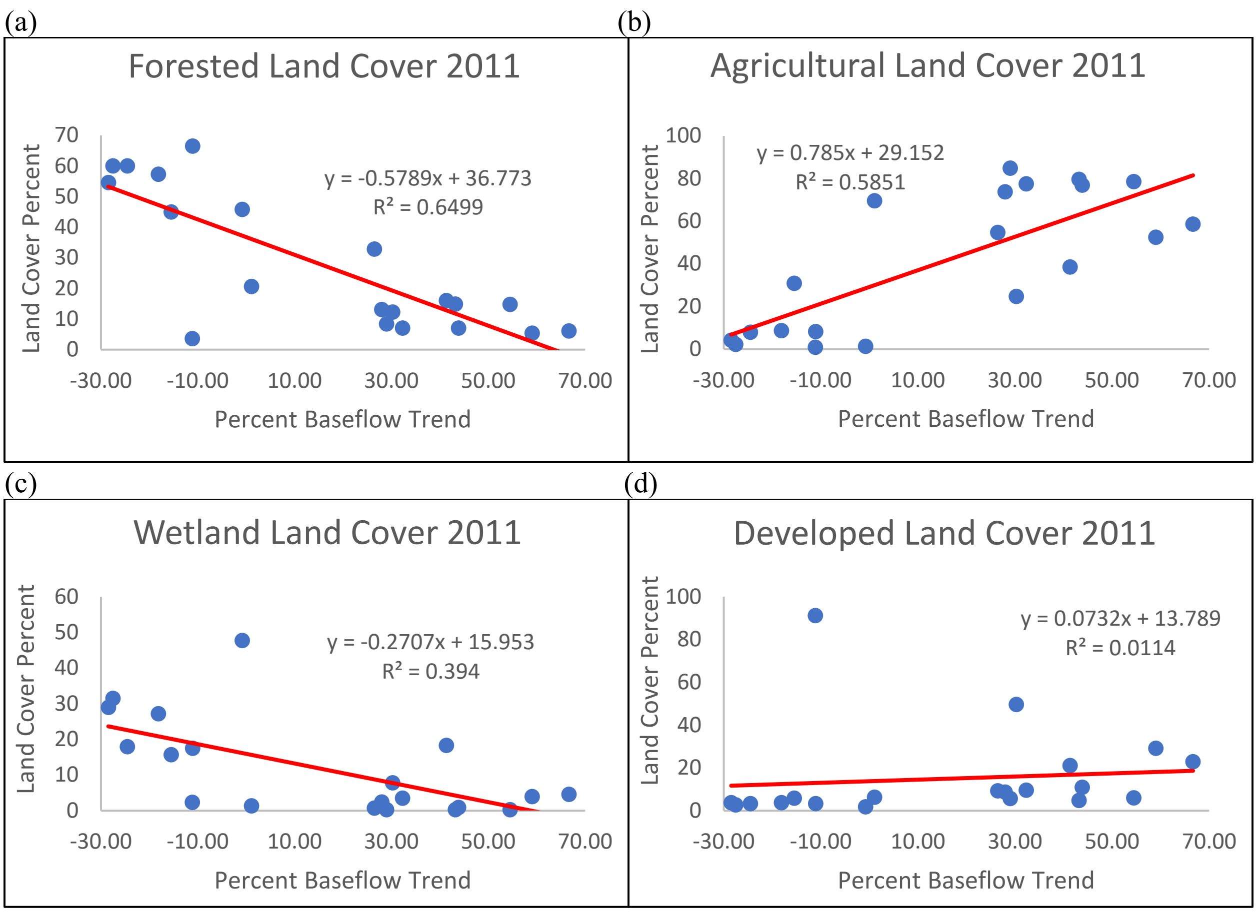


Figure 4 (a) Forested land cover, **(b)** Agricultural land cover, **(c)** Wetland land cover, **(d)** Developed land cover each from NLCD 2011, percent per basin calculated in ArcGIS 10.4, baseflow from USGS Groundwater toolbox, calculated using USGS stream gauge data. Trend percent calculated using Microsoft Excel.

(a) (b)

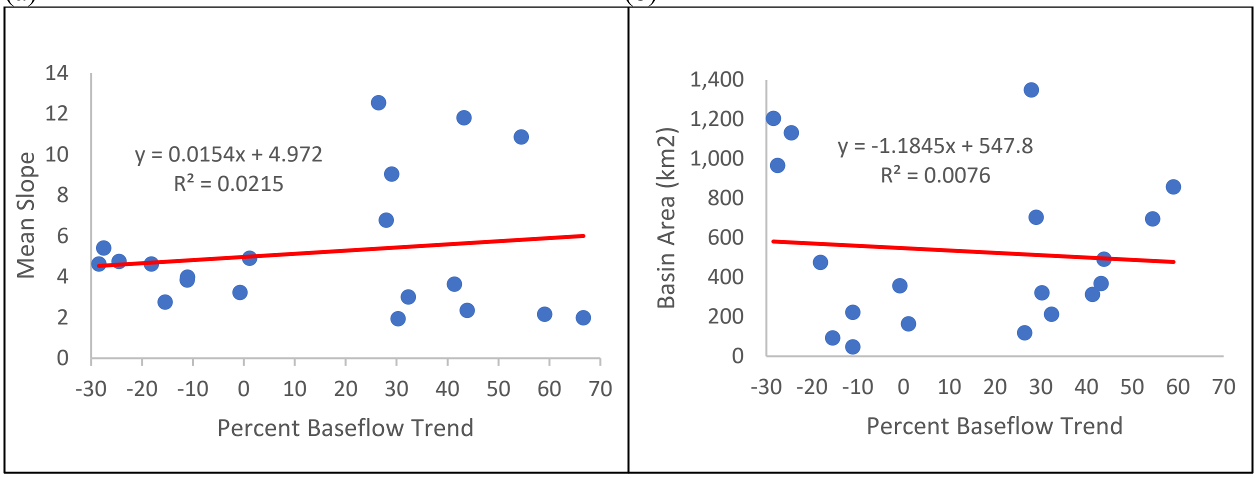


Figure 5 (a) Mean slope and **(b)** Basin area calculated in ArcGIS 10.4. Baseflow from USGS Groundwater toolbox and calculated using USGS stream gauge data.

2.4.6 Aquifer type and number of wells

Well construction data was incomplete, but 100% of the wells that did have data and were in the same basin were drawing water from the same aquifer type. Therefore, it is assumed that all the high-capacity wells in the same basin are drawing from the same aquifer type. It is a generally accepted practice to drill new wells to approximately the same depth as other wells in the area if those wells have been producing a reliable supply of water. Of the 20 basins in the study, 5 basins were found to have wells withdrawing from an unconfined aquifer, and 15 basins were found to have wells withdrawing from a confined aquifer. The number of wells is recorded as a negative number if the aquifer type is unconfined, and the number of wells is recorded as a positive number if the aquifer type is confined. The number of high-capacity wells in operation during 2015 in each surface basin is recorded in Table 2. The number of wells varies between 0 to 317, with the average number of wells calculated at 63.5 per basin. The number of wells in a basin is related to the baseflow trend percent with an r^2 of 0.4714 (Figure 6). Table 2 shows that in basins with no high-capacity wells, baseflow had a declining trend over the study period (1984–2014). As the number of wells withdrawing from the confined aquifer increased, the baseflow tread increased from a declining trend of approximately 15% to an increasing trend of almost

67%. This increase illustrates a mitigating effect to the decreasing trend related to environmental variables alone. As the number of wells withdrawing from an unconfined aquifer increases, the already declining baseflow trend intensifies from 18% to over 28%, illustrating the contribution high-capacity wells have in basin baseflow decline in areas where aquifers are connected to surface water.

Table 2 Mean slope, basin area, and number of wells per basin

Station ID	Station Name	Mean Slope	Area (sq. km)	Number Wells 2015
04074950	Wolf River at Langlade, WI	4.63	1,205.24	−34
04060993	Brule River at US Hwy 2 Near Florence, WI	5.41	968.03	−2
04024430	Nemadji River Near South Superior, WI	4.76	1,133.13	−1
05394500	Prairie River Near Merrill, WI	4.63	476.26	−6
05397500	Eau Claire River at Kelly, WI	2.76	93.00	0
04087088	Underwood Creek at Wauwatosa, WI	3.85	48.48	29
05393500	Spirit River at Spirit Falls, WI	3.99	222.71	0
04063700	Popple River Near Fence, WI	3.23	357.30	0
05370000	Eau Galle River at Spring Valley, WI	4.92	165.26	8
05406500	Black Earth Creek at Black Earth, WI	12.55	119.61	8
05436500	Sugar River Near Brodhead, WI	6.78	1,349.55	163
05432500	Pecatonica River at Darlington, WI	9.04	705.23	34
05543830	Fox River at Waukesha, WI	1.95	322.45	148
05430150	Badfish Creek Near Cooksville, WI	3.02	212.99	20
05426250	Bark River Near Rome, WI	3.65	313.97	154
05414000	Platte River Near Rockville, WI	11.81	368.54	7
05431486	Turtle Creek at Carvers Rock Road, Clinton, WI	2.36	492.00	73
05413500	Grant River at Burton, WI	10.86	697.14	8
05429500	Yahara River at Mc Farland, WI	2.16	858.94	257
05430175	Yahara River Near Fulton, WI	2.00	1,341.06	317
	max	12.55	1,205.24	317
	min	1.95	968.03	0
	mean	5.218	1,133.13	63.5

2.5 Discussion

This study examined the annual baseflow of 36 streams across the state of Wisconsin that had a minimum of 30 years of continuous streamflow data using the USGS program Groundwater Tool Box. The baseflow trend over the study period (1984–2014) was found to be spatially separated between declining baseflows in northern Wisconsin and increasing baseflows in the southern portion of the state. Cumulative baseflows were graphed against cumulative precipitation to detect any deviations in the relationship slope. Twenty basins exhibited a deviation in the slope suggesting an anthropogenic variable was affecting baseflows.

The study found that as the number of wells withdrawing from the confined aquifer increased, the baseflow trend changed from a declining trend of approximately 15% to an increasing trend of almost 67%. This increase illustrates a mitigating effect to the decreasing trend related to climate variables alone. As the number of wells withdrawing from an unconfined aquifer increases, the already declining baseflow trend intensifies from 18% to over 28%. It illustrates the contribution of high-capacity wells to baseflow decline in areas where aquifers are connected to surface water, similar to studies in the Oklahoma panhandle (Wahl and Tororelli 1997).

Several basin characteristics were found to be moderately related to baseflow variability. The delineated surface basins were used to analyze the relationship between the basin characteristics (land cover, size, soil, topography) and basin baseflow and/or baseflow trend. On a state-wide basis none of the basin characteristics had a significant relationship with baseflow. On the other hand, several of the characteristics did have a moderate relationship with baseflow trend. Increases in agricultural land cover, increases in the percent of well drained soils, and increases in the amount of available water storage, as in a study by Shaw et al. (2013), were related to increased trend rates in stream baseflow. These increases could be related to the increased use of agricultural irrigation on agriculture fields across the state. Irrigation allows farmers to grow high-water demand crops in coarse soils (Kraft et al. 2012, Borchardt et al. 2016). Decreased baseflow trend rates were observed, as the percent of forested land cover increased

in agreement with previous studies (Smith 1991, Hicks et al. 1991) most likely due to the relatively high ET rates of trees versus grasses, shrubs, and crops.

The variables that were found to be related to baseflow trend rates were used in a follow up study using PDA (Panel Data Analysis) and discussed in the next chapter. The follow up study's purpose was to develop a model that uses free and easily downloadable data to predict baseflow change. The model was used to predict the effect of either adding an additional high-capacity well or the abandonment of an existing high-capacity well within a basin, on the baseflow of the stream in that basin. Current modeling techniques are time consuming and require large quantities of data. It is hoped that an easy-to-use analytical model can be created for preliminary investigation of the effects of high-capacity well permitting and/or abandonment.

2.6 Conclusion

This study highlights that environmental stresses are related to baseflow declines across the state of Wisconsin, and that the decreases are being mitigated or completely reversed by the addition of groundwater to the surface from below the confining layer. These artificial additions to baseflow may be beneficial to aquatic species that rely on the cooler groundwater recharges to their streams. But these withdrawals from our groundwater resources to produce agricultural products in unsuitable environments may not be the best use of this nonrenewable resource. This knowledge will both add to science's understanding of hydrological processes and provide scientific basis for policy makers to determine how the permitting of additional high-capacity irrigation wells will affect the baseflow of streams in the basin.

CHAPTER 3 EFFECTS OF CLIMATE, BASIN CHARACTERISTICS, AND HIGH-CAPACITY WELLS ON BASEFLOW IN WISCONSIN[2]

3.1 Introduction

Understanding the factors that affect baseflow processes is critical to protecting both water quality and supply (Price 2011). Baseflow is important to streams because of its cooler temperature and better quality than stormflow, and its ability to maintain streamflow during dry periods. Baseflow decreases and stream temperature increases will lead to decreases in aquatic biodiversity (Brown and Krygier 1970). Because baseflow is groundwater that discharges to surface water, groundwater that normally would have discharged as baseflow to surface water can be diverted away from discharge points by the gradients created by high-capacity wells (Sophocleous 2002). High-capacity wells, used to irrigate agriculture, can significantly impact groundwater storage and the associated interaction of surface to groundwater systems (Sophocleous 2002, Wahl and Tororelli 1997). Several studies documented baseflow declines in the state of Wisconsin, United States due to the increased use of groundwater for agricultural irrigation from unconfined aquifers that are well connected to surface waters (e.g., Kraft et al. 2012, Weeks et al. 1965, Wahl and Tororelli 1997, Fienen et al. 2018). Groundwater pumping affects surface waters (rivers, lakes, streams, and wetlands) by reducing baseflow that feeds into them. Extreme groundwater pumping has also been shown to extract surface water out of the stream bed and into the aquifer (Barlow and Leake 2012, Zipper et al. 2019, Li et al. 2020).

Baseflow can vary both spatially and temporally due not only to groundwater pumping but also to climate, topography, and human activities (e.g., Ayers et al. 2021, Price 2011, Santhi et al. 2008). Climate factors such as precipitation and temperature influence baseflow by controlling the availability of water (e.g., Ayers et al. 2021, Price 2011). Topographic factors then influence if the available water will

[2] Borchardt, S., Choi, W., and Choi, J. Effects of Climate, Basin Characteristics, and High-Capacity Wells on Baseflow in the State of Wisconsin, United States. *JAWRA Journal of the American Water Resources Association*, *58*(2), 135-148.

infiltrate the land surface and recharge surface water over time or will flow across the surface and add to streamflow as surface runoff (e.g., Ayers et al. 2019, Zhang and Schilling 2006). In addition, land use also affects how and when available water reaches surface waters. Increases in urbanization will lead to increased stormflows and decreased baseflows as a result of increases in impervious surfaces, whereas increases in agricultural land use have produced mixed baseflow responses depending on management practices (Price 2011).

The effects that land use, irrigation, and/or climate change have on baseflow could be amplified or mitigated by the subsurface topography (Dubé et al. 1995). The subsurface topography can have a strong influence on groundwater flow and baseflow (Price 2011). Price (2011) describes subsurface topography as the relief of the first confining layer, more specifically it is the subsurface strata that prompts the horizontal movement of groundwater. The groundwater basin size and shape can be different than the surface water basin and they can vary over time as well. During high moisture conditions, when the water table is high, the soil moisture surface is likely to follow that of the surface topography (Hutchinson and Moore 2000). On the other hand, when conditions are dry, and the water table is low, the soil moisture surface is likely to follow the topography of the confining layer (Price 2011). Fienen et al. (2018) also note that wells outside the surface basin can impact the baseflow by changing the local flow field. These changes in the water table elevation and groundwater flow will shift the peaks that define the basin area. Therefore, whether to use surface basins or groundwater basins as units of analysis may produce different results (Borchardt 2018). The discrepancy between surface water and groundwater divides makes a large difference in annual baseflow values (Gebert et al. 2007). The dynamic nature of the groundwater basin boundaries makes it difficult to determine which wells are potentially affecting baseflow at a given stream gauge. Several studies including Freer et al. (1997) and Hutchinson and Moore (2000) found that the topography of the confining layer (subsurface topography) and the properties of the soil overlaying the confining layer are better predictors of the water table than surface topography. On the other hand, Li et al. (2018) found several surface topographic variables that contribute to streamflow

variability, but the effects were not consistent. Therefore, it is necessary to consider both surface and subsurface topography when examining the effect of high-capacity wells.

The aim of this study is to investigate how climate variables and human activities affect baseflow across Wisconsin. This study builds on a previous one (Borchardt 2019) that examined baseflow trends and related factors in Wisconsin, and utilizes a range of regression models to answer the following research questions: (1) How are the temporal and spatial variabilities of baseflow affected by climate and basin physical characteristics (2011–2017)? (2) How are baseflow trends related to withdrawal rates of high-capacity wells and aquifer types? and (3) To what extent does the variability of groundwater basin boundaries influence baseflow? The study intends to sort out factors that could affect baseflow differently by time and space between 2011 and 2017 across the state of Wisconsin.

3.2 Materials and Methods

3.2.1 Overview

In this study, precipitation, temperature, drainage class, available storage, land cover, slope, and the recorded well withdrawal rates were used to predict baseflow variability across basins. The variables were found to be related to baseflow in previous studies (e.g., Borchardt 2019, Santhi et al. 2008, Lorenz and Delin 2007). Thirty US Geological Survey (USGS) streamflow monitoring sites were selected for the analysis, and each site had continuous daily streamflow during the study period (2011–2017). The years 2011–2017 were chosen for their availability of wells withdrawal data. Annual baseflow was derived from the streamflow data, and regression analysis was used to determine which variables affected baseflow variability during the study years. The list of the USGS sites and associated variables can be found in Appendix B and a list of the variables can be found in Table 3.

Table 3 Model variables used in the PDA models 1–5

Variable	Designation	Units
Annual stream baseflow	Baseflow	cm
Annual Precipitation	Precip	mm
Annual growing degree days base 10°C	GDD_10	°C
Available water storage	AS_150	cm
Soil drainage class	DrainClass	unitless
Average percent slope	Slope	percent
Percent of forested land cover	PerFor	percent
Percent of agricultural land cover	PerAg	percent
Percent of urban land cover	PerUrban	percent
Modified annual withdrawal rate	WxDd	$m^3 \times 10^{-5}$
Basin over unconfined aquifer	Unconfined	unitless
Basin over confined aquifer	Confined	unitless
Basin shape determined by surface topography	Surface	unitless
Basin shape determined by ground water topography	Groundwater	unitless

3.2.2 Baseflow

Annual baseflow was calculated from streamflow data collected for the years 2011–2017 at the 30 USGS sites using the USGS computer program Groundwater Toolbox (GWTB) (http://water.usgs.gov/ogw/gwtoolbox/, last accessed on 15 September 2018). GWTB contains six hydrograph-separation methods to calculate groundwater discharge, and one recession-curve displacement method (RORA) to estimate groundwater recharge (Barlow et al. 2015). The RORA method was chosen for this study to represent baseflow. The RORA recharge estimates have been found to be slightly greater than those estimated using the hydrograph-separation methods due to some loss of groundwater by riparian evapotranspiration versus discharge as baseflow to the stream (Barlow et al. 2015). These losses however are relatively small. The RORA program estimates net recharge. Net recharge is recharge minus leakage to deeper aquifers and losses caused by groundwater evapotranspiration (Rutledge 2000). It is assumed that groundwater discharged to streams is an episodic response to storms, unlike the hydrograph-separation methods which assume a continuous process (Rutledge 2007). The RORA method is a recession-curve displacement method based on a mathematical

solution. A recession index (*K*) is specified for each basin based on the time required for groundwater to discharge to the surface water. *K* is estimated using a semilogarithmic plot of streamflow as a function of time. The index is then used to calculate the solution for the conditions related to the instantaneous rise in height of the water table over the basin, and the volume of water that drains from groundwater storage after each precipitation event (Barlow et al. 2015).

3.2.3 Basin types

Basins with daily recorded streamflow during the study period (2011–2017) were filtered to include only unregulated streams with minimal wastewater discharge measurements. The selected basins were then delineated for both the surface contributing runoff to the stream and the area of groundwater contributing baseflow to the stream at the gauging station because groundwater basins do not always coincide with surface water basin boundaries (Borchardt et al. 2016). The gauging stations were used as pour points to delineate only the groundwater area that contributes water to each gauging station. The delineation of the groundwater basins followed the same process as the delineation of the surface water basins except that an interpolated groundwater elevation was used in lieu of the Digital Elevation Model (DEM) as described in Borchardt (2018). The interpolated groundwater elevation was determined by subtracting from the DEM the "depth to groundwater" data obtained from well drilling reports.

Since groundwater basin divides generally follow surface topography in wet years and subsurface topography in dry years, we delineated the groundwater basin only for the dry years between 2011 and 2017. Data retrieved from the Wisconsin State Climatology Office website (http://www.aos.wisc.edu/~sco/clim-history/state/graphics/WI-precip-annual.gif) reveals that only 2012 was a dry year, and the drought of 2012 caused low groundwater levels from late 2011 until spring of 2013 (Han et al. 2018). Therefore, the static water level of wells drilled during this time period were used to create the groundwater DEM used to delineate the groundwater basin for 2012. We used the surface

basin for the years 2011 and 2013–2017 since groundwater basins generally follow the size and shape of the surface water basins in wet years (Hutchinson and Moore 2000).

3.2.4 Climate variables

Growing Degree Days (GDD) was used as the temperature variable because it is a better measure of temperature during the growing season when irrigation is in use, and it eliminates the negative temperature recordings from the annual sum. The GDD is a measure of the mean temperature above the base temperature for each day (Equation 2).

$$GDD = T_m - T_b \text{ for } T_m > T_b \\ T_b \text{ otherwise} \qquad \text{Equation 2}$$

where T_m = daily mean temperature (°C)
T_b = base temperature (set at 10°C).

Annual GDD data (annual sum of daily GDD) was obtained for the weather station that was closest to each delineated basin from the Midwestern Regional Climate Center (Cli-MATE 2018). The GDD available from the Midwestern Regional Climate Center is base 50ºF (10ºC), the base is appropriate for this study because agriculture field irrigation rarely is implemented in temperatures below 10ºC in Wisconsin. Because temperate data does not vary significantly over relatively short distances, the use of the nearest weather station is appropriate. It is denoted by GDD_10 hereafter.

The precipitation data was obtained from the National Centers for Environmental Information for the state of Wisconsin (NCEI n.d.). Because weather stations are not necessarily located in the study basins and precipitation can vary across relatively short distances, precipitation data was interpolated using the kriging method. The weather stations with the most complete data set were selected (Appendix B). The data from the weather station closest to each selected weather station was used to replace any missing data. The data from NCEI contains precipitation totals for each month and a yearly total. Months

with missing data for 1–9 days were indicated with an “X”, and months with >9 days of missing data were left blank. For months containing missing data, if the monthly data from the adjacent weather station is greater than the data from the original station, the greater value was used in place of the missing data for that month at the original station. Sixty-eight stations were selected in Wisconsin, approximately one station per county. Two stations in Minnesota and one in Michigan were also selected to mitigate edge effects following the interpolation process. The yearly totals from 2011 through 2017 were recorded on a spreadsheet for each station along with each station’s latitude and longitudinal co-ordinates. Using ArcGIS 10.4 from ESRI, the data from the spreadsheet was mapped. The interpolation tool kriging in ArcGIS was used to create a raster layer with a 2-km resolution. Kriging weights the surrounding measured values to estimate a value in an unmeasured location using a formula within the ArcGIS program. The weights are based on both the distance between the measured points and the prediction location and on the overall spatial arrangement of the measured points (ESRI 2016). The mean annual precipitation (in mm) for each study year in each basin was then calculated in ArcGIS, and is denoted by Precip hereafter.

3.2.5 Basin physical characteristics

We used both available water storage (denoted by AS_150) and soil drainage class (denoted by DrainClass) to characterize the soil, and both were downloaded from the Soil Survey Geographic Database, part of the United States Department of Agriculture. The use of both is further explained in Borchardt (2019). However, we modified the use of the DrainClass from percent of well-drained soil to the mean value for the basin. Each drainage class was classified numerically 1–7, with 1 representing excessively drained and 7 representing very poorly drained, and the mean was calculated for each delineated basin. Both the AS_150 and DrainClass map layers were downloaded from ESRI (19 April 2019 and 5 June 2019, respectively). The topographical characteristics of the basin were represented by the average percent slope.

The landcover was downloaded from the Multi-Resolution Land Characteristics Consortium for years 2011, 2013, and 2016. The data for 2011 was used for study years 2011–2012, 2013 for 2013–2014, and 2016 for study years 2015–2017. The layers were created from the National Land Cover Database at a resolution of 30m and contain 16 classes of landcover. The layer was reclassified to reduce the number of classes to eight (water, developed, barren, forested, shrubland, herbaceous, agriculture, and wetland). The data was then clipped to the area of each delineated basin. The percentage of the three most prominent land covers (forested, agricultural, and urban) were calculated for each time in each basin, and it is denoted by PerFor, PerAg, and PerUrban, respectively.

3.2.6 Annual groundwater withdrawal rate

High-capacity well data for the state of Wisconsin was acquired from the Wisconsin Department of Natural Resources (WDNR) through email correspondence (Smail 2018) (see Figure 6 for the location). The state of Wisconsin has required owners of high-capacity wells to report annual groundwater withdrawal only since 2011, therefore actual reported values for years 2011–2017 were used in the regression analysis. It should be noted that the reporting of the annual withdrawal rate is on the honor system and is subject to some inconsistencies.

The extent to which a well affects the baseflow of a stream is in part related to the distance of the well from the stream. But when there are numerous wells within a single basin, it becomes difficult to determine this distance. Furthermore, wells can divert groundwater (by bending the groundwater flow path) from a tributary to the main stem of the stream (Fienen et al. 2018). To simplify the distance calculation, we measured the distance from the weighted mean center of all the wells within the basin to the stream gauge located at the basin outlet. Therefore, with the premise that wells closer to a stream have more effect on the baseflow to the stream than wells farther away, we used a modified annual rate (MAWR) for the withdrawal variable.

The annual withdrawal rate is reported in gallons and was converted to $m^3 \times 10^{-5}$ for this analysis. Then we modified the annual withdrawal rate by multiplying by the relative distance of the wells from the basin outlet to account for the different effects of well locations to baseflow measured at the outlet. The MAWR was determined by combining the total annual rate of withdrawal from all the high-capacity wells within each basin and the relative distance of the weighted mean of those wells from the basin outlet. The first step was to determine which wells were in each basin, and the second was to determine the withdrawal rate from each, the weighted mean center of the wells within the basins was determined using the withdrawal rate as the weight. This moved the mean center closer to the well with the highest withdrawal rate for any given year. Then the distance (d_{ij}) between basin i's weighted mean center for year j and the individual basin outlet was calculated in meters. The relative distance (RD_{ij}) between the weighted mean center for basin i in year j and the basin outlet is then calculated, and subsequently, the MAWR was calculated according to Equation 3.

$$\text{MAWR}^{ij} = \frac{\text{AWR}}{RD_{ij}} \qquad \text{Equation 3}$$

where AWR_{ij} denotes annual withdrawal rate and $RD_{ij} = \frac{d_{ij}}{\Sigma d_{ij}}$ is the sum of distance for all the basins in all the study years. The MAWR is denoted by WxDd, and its unit is $m^3 \times 10^{-5}$.

3.2.7 Aquifer types

Because groundwater withdrawals from unconfined and confined aquifers can have different effects on baseflow, we determined the aquifer type for each well. We examined two data sources, well construction reports and a geological map, to determine the aquifer type. Well construction reports are filed with the WDNR after the completion of a well installation, and they record both the well depth and the depth of the confining layer. By comparing the two depth records, we could determine which wells are drawing from the confined aquifer and which are drawing from the unconfined aquifer. Well construction report data compiled by the Wisconsin Geological & Natural History Survey was received

from the University of Wisconsin-Extension via email correspondence (Mavel 2018). Well construction reports are only available for a small portion of the wells within each basin. It is a customary practice for well drillers to drill to the depth on a par with other wells in the general area with a reliable water source. Therefore, it is assumed that if all the wells with a construction report are pumping from the same aquifer, then the wells without a construction report are also withdrawing from that same aquifer in each basin. Well locations were also compared to a map layer titled "Aquifers of Alluvial and Glacial Origin". The aquifer types layer was delineated by the USGS from data in The Ground Water Atlas of The United States and was downloaded from ArcGIS online (AGOL 2002) (Figure 6). Per the aquifer map layer, 26 of the 30 basins were located over only one aquifer type. After comparing these two data sources, we determined if each basin's wells were drawing groundwater mainly from the confined or the unconfined aquifer. The determination was primarily based on the data derived from the aquifer map layer with the construction reports acting as a verification.

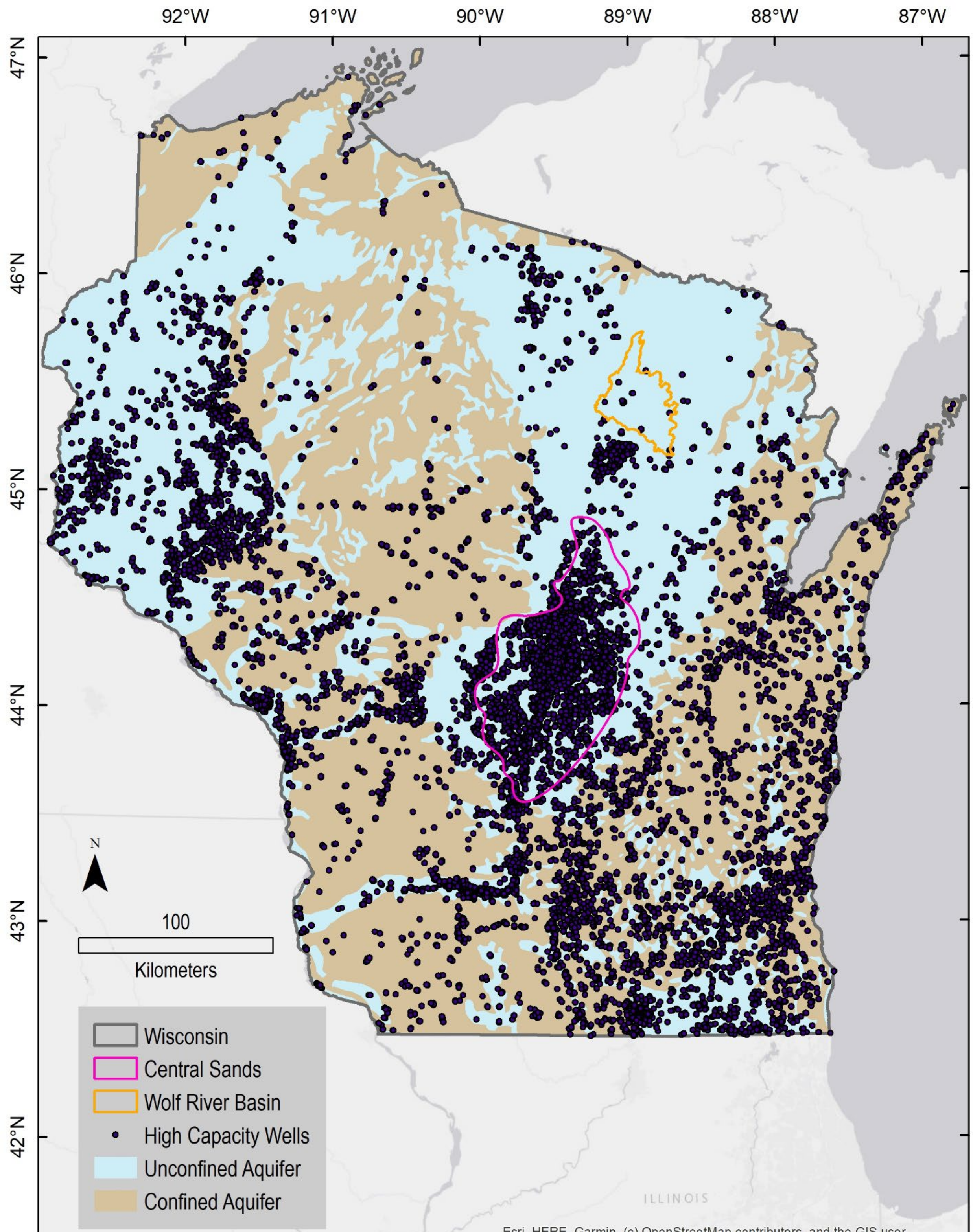


Figure 6 Location of high-capacity wells, aquifer types delineated by the USGS from data in The Ground Water Atlas of The United States, the Wolf River basin, and the Central Sands.

3.2.8 Regression analysis

We employed the panel data analysis (PDA) to build regression models. PDA is a statistical method used to analyze data simultaneously varying over time and space (or sector). The dependent variable *Y* (annual baseflow in cm) for the basin *i* at time *t* is modeled using explanatory variables X_k as follows in equation 4:

$$Y_{it} = \beta_0 + \beta_1 X_{1it} + \beta_2 X_{2it} + \cdots \beta_k X_{kit} + u_{it} \qquad \text{Equation 4}$$

where β_0 is the constant term and *u* is the error term. It should be noted that some explanatory variables can be time-invariant.

PDA can be divided into four main categories: independently pooled panels, between estimation models, fixed effect models, and random effect models (Min and Choi, 2019). The pooled regression model is a method of applying to the ordinary least squared model incorporating different observations from different periods of time, ignoring temporal changes and the objects' difference in the panel data. Between estimation models use the variables averaged over time, using only cross-sectional information, and removing time variation in the data. Fixed effect models, also called within estimation models, replace time-invariant explanatory variables with a time-invariant term α_i representing different intercepts by object (Equation 5):

$$Y_{it} = \beta_0 + \beta_1 X_{1it} + \beta_2 X_{2it} + \cdots \beta_{\mathrm{k}} X_{\mathrm{k}it} + \alpha_i + u_{it} \qquad \text{Equation 5}$$

where all the explanatory variables are time-variant. They examine the variability within each object. Random effect models assume that α_i in the model follow a probability model, independent of explanatory variables. In other words, α_i is very small or all factors are controlled for, which is a better assumption than that in fixed effect models.

We used the plm package of R (Croissant and Millo, 2008) using the between estimation and random effect models to focus on time-invariant and time-variant variables, respectively. We ran PDA for different combinations of aquifer types and basin types. It was first run on the entire data set, and then on the divided sets. The analysis was run two times for each aquifer type. The first run included variables from within the surface basin. The second run used the same variables but from within the groundwater basin (Table 4). We inserted all the explanatory variables, and the plm package automatically eliminated insignificant variables.

Table 4 PDA Regression models

Model	Aquifer type	Basin type	Number of basins
1	Confined and Unconfined	Surface	30
2	Unconfined	Surface	13
3	Confined	Surface	17
4	Unconfined	Groundwater	13
5	Confined	Groundwater	17

3.3 Results and Discussion

3.3.1 Descriptive statistics of the variables

The descriptive statistics for the annual baseflow estimated using the RORA method is presented in Table 5. The mean is 26.7 cm, and the distribution is quite symmetrical between the first and third quartiles. The data stretches further to the maximum than to the minimum. We also present the descriptive statistics of baseflow predicted by model 1 (random effect) for comparison. There are some discrepancies, but the magnitude of each statistic is generally comparable. The biggest discrepancy is found in the maximum. The predicted maximum is smaller than the observed by about 5.7 cm.

Table 5 Descriptive statistics for observed and model 1-predicted annual baseflow during 2011–2017 for the 30 basins selected for the study

Baseflow	Minimum	1st quartile	Median	Mean	3rd quartile	Maximum
Observed	7.95	19.13	25.77	26.70	32.12	57.66
Model 1 Predicted	6.85	22.27	27.04	26.70	30.36	51.92

The distribution of each explanatory variable is presented in Figure 7. Most of the variables have quite symmetrical distributions. Notable exceptions are PerAg, PerUrban, and WxDd. Most of the basins have less than 40% agricultural land cover with the median of about 10%. PerUrban has a more skewed distribution than PerAg, with the median of about 5% and the maximum close to 100%. Highly urbanized basins are concentrated in the southeastern corner of the state. WxDd varied extremely widely, thus is shown as logarithm. The log WxDd has a quite symmetrical distribution with a few extreme outliers below zero.

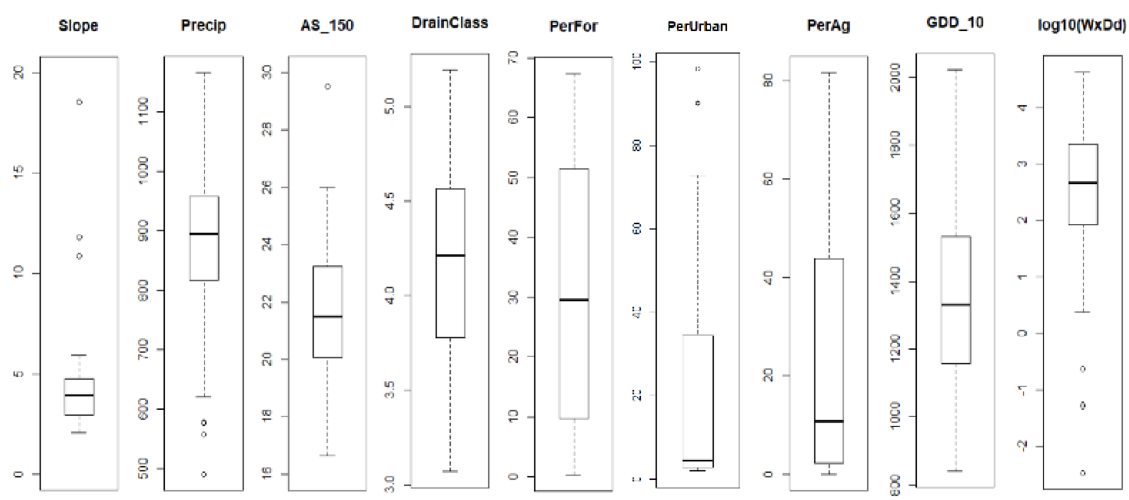


Figure 7 Box and whisker plots of the explanatory variables used in PDA models 1–5.

3.3.2 Model 1

Table 6 Panel data analysis results for model 1 using between estimation and random effect models

	Between estimator	Random effect
Coefficients for significant variables ($p < 0.05$)	0.221PerFor	0.029Precip –4.786DrainClass –0.015GDD_10
R^2	0.38272	0.35691
p-value for F statistic	0.00026842	< 2.22e–16

The result for model 1 where all the basins were considered is presented in Table 6. PerFor was found to be the only significant variable when we used the between estimator. When the time-variant variables were averaged over time, only PerFor was left to explain the variability of baseflow across basins. PerFor varied widely across the state, from 0.29% to 67.40% with the median of 29.48%, and basins with more forest cover tended to have more baseflow. The catchment 04025500 has the greatest observed baseflow and the highest PerFor. R^2 is higher than with the random effect model even though there is only one explanatory variable that is statistically significant. It is likely because PerFor kept its large variability whereas other variables' variabilities were reduced in the model. In addition, PerFor is correlated with other variables regarding basin characteristics and land cover. Therefore, it makes sense that all the other ones were left out.

In the random effect model, both time-invariant (DrainClass) and time-variant (Precip and GDD_10) variables significantly explained the variability of baseflow (Table 6). Precip had a positive coefficient whereas DrainClass and GDD_10 had negative. Lower numbers in DrainClass indicate better drainage of the soil, thus the result indicates that baseflow increases with better drained soils. The negative coefficient of GDD_10 suggests the effect of higher evaporation with higher temperatures on baseflow. Model 1 suggests that precipitation and temperature variabilities play larger roles than basin characteristics in baseflow variability when time is considered.

3.3.3 Models 2 and 3

When only the basins over unconfined aquifers were considered (model 2), Precip, DrainClass, and GDD_10 were found to be significant with the random effect model whereas none with the between estimator model (Table 7). The significant variables with the random effect are the same as in model 1, suggesting both climate and drainage characteristics matter for baseflow. The magnitude of the DrainClass coefficient and the GDD_10 coefficient approximately doubled respectively compared to model 1, suggesting stronger influences of evaporation and soil drainage on baseflow over unconfined aquifers than over confined ones. Because the surface water is more strongly connected to unconfined aquifers than to confined ones, evaporation and soil drainage have stronger effects on baseflow over unconfined aquifers. The non-significance of the between estimation model suggests that the interannual variability of baseflow is so large whereas the inter-basin variability is not so large. The large interannual variability was eliminated by the between estimator whereas the inter-basin variability was not large enough to be explained by any explanatory variables.

Table 7 Panel data analysis results for models 2 and 3 using between estimation and random effect models

		Between estimator	Random effect
Model 2	Coefficients for significant variable ($p < 0.05$)	None	0.028Precip −9.236DrainClass −0.028GDD_10
	R^2	0.10856	0.31343
	p-value for F statistic	0.27161	3.386e–07
Model 3	Coefficients for significant variables ($p < 0.05$)	–0.088PerUrban	0.035Precip −0.007GDD_10
	R^2	0.25306	0.43828
	p-value for F statistic	0.039558	2.9667e–15

When the analysis was conducted for the basins over confined aquifers (model 3), the variability of baseflow was explained by PerUrban with the between estimator and Precip and GDD_10 with the random effect. PerUrban is negatively correlated with PerFor, therefore the coefficient is negative unlike

in model 1. The result is essentially identical to that from model 1. With the random effect model, only Precip and GDD_10 are statistically significant variables. Unlike over unconfined aquifers, drainage characteristics were not an important factor, and the Precip coefficient is larger. The non-significance of basin characteristics is likely because the aquifer is detached from surface water. In summary, for the basins over confined aquifers, baseflow is better explained with climate variables only compared to the basins over unconfined ones.

3.3.4 Models 4 and 5

Model 4 is the same as model 2 except for that groundwater divides were used to delineate basins boundaries. The regression results (Table 8) are almost identical to those from model 2 with minor differences in coefficients. R^2 with the random effect model increased marginally from 0.313 to 0.321. Therefore, whether to use surface water or groundwater divides did not affect baseflow in the basins over unconfined aquifers.

Table 8 Panel data analysis results for models 4 and 5 using between estimation and random effect models

		Between estimator	Random effect
Model 4	Coefficients for significant variables ($p < 0.05$)	None	0.026Precip −7.649DrainClass −0.026GDD_10
	R^2	0.085701	0.3208
	p-value for F statistic	0.33172	2.1399e–07
Model 5	Coefficients for significant variables ($p < 0.05$)	0.2096Precip −0.5272PerAg −0.5113PerUrban	0.024Precip −0.008GDD_10
	R^2	0.68695	0.35795
	p-value for F statistic	0.01398	4.5044e–11

Noticeable effects of groundwater divides were found for the basins over confined aquifers (model 5) when the between estimator was used. Precip, PerAg, and PerUrban were found to be significant variables and R^2 was >0.68. The time-averaged annual precipitation is a significant variable

only in model 5 with the between estimator. We think it is because the basins are spread across the state and the variability of precipitation is larger than for the basins over unconfined aquifers. In this set of basins, agricultural and urban land covers are more prevalent than forest. For example, the median of PerAg and PerUrban is 38% and 17% respectively whereas that of PerFor is 10%. The negative effect of agricultural and urban land covers on baseflow is not surprising by itself, but their significance is due to their prevalence and large variability.

The effects of groundwater divides seem to have disappeared with the random effect model. Precip and GDD_10 are significant variables like in model 3, and their coefficients are similar. R^2 is slightly lower than model 3. It indicates again the large interannual variability of baseflow and climate variables.

We examined the shape of surface water and groundwater basins in detail (Figure 8). It seems groundwater basin boundaries generally follow surface topography over unconfined aquifers. There was not much discrepancy between groundwater and surface water basin boundaries at higher bedrock elevations, and there was greater discrepancy at lower elevations. The groundwater basin areas decreased in size compared to the surface water basin boundaries at lower bedrock elevations (Figure 8a). The basin boundary discrepancy over confined aquifers appeared to be particularly large in the southeast where the percentage of urban land cover was high. On the other hand, the discrepancy is quite small in forest-dominated basins (Figure 8b). This is why land cover variables were significant in model 5 with the between estimator.

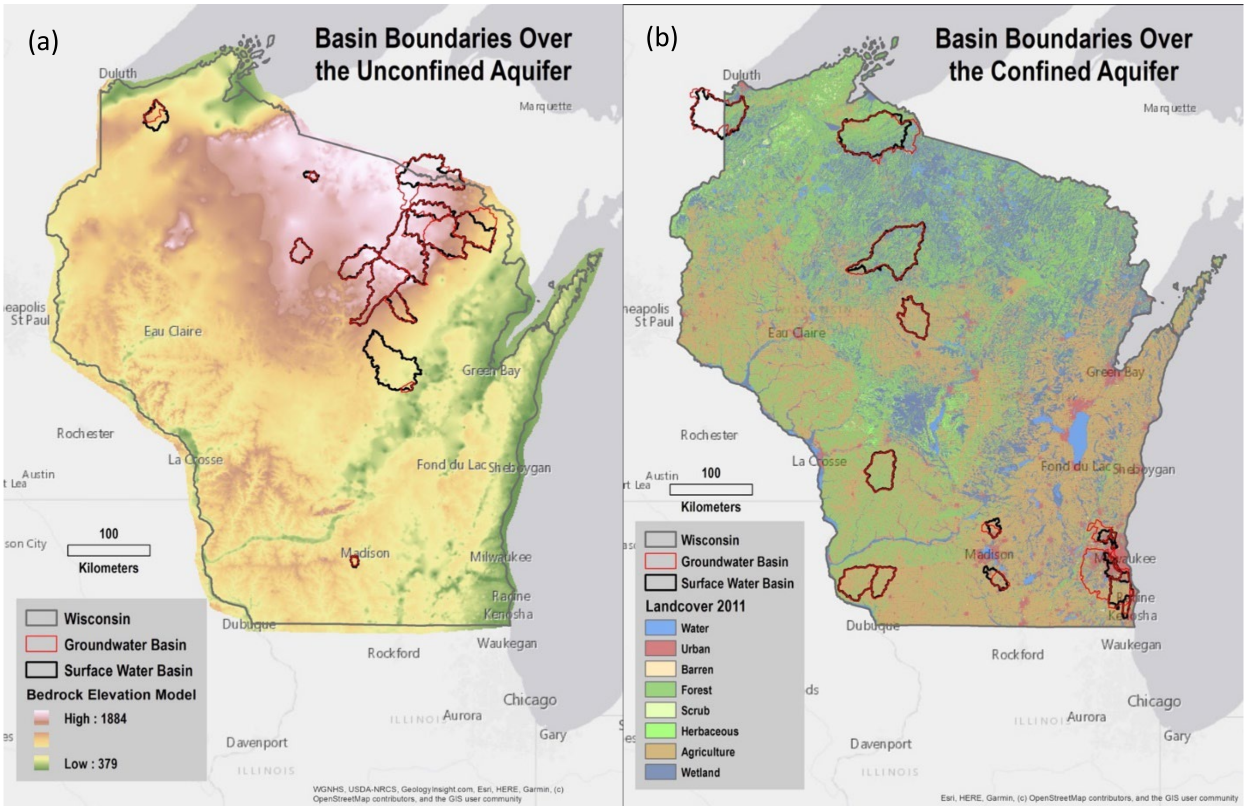
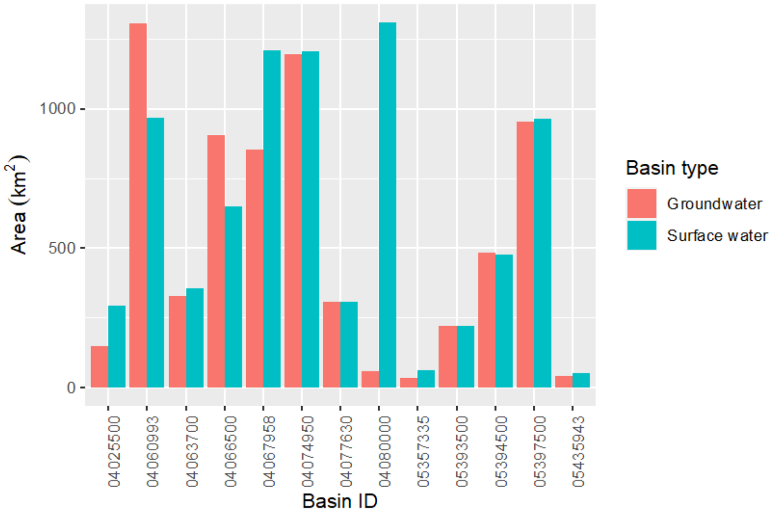
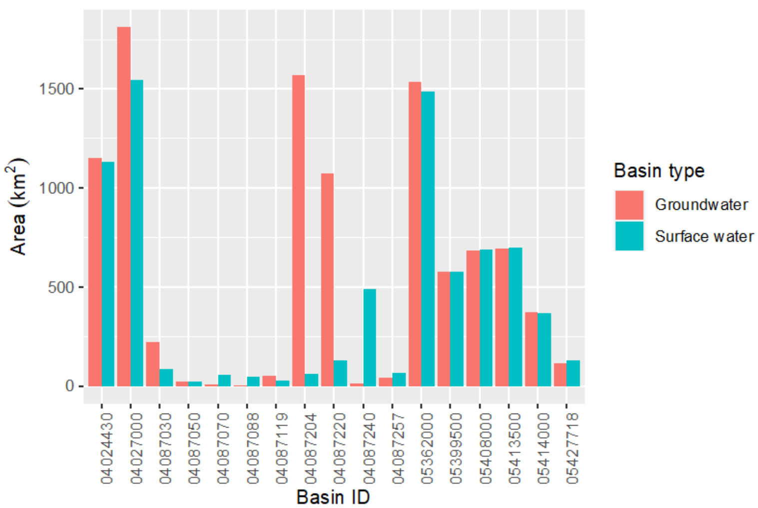


Figure 8 (a) Groundwater and surface water basin boundaries over unconfined aquifers and bedrock elevation downloaded from esri ArcGIS online. **(b)** Groundwater and surface water basin boundaries over confined aquifers and landcover data downloaded from the Multi-Resolution Land Characteristics Consortium for the year 2011.

The overall area within the basin boundaries varied less in the basins over the unconfined aquifer than those over the confined aquifer (Figure 9). Six out of the thirteen basins over the unconfined aquifer had a change in area from the groundwater basin to the surface water basin area of less than 10%. Only two of the remaining basins had a decrease in size over 10% (04066500, 04060993), five basins however had an increase in size greater than 10% ranging from approximately 18% (05435943) to greater than 95% (04080000) (Figure 9a). Seven out of the eighteen basins over the confined aquifer had a change in area from the groundwater basin area to the surface water basin area of less than 11%. Six of the remaining basins had groundwater basins that were larger in size than their surface water basin, and five had smaller groundwater basins than their surface water basin. The percent decrease of all the basins over the confined aquifer ranged between over 2400% (04087204) to less than 2% (05414000), and the percent increase in size ranged from less than 1% (05399500) to greater than 97% (04087240) (Figure 9b).



(a)



(b)

Figure 9 Areas of groundwater basins and surface water basins in the year 2012 over **(a)** unconfined aquifers and **(b)** confined aquifers.

3.3.5 Effects of groundwater withdrawal

The groundwater withdrawal was not a significant variable in any model when it was modified with the relative distance to basin outlets. The data comes in volume, and because the same amount of withdrawal can have different effects on baseflow depending on the basin size, we first converted to depth by dividing by area. When we used the withdrawal depth in regression models it was found to be insignificant. We then used the modified annual withdrawal rate (WxDd) for the regression models to find it insignificant again.

We speculate for reasons for the insignificance. A possible reason is that the distribution of WxDd is extremely skewed, like an exponential distribution with a sharp decline. It was very high in particular years in particular basins, with little to no correlations with other variables. When we examined the correlation between WxDd and observed baseflow each year, the correlation was always negative and statistically insignificant. We suspect the effect of groundwater withdrawal on baseflow, but the statistical approach we employed failed to demonstrate it. It could also be because the relationship between groundwater withdrawal and baseflow is not direct. The effect could occur with temporal and/or spatial lags or via another mechanism, and exploring them is beyond the scope of this study.

3.4 Conclusions

The study investigated the spatial and interannual variability of baseflow in Wisconsin using the panel data analysis method for the period 2011–2017. The findings are summarized as follows: (1) precipitation and temperature variable are significant in explaining the temporal variability of baseflow whereas land cover variables are important when the temporal variability is not considered; (2) the drainage condition is important for baseflow over unconfined aquifers; (3) evaporation and soil drainage are important in basins over unconfined aquifers whereas precipitation the most significant over confined aquifers; (4) whether to use surface water or groundwater divides to delineate basins matters in particular conditions, and (5) groundwater withdrawal rates do not significantly affect baseflow when using statistical analysis. Overall, we cautiously argue that groundwater basins should be considered when delineating basin boundaries for baseflow studies, and statistical analyses show limited too little success in revealing the effect of high-capacity wells on baseflow in Wisconsin at the annual scale. A process-based modeling approach would be necessary.

This research yielded knowledge of the role of hydrological stress, both natural and anthropogenic, on stream baseflow. The results will be useful for hydrologists and water resources managers interested in environmental change impacts and adaptations. Precipitation and temperature were

significant variables in each of the models representing separate aquifers. Additionally, we expect that this research will lead to further research that investigates how the state's groundwater resource can be best used and how to balance that resource between the state's agricultural needs and environmental concerns.

CHAPTER 4 SIMULATED EFFECTS OF CLIMATE CHANGE AND WITHDRAWALS FROM HIGH-CAPACITY WELLS ON THE STREAMFLOW AND GROUNDWATER ELEVATIONS IN NORTHEASTERN WISCONSIN

4.1 Introduction

This study attempted to demonstrate the simultaneous effects of climate change and groundwater withdrawal from high-capacity wells on the hydrological system within the study area. The study used both surface and subsurface characteristics to investigate how climate variables and human activity together, affect surface water and groundwater in Wisconsin through modeling. Models give managers the capability of providing what-if scenarios, using the combination of varying climates and withdrawal rate scenarios to interested parties. The goal of the study was to develop two computer water flow models for the state. The goal of the two models was to create a tool that water managers can use to predict the effect of permitting or abandoning high-capacity wells in a changing climate. One model to model the surface water flow and the other to model the groundwater flow. The models looked at the relationship between surface water and groundwater in the Wolf River basin (WRB) in northeastern Wisconsin. The WRB was chosen as the study basin due to its extensive use of groundwater for agricultural irrigation and its glacial aquifer that is well connected to surface waters. The flow models are expected to be able to exhibit the relationship between the groundwater, the surface water, climate change and the withdrawal rate of the high-capacity wells within and adjacent to the basin boundaries.

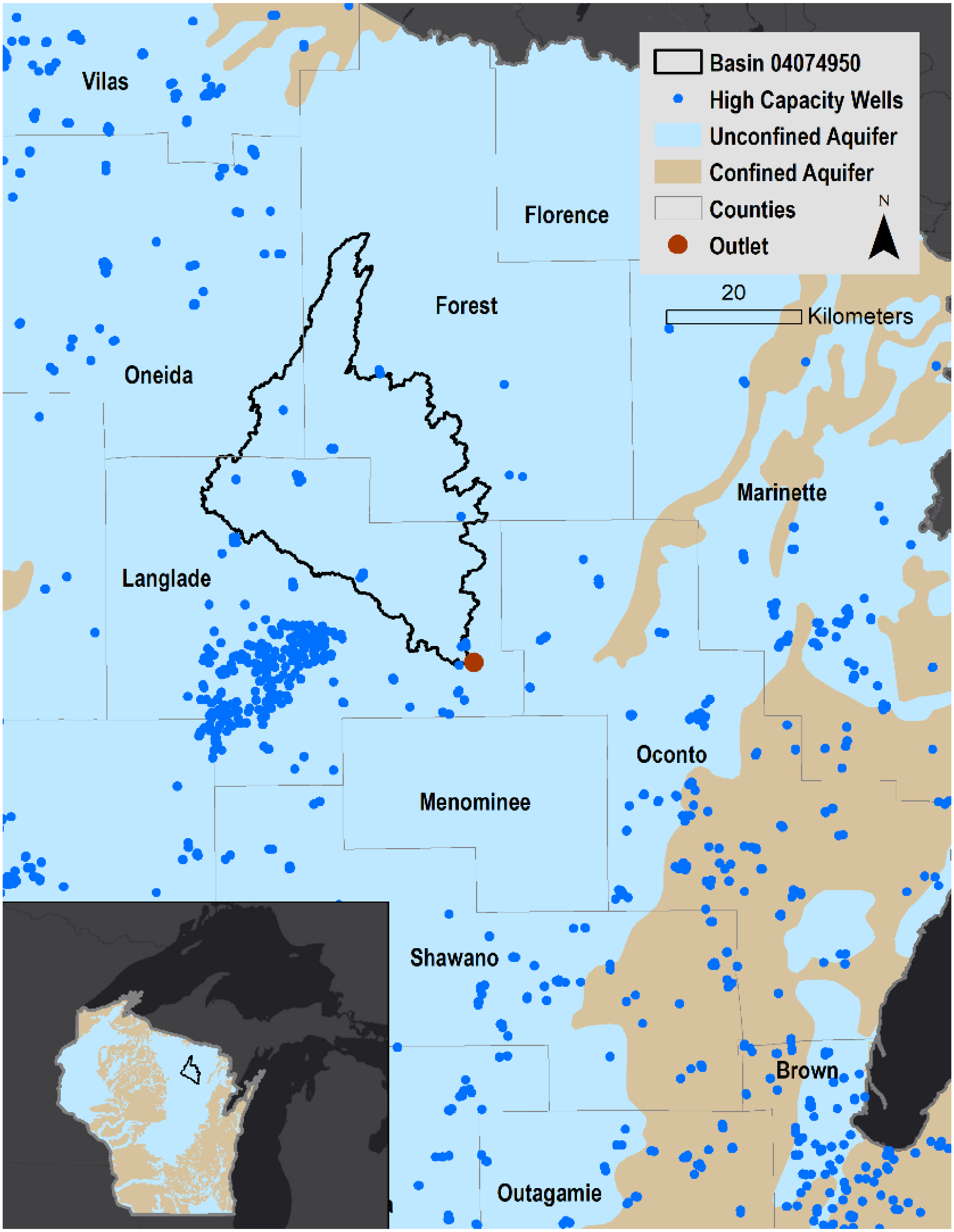


Figure 10 Wolf River basin delineated in Arcmap from the outlet point at the USGS gauging station at Langlade.

4.2 Research Design

4.2.1 Study area

The WRB used in this study is an example of the varied geology and land-uses found within the state of Wisconsin. The WRB spans parts of several counties, Forest, Langlade, and Oneida, in northeastern Wisconsin (Figure 10). The WRB has a drainage area of approximately 1,200 km^2: 54% consists of forested landcover and 3% is agricultural. The surface geologic formation consists of glacial unconsolidated sand and gravel overlying Precambrian bedrock (Mickelson 1987). These deposits range in thickness from less than 6 m in the northeastern and western parts of Langlade County to over 150 m in the central part of the county. The geologic material is very coarse textured and contains a large percent of sand- and gravel-sized particles (Batton 1987; Mickelson 1987). Elevations vary in the Wolf River basin from approximately between 330 and 575 m above sea level. The gauging station for the Wolf River (US Geological Survey site number 04074950) is located at latitude 45°11'24" and longitude 88°44'00". The Wolf River basin has 18 high-capacity wells upstream of the gauging station. The total recorded withdrawal from these wells was 3.407×10^5 m^3 in 2017. Although the land-use composition, and population has changed little over the last 3 decades, the number of high-capacity wells has increased 80% within the basin.

4.2.2 Modeling overview

Several modeling scenarios were run to assess the streamflow and recharge variations due to climate stresses in SWAT, the resulting recharge values were then be used as inputs to the MODFLOW simulation to assess both climate and anthropogenic stresses on the basin. A steady-state 3-dimensional MODFLOW groundwater model was then constructed for the basin delineated with the SWAT model to provide initial conditions for the groundwater simulations that were utilized to characterize groundwater conditions before and after the introduction of high-capacity wells. The MODFLOW basin model

consisted of three hydrostratigraphic units or layers representing a glacial unconfined aquifer. The first layer represented the surficial deposits underlying the soil layer but above the bedrock consisting of glacial till, the 2nd and 3rd layer represented the Precambrian bedrock. The thickness of each hydrostratigraphic unit was interpolated from Well-Construction Reports obtained from Wisconsin Department of Natural Resources (WDNR). Hydraulic conductivity (K) was determined from previously published geologic studies in the basin region, and then calibrated to the current groundwater-level data. All the datasets were integrated to construct a basin-scale groundwater flow model using the computer programs SWAT and MODFLOW.

4.2.3 Constructing the Wolf River Basin SWAT model.

The SWAT model was constructed using the Arcmap extension ArcSWAT 2012.10.19 from Texas A&M University (https://swat.tamu.edu/software/arcswat/). The surface basin and sub basins draining surface runoff to the USGS gauging station at Langlade (site number 04074950) and the stream network within the basin were delineated in SWAT using a digital elevation model (DEM) downloaded from the USGS web site (USGS n.d.) at an 8-meter resolution. The surface characteristics within each sub basin were calculated in SWAT: slope was calculated from the DEM, soil class was determined from the SSURGO database in SWAT, and land-use was determined using the National Landcover Database 2011 also provided in the SWAT program. The surface characteristics will determine how much precipitation will infiltrate to the groundwater and how much will run over the surface to the surface waters within each sub basin. Areas with the same slope, land-use, and soil were grouped together in Hydraulic Response Units (HRU) that are assumed to respond similarly to climate variables. The total number of HRU's were reduced by only creating combinations of land use/soil/slope that exceed a prescribed threshold of area in each sub basin. This reduction was implemented to increase model efficiency. Next SWAT was used to extract climate data from the nearest reporting weather station to each sub basin. The climate data extracted consists of daily precipitation, maximum and minimum daily temperature, solar

radiation, wind speed, and relative humidity. The weather generator in SWAT was used to compensate for missing climate data; the weather generator used the average climate statistics measured at the nearest reporting station. The generated climate data did not match observed data on a daily basis but did closely match the observed data on a long-term basis such as the average monthly and annual values used in this study. The SWAT first run was based on 4 years, 2009–2012, with the first three years used to stabilize the run; therefore, only the year 2012 was used for the output files. SWAT was run three times, first with current climate scenarios, second using the future precipitation projections per Wisconsin Initiative on Climate Change Impacts (WICCI), and the third run used both the future precipitation and temperature projections for the study area from the WICCI.

4.2.4 Constructing the Wisconsin River Basin SWAT model

Because groundwater divides and surface-water divides do not always coincide, and groundwater divides are not as easy to detect as surface-water divides. Also, because groundwater divides are dynamic, moving in response to environmental and anthropogenic stresses and following the subsurface topography versus the surface topography in dry seasons (Borchardt 2018) a second basin was delineated in SWAT. Since the bedrock in the study area slopes from the NW to the SE, the area to the north and to the west of the Wolf River basin needed to be analyzed in SWAT for use in the MODFLOW model. By inserting a basin outlet on the Wisconsin River just downstream of where the Big Rib River and the Eau Claire River converge with the Wisconsin, SWAT was able to delineate an area covering the surface area to both the north and the west of the Wolf River basin (Figure 11). The same steps were completed to construct the SWAT model for the Wisconsin River Basin that were taken to construct the SWAT model for the Wolf River Basin.

4.2.5 Future climate predictions

To model how streamflow and recharge will be affected by future changes in the state's climate the .wgn weather input files in SWAT were revised to reflect predicted changes to Wisconsin's climate by the middle of the 21st century using the RCP4.5 and RCP8.5 model predictions. The WICCI has scaled down the RCP4.5 greenhouse gas submissions scenario (Thomson et al. 2011) for the state. The WICCI created and has made available on their web site (https://wicci.wisc.edu/wisconsin-climate-trends-and-projections/), maps showing the projected changes in both precipitation and temperature between the years 2041–2060. The RCP4.5 scenario assumes that some measures are taken to reduce emissions and conserve forest land to store carbon; the RCP4.5 scenario limits carbon emissions to 35% higher than 2005 levels. The percent change in precipitation during each season (Table 9) for the study area was reflected in the revised .wgn files and the SWAT model was run, and outputs collected. The .wgn files were then updated with the projected changes for each season for both minimum and maximum temperature, and again the model run, and out puts collected.

The RCP8.5 model predictions were mapped globally by esri (https://uwm.maps.arcgis.com/home/item.html?id=8bdb6fbd60d346cfb272b6892ad45252) but have not been downscaled for the state of Wisconsin. The RCP8.5 model assumes very high levels of radiative forcing due to high population growth and the continued lower incomes in developing countries. The model projects the radiative forcing will reach 8.50 W/m^2 by 2100 (Van Vuuren, et al., 2011). The RCP8.5 model is the most extreme scenario, but it is considered to be very likely. Since the RCP8.5 model is not downscaled for the state, the predictions are not broken down by season, nor are changes in the maximum and minimum daily temperature calculated separate from average temperature. The temperature change is expected to be between 3 and 3.25 ºC higher, since RCP4.5 projected winter, spring and fall to be warmer than the summer maximum daily temperature, 3.25 ºC was used for winter, spring and fall and then 3.0 ºC was used for the summer. For the minimum daily temperature fall was projected to warm less than the other season in the RCP4.5 model so 3.25 ºC was used for winter, summer, and spring, and 3.0 ºC was used for the fall in the RCP8.5 model (Table 9). The RCP8.5 model predicts that precipitation to be between 25 and 50 mm above the annual average which equates to

approximately 5% annually which is the same as the annual prediction for the scaled down RCP4.5 model by WICCI, therefore the RCP4.5 seasonal values were used for the seasonal RCP8.5 values (Table 9).

Table 9 Upper panel: Future average increases in climate variables over years 2014–2060 relative to recent historical 30-year averages 1981–2010 downscaled from RCP4.5 model. Lower panel: Future averages increases in climate variables over years 2040–2059 relative to recent historical 20-year averages 1986–2005 from the RCP8.5 model

Season	Month	Precipitation increases	Daily Max. Temperature increase °C	Daily Min. Temperature increase °C
Winter	Dec, Jan, Feb	10%	2.77	3.89
Spring	Mar, Apr, May	10%	2.77	2.77
Summer	Jun, Jul, Aug	5%	2.22	2.77
Fall	Sep, Oct, Nov	5%	2.77	2.22
Annual			2.63	2.91

Season	Month	Precipitation increases	Daily Max. Temperature increase °C	Daily Min. Temperature increase °C
Winter	Dec, Jan, Feb	10%	3.25	3.25
Spring	Mar, Apr, May	10%	3.25	3.25
Summer	Jun, Jul, Aug	5%	3.0	3.25
Fall	Sep, Oct, Nov	5%	3.25	3.0
Annual			3.19	3.19

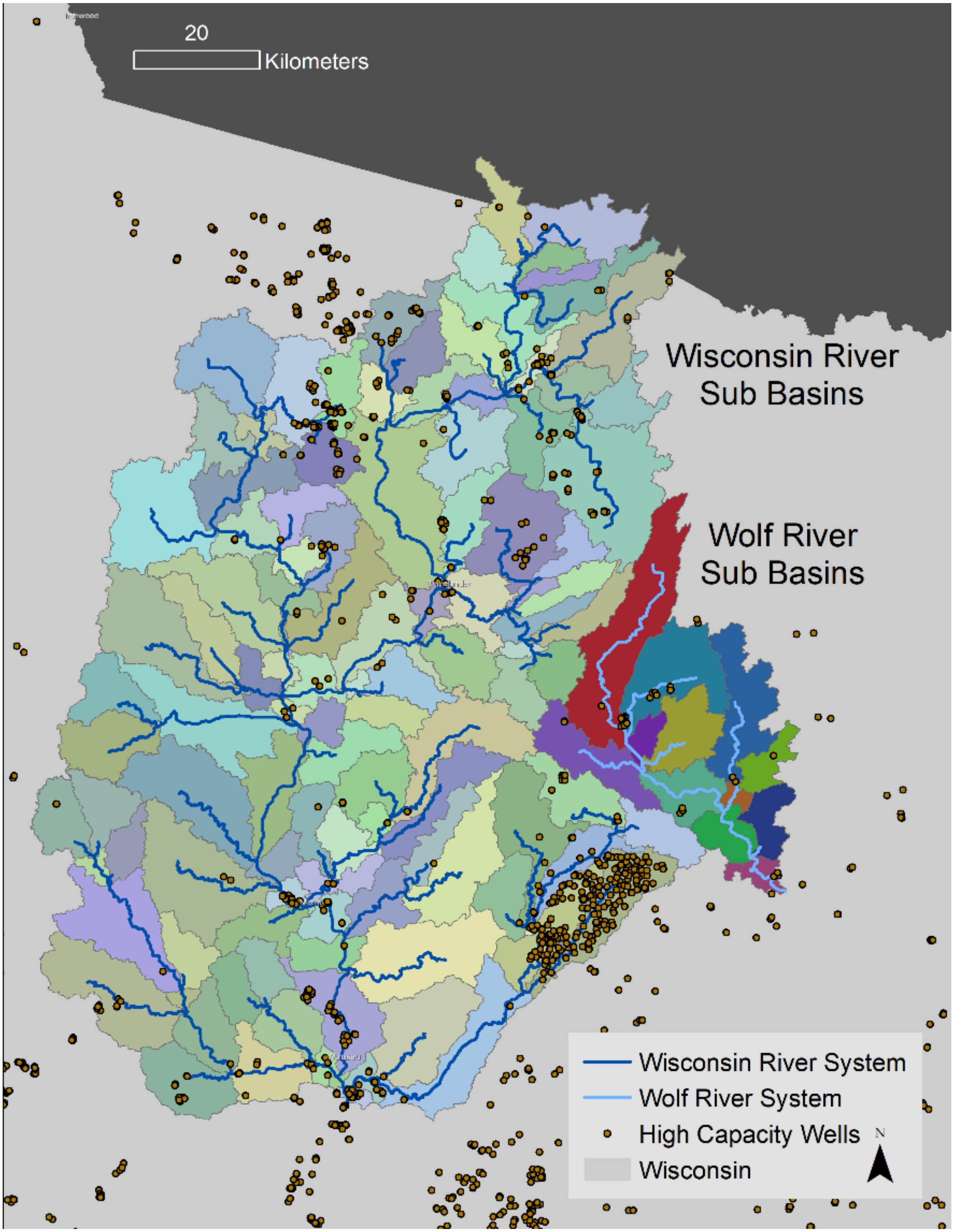


Figure 11 Wisconsin and Wolf River sub basins and river networks delineated from the SWAT computer program.

4.2.6 Constructing the MODFLOW model

The MODFLOW model is constructed as a 3D grid system using the graphic interface Groundwater Vistas Version 7 (GWV7) from Environmental Simulations Incorporated. GWV7 has been in use for over 20 years and contains interfaces for several versions of MODFLOW, MODPATH, and PEST (Rumbaugh et. al. 2017). Since GWV7 can import shapefiles from Arcmap, the output files from MODFLOW are georeferenced and can also be exported for use in Arcmap. The initial set up for this study consisted of 620 rows and 492 columns of 250 meters each and 3 evenly spaced vertical layers between 200 and 600 meters above sea level. The study basin was digitized by tracing the outline of the two combined SWAT models, the Wolf River basin, and the Wisconsin River basin, in Arcmap. The digitized shape file was used in leu of the original SWAT shape files to reduce the file size for downloading into the MODFLOW model. After the new digitized shape file was imported into MODFLOW the cells outside the boundary were classified as inactive. The SWAT output shape files for each river system were also imported into the MODFLOW model. The SWAT shape files for each river system contain maximum and minimum river stage elevations and the length of each segment in the river systems for both the Wolf River and the Wisconsin River.

4.2.6 Defining the MODFLOW layer elevations

Layer elevations were determined using a combination of existing datafiles, data derived through interpolation, and literature review. The 8m resolution DEM that was used in the SWAT models was resampled to a 50m resolution raster file using Arcmap, and then converted to a SURFER file for use in the GWV7 interface. The SURFER file was then used to define the top elevation for layer 1. The top of layer 2 is the bedrock surface. The top of the bedrock was determined from well construction reports, completed at the time of well construction, which are archived by the WGNHS. From the thousands of well reports in the study area basin, those that had a well depth of greater than 140 feet (232 reports) were chosen to determine stratigraphic thickness. Even at depths greater than 140 feet, not all the wells reached

the Precambrian bedrock which forms the lower boundary of the groundwater system. A subset of the above well data containing well reports that did contain depth to bedrock information was used to produce a bedrock contour map. The subset contained 133 well reports which were used with the kriging tool in Arcmap to interpolate a raster representing the bedrock's depth below the surface. This raster was then subtracted from the surface resampled DEM to create a contour map of the bedrock surface. The resulting raster was also converted to a SURFER file and then used to define the top elevation of layer 2 (the bottom of the aquifer). Batten (1987) describes the hydraulic conductivity in the upper bedrock layer considerably different than the lower layer, therefore for this study the upper layer (layer 2) is considered fractured bedrock, while the lower layer (layer 3) is considered unfractured bedrock. The thickness of layer 2 is set at 26 meters. A simple raster subtraction was completed in Arcmap to arrive at the raster file to be used for the top elevation of layer 3. A small number of well reports recorded a clay layer (11 reports). A visual inspection of the well locations found them to be disbursed throughout the basin and not cluster in any particular area; therefore, a decision was made to not create a clay layer for the MODFLOW model. The subsurface layers for this model are a rough interpretation of the actual field conditions but will still supply us with knowledge of the hydrological processes within this basin.

4.2.7 Creating recharge and hydraulic conductivity zones

Zones were created for both the recharge and the hydraulic conductivity (K) to simulate physical conditions within the study area. Two recharge zones were created to coincide with the two SWAT models; zone 1 coincides with the Wisconsin River basin, and zone 2 coincides with the Wolf River basin (Figure 11). The output recharge values from the SWAT models were then used as the input values for the MODFLOW recharge database for both zones. The zones for the K values were created using a combination of well construction reports and a shape file of surficial deposits. Well constructions reports have detailed reports of the depths of each layer, and the layer's general composition is specified as sand, gravel, till, stone type, etc.; the material specification does not have the detail required to make an exact

determination of the layer's parameters of hydraulic conductivity, but there is enough information to make an estimate based on previous literature, and to verify information provided in the shape file of the surficial deposits. The Shape file is available for download from the Wisconsin Department of Natural Resources (WDNR) (https://data-wi-dnr.opendata.arcgis.com/datasets/78e4a7348d7849cd9e2b00ef6117df04_0/explore?location=44.766028%2C-89.815361%2C7.51) and is shown in Figure 12a below. Surficial deposits are the unconsolidated materials above the bedrock but below the soil. The soil layer is defined as the material in the first 5 feet below the land surface and were modeled in the SWAT models. The texture and the K values of the surficial deposits affect the rate at which infiltrating water will reach the water table (WDNR 2007). The shape file was used as a guild to digitize three K value zones within the top layer (sand, sand and gravel, and loam) coinciding with zones 1,4, and 5 (Figure 12b). Zone 2 relates to layer 2 (fractured bedrock), and zone 3 relates to layer 3 (unfractured bedrock).

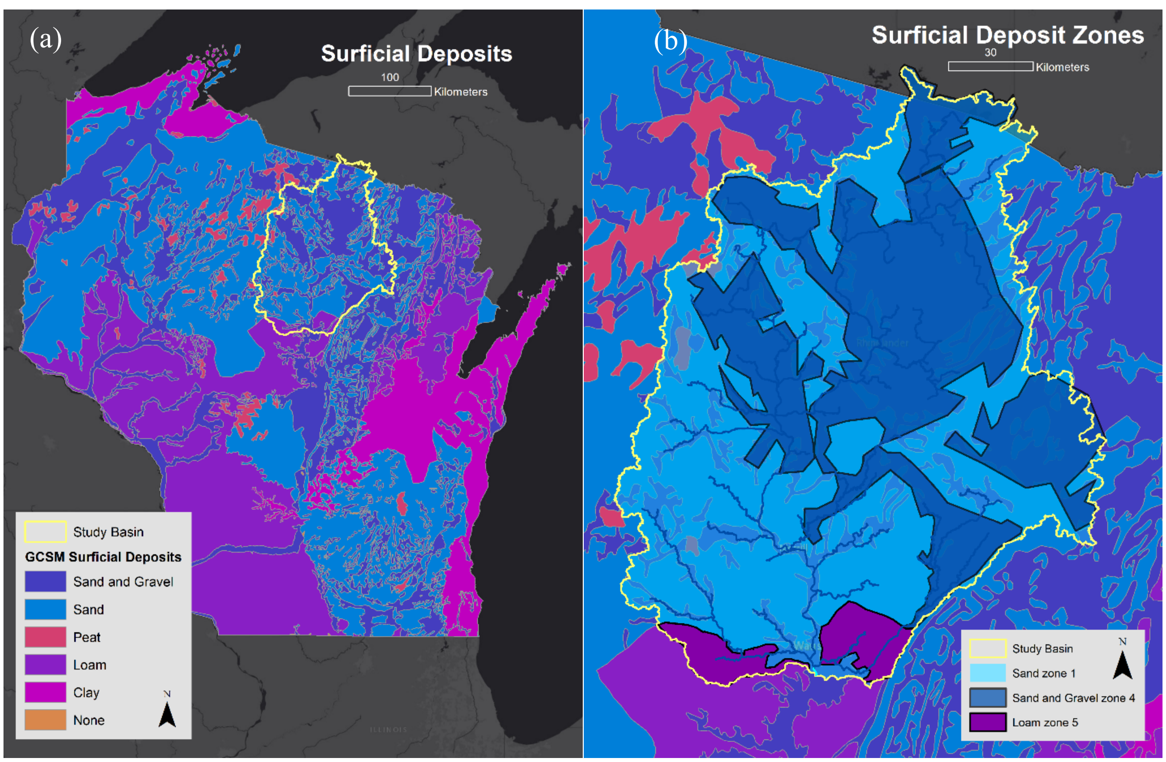


Figure 12 (a) Shape file of the surficial deposits downloaded from the Wisconsin Department of Natural Resources Bureau of Technology Services https://www.arcgis.com/home/item.html?id=ele89ae505594459a46407f1daf4ad5d **(b)** Digitized hydraulic conductivity zones traced from the surficial deposits shape file.

The K values for each hydraulic conductivity zone were estimated from literature. The K values for zones 1–4 are from Batten (1987) (Appendix D), the K value for the loam (zone 5) is from Carsel and Parrish (1988) (Appendix D). Batten (1987) did extensive research on the water resources of Langlade County, which included the hydraulic properties for the aquifer and the confining layer. Batton (1987) tested 10 test wells installed by the USGS for K; values ranged from 0.7–24.1 ft/d (0.21–7.34 m/d) (average 3.78 m/d). Additionally, K was calculated from slug tests performed at 3 irrigation wells in the Antigo flats area; an average K value was found to be 145 ft/d (44.2 m/d). The Table in appendix D summarizes the K values of the aquifer found throughout the county. Batton (1987) also tested 55 wells that are withdrawing water from the Precambrian bedrock. Values ranged from 0.00001 to 34.6 ft/d (3.05×10^{-6}–10.55 m/d). The average for the full depth of the Precambrian bedrock was 3.7 ft/d (1.13 m/d), with an average of 9.7 ft/d (2.96 m/d) in the upper 20ft (6.1 m) of the layer, and an average of 0.05 ft/d (0.015 m/d) for the portion below 150 ft (45.72 m). The initial K values used in the MODFLOW model are summarized in Table 10 below.

4.2.8 Determining withdrawal rate

High-capacity well data for the state of Wisconsin was acquired from the Wisconsin Department of Natural Resources (WDNR) through email correspondence (Smail 2015). In Wisconsin, the number of high-capacity wells (pumping capacity of at least 265 liters per minute) has increased substantially from less than 4,000 in 1983 to over 15,000 in 2017. The state of Wisconsin has only required owners of high-capacity wells to report annual groundwater withdrawal since 2007, and since records are incomplete prior to 2011, only records from 2011–2017 were used for this study. The withdrawal rate is reported in gallons annually but was converted to $m^3\times10^{-5}$ for this study. It should also be noted that the reporting of the annual withdrawal rate is on the honor system and is subject to some inconsistencies. The withdrawal rate from low-capacity wells is generally used to service single family homes with onsite septic systems, therefore

the groundwater is returned on site. These wells make up a small portion of the total water usage in the basin; therefore, they were not included in the models.

The wells in the study areas are a mix of irrigation, industrial, and municipal wells. Municipal wells withdraw groundwater uniformly throughout the year. Industrial wells such as those used to wash gravel at pit operations are semi seasonal, and irrigation wells are only used during the growing season. Only wells with screen depth information were used in the study, of the 373 wells in the study area with both withdrawal rate and screened depth information 309 had recorded use in 2012.Through visual inspection of the graph below (Figure 13), which illustrates the distribution of groundwater withdrawal during the calendar year 2012, it can be observed that the withdrawal rate more than doubles in the months of June through September. Therefore, it can also be hypothesized that a substantial percentage of the wells in both the Wisconsin and the Wolf River Basin are used for irrigation. To calculate a maximum static daily pumping rate the pumping rate for the month with the highest rate (July) is divided by the number of days in the month (31) to get the highest daily rate for 2012 for each high-capacity well. The shape file containing the well locations, screen depths, and calculated static withdrawal rate was imported into GWV7.

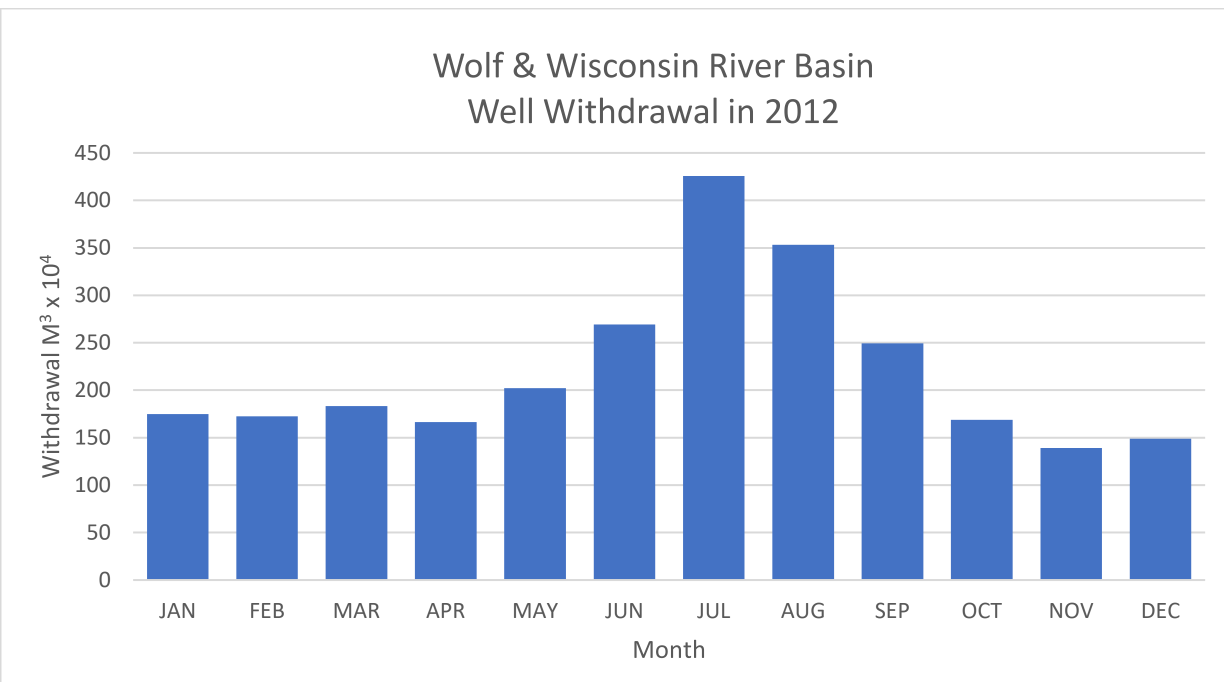


Figure 13 Monthly reported withdrawal rate per WDNR records for the year 2012 within the study area.

4.2.9 Calibrating the model

The calibration was completed with the PEST (Model-Independent Parameter Estimation and Uncertainty Analysis) program also available in GWV7. PEST uses the model's input and output files to adjust the model's parameters to bring the estimated head values as close as possible to supplied target values of observed data (Doherty 2015). The PEST program used the K value parameter in both the horizontal direction (x, y) and the vertical direction (z) for all 5 zones to align estimated head elevations to the 16 target values. The targets were taken from the wells shape file that was filtered for only the wells that were drilled during 2012; 18 wells made up the initial target set. The PEST model did not converge with the 18 targets, two of the targets were outliers, the targets with the highest difference between target head and model head, were removed. PEST was then run on the remaining 16 targets. The PEST program converged, and the K value parameters were adjusted to those listed in Table 9.

Table 10 Hydraulic conductivity values before and after calibration

			Before PEST		After Pest	
Layer	Material	Zone	$K_{x,y}$	K_z	$K_{x,y}$	K_z
1	Sand	1	3.78	0.378	4.4309	0.278597
2	Fractured bedrock	2	2.96	0.296	0.1502	0.01167747
3	Bedrock	3	0.015	.0015	0.331743	.0007279559
1	Sand and gravel	4	44.2	4.42	46.1775	3.09043
1	Loam	5	0.25	0.025	0.250936	0.0253569

4.3 Modeling Scenarios

To model how predicted climate changes and potential increases in high-capacity well withdrawal increases would affect ground-water elevations and streamflows, both models were run four times. The SWAT model 1 was run using the current climate conditions. A second time (model 2) using the future predicted seasonal precipitation values. A third time (model 3) using the future predicted seasonal values for both precipitation and temperature values from the RCP4.5 model. The last model used the future

predicted seasonal values for both precipitation and temperature values from the RCP8.5 model. The MODFLOW model was then run using the current climate SWAT recharge (model 1) and current high-capacity well withdrawal rates. The model was then run a second time using the SWAT recharge rate from model 3. Model 3 was chosen because the RCP 4.5 scenario was assumed to be more accurate due to the downscaling performed for the state. Then the model was run a third time using both recharge from SWAT model 3 and a withdrawal rate three times the current rate. The model was then run a fourth time using the recharge from SWAT model 3, a withdrawal rate three times the current rate, but the high-capacity wells with the highest withdrawal rate were closed. The wells that were chosen to close were those that had a calculated daily flow rate of over 3,000 $m^3 \times 10^{-5}$ and were not municipal wells. Nine wells were found to withdraw over 3,000 $m^3 \times 10^{-5}$ daily, of those nine six were municipal wells in the city of Wausau area leaving 3 irrigation wells to model as closed wells. The SWAT models were compared for both changes in streamflow and in recharge rate; the MODFLOW models were compared for changes in the groundwater elevation.

4.4 Results

4.4.1 SWAT model 2

The results for the four SWAT models that were run on the two adjoining basins exhibited both increases and decreases in recharge and streamflow. The SWAT models for the first run used the current climate scenarios, the second run used the future precipitation projections per the WICCI. and the third and fourth run used both the future precipitation and temperature projections for each basin from the WICCI and esri. When the model used the increased predicted precipitation values in the input weather files (second run); the Wolf River basin showed a 16.74% increase in recharge and a 14.13% increase in the average annual streamflow rate, (Table 11, Figure 14a) and the Wisconsin River basin showed a 15.94% increase in recharge and a 14.63% increase in the average annual streamflow rate (Table 11, Figure 14b). It is interesting to note that the percentage increases to both groundwater recharge and

streamflow rate in both basins, was double that of the projected precipitation percent increase which was an average annual increase of only 7.5%. These increases are expected when the precipitation variable is increased while all the other variables remained constant. Since the other variables (land use, soil type, and temperature) remained constant, evapotranspiration (ET) only increased ≈ 0.7%, leaving all the additional precipitation available for infiltration (recharge, baseflow) or runoff (storm flow).

4.4.2 SWAT model 3

On the other hand, when both increased predicted precipitation and temperature values were used as the input for the weather files decreases in both recharge and streamflow were predicted. The Wolf River basin showed a decline in recharge of 19.63% and a decline of 23.39% in the average annual streamflow, (Table 11, Figure 14a) and the Wisconsin River basin showed a decline in recharge of 17.32% and a decline of 19.33% in the average annual streamflow using the RCP 4.5 model values (third run) (Table 11, Figure 14b). These declines were projected despite the average annual increase in the precipitation rate of 7.5% due to the significant increase in ET. The average annual increased in temperature of ≈ 2.8°C, related to a projected increase in ET of 104.8 mm/yr. (≈ 24.7%) for the Wolf River basin and 100.1 mm/yr. (≈ 22.0%) for the Wisconsin River basin, over the increase seen for the precipitation alone. The increase in ET reduced the available precipitation for infiltration or runoff by an amount over the projected increase in annual precipitation decreasing both recharge and streamflow for both basins.

4.4.3 SWAT model 4

When the RCP 8.5 model values (forth run) were used the declines in both recharge and streamflow were less than those predicted when using the RCP 4.5 model values. The Wolf River basin showed a decline in recharge of 16.48% and a decline of 20.96% in the average annual streamflow (Table 11, Figure 14a)., and the Wisconsin River basin showed a decline in recharge of 16.95% and a decline of

19.33% in the average annual streamflow (Table 11, Figure 14b). Changes in ET were mixed, in the Wolf River basin ET decreased from the run using RCP 4.5 to the run using RCP 8.5 from 528.3 mm/yr. to 518.6 mm/yr., while ET increased in the Wisconsin River basin from 555.1 mm/yr to 559.1 mm/yr. These mixed results were due to the difference in the scale the future climate changes were predicted. The RCP 4.5 predictions were down scaled for the state of Wisconsin by the WICCI, while the RCP 8.5 values were mapped from global predictions by esri. This difference in scaling resulted in higher winter daily minimum temperature increase predictions for the RCP 4.5 models (3.89 °C) than for the RCP 8.5 values (3.25 °C) (Table 9), this difference may explain the mixed results for the model runs but is beyond the scope of this study.

Table 11 Results of 4 SWAT model runs for the Wolf River Basin and the Wisconsin River Basin

Basin	Precip. (mm/yr)	ET (mm/yr)	Recharge (mm/yr)	% Change	Streamflow (m^3/s)	% Change
Wolf River	744.4	420.7	130.23	0.0	10.26	0.0
WoR Future Precipitation	789.4	423.5	152.03	16.74	11.71	14.13
WoR Future P & T RCP 4.5	789.4	528.3	104.66	−19.63	7.86	−23.39
WoR Future P & T RCP 8.5	789.4	518.6	108.76	−16.48	8.11	−20.96
Wisconsin River	790.6	452.0	160.67	0.0	95.42	0.0
WiR Future Precipitation	839.1	455.0	186.28	15.94	109.38	14.63
WiR Future P & T RCP 4.5	839.1	555.1	132.84	−17.32	76.98	−19.33
WiR Future P & T RCP 8.5	839.1	559.1	133.44	−16.95	76.98	−19.33

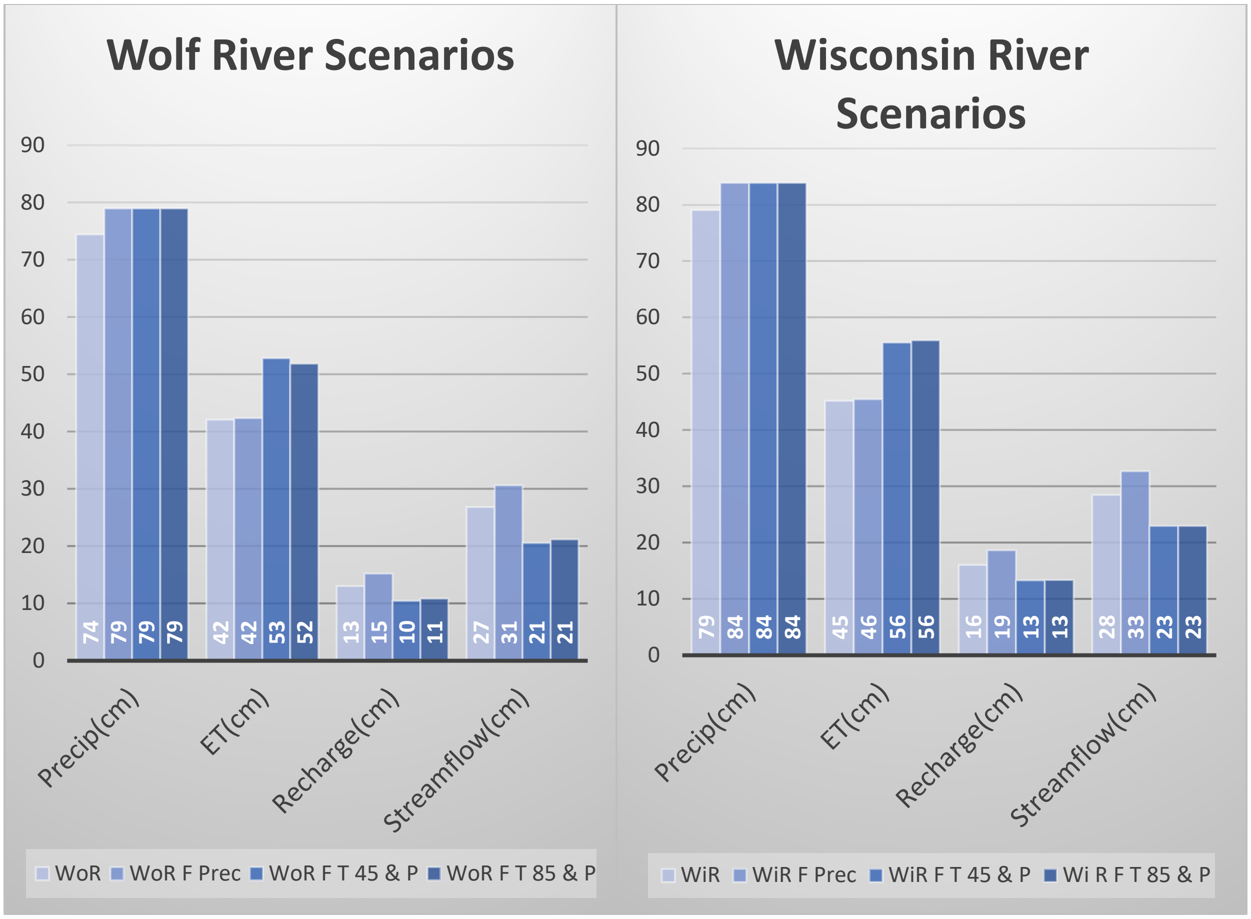


Figure 14 (a) results of four SWAT model runs for the Wolf River basin in cm. annually. **(b)** Results of four SWAT model runs for the Wisconsin River basin in cm annually.

4.4.4 Overview MODFLOW models

The results for the four MODFLOW models for the study area (the combined Wisconsin and Wolf River basins) exhibited groundwater elevation decreases related to both climate and anthropogenic stresses. The first run (model 1) used the current climate recharge results from the first SWAT model. The second run (model 2) used the future predicted climate recharge rate from the third SWAT model (RCP4.5). The third run (model 3) used both the future predicted climate recharge rate and the potential increased high-capacity flow rate of three times the current rate. The withdrawal rate was increased three times to simulate the rate increase over the last three decades. The fourth model run (model 4) predicted the effect of closing 3 high-capacity irrigation wells in the future after the threefold increase.

4.4.5 Difference between MODFLOW model 2 and model 1

The mean decline in hydraulic head, which was contributed to a change in climate over five and half decades (1995–2050) (model 2 – model 1), is 2.9 meters (Table 12). The decline is evenly distributed across the study area, with some higher declines seen near the no flow boundaries to the north and west, and some areas of increased hydraulic head near the basin outlet in the southern part of the study area (Figure 15). The relatively uniform decline in hydraulic head was expected because the only change between model 1 and model 2 was the recharge rate, all other variables remained constant. The recharge rate percent decrease in the 2 zones, representing the 2 individual basins, was close with a 19.63% decrease predicted in the Wolf River basin and a 17.32% decrease predicted in the Wisconsin River basin. The greater declines to the north and west, and the increases exhibited at the outlet of the Wisconsin River were not expected and are assumed to be related to the use of the no-flow boundary for the model.

4.4.6 Difference between MODFLOW model 3 and model 2

The mean additional change in hydraulic head, which was contributed to a potential three-fold increase in the withdrawal rate from high-capacity wells over the same period (1995–2050) (model 3 – model 2), was an increase of ≈ 0.4 meters (Table 12). This slight increase however is across the entire study area; there are significant declines in hydraulic head seen in areas near clusters of high-capacity wells specifically in an area called the Antigo flats. The Antigo flats are located in the southeast portion of the study area, the area is intensely farmed and irrigated to produce potatoes. Most of these declines are between 0.5 meters and 3 meters (Figure 16a). There are also increases in hydraulic head observed at the outlet of the Wisconsin River and these again are assumed to be related to the use of the no-flow boundary for the model. The increases per the model were as high 630.4 meters which is unrealistic in this study area. The increases were not investigated in this study as the increases above 50 meters amounted to only 0.28% of the cells in the study.

4.4.7 Difference between MODFLOW model 4 and model 2

The last model run predicted the mean additional change in hydraulic head, which was contributed to a potential three-fold increase in the withdrawal rate from high-capacity wells, but with the closing of 3 high-capacity wells, over the same period (1995–2050) (model 4 – model 2). The result was also an increase of ≈ 0.4 meters across the entire study area (Table 12). The same increases in hydraulic head were noted in this model as in the prior model. However, the maximum declines were mitigated from ≈ 43.3 meters to ≈ 42.8 meters a difference of 0.5 meters and the declines around the cluster of wells in the southeastern portion of the study area, in the Antigo Flats, were significantly mitigated (Figure 16aa, 15bb). This shows that the closure of even a small number of high-capacity wells, 3 in this study, can make a significant impact on groundwater elevation.

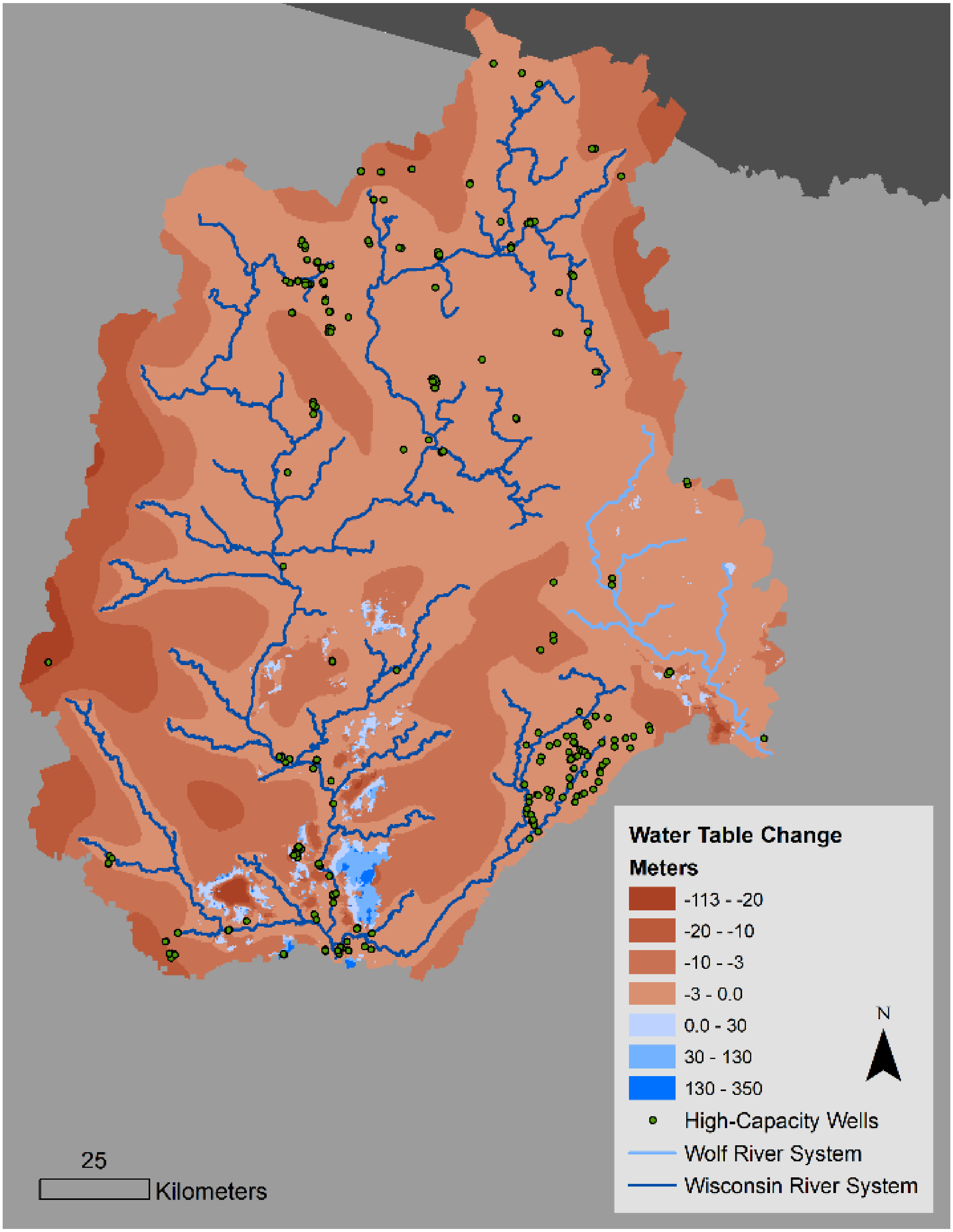


Figure 15 Difference in hydraulic head measured in meters between the MODFLOW models 2 and 1, due to a predicted change in the climate.

Table 12 Change in hydraulic head (in meters) between model 2 and model 1, between model 3 and model 2, and between model 4 and model 2

	Head elevation change between models 2 and 1	Additional change with 3x withdrawal between models 3 and 2 in meters	Additional change with 3x withdrawal and closure of 3 wells between models 4 and 2
Maximum increase	349.6	630.4	630.4
Maximum decline	−113.3	−43.3	−42.8
Mean	−2.9	0.4	0.4
Standard Deviation	9.5	7.5	7.5

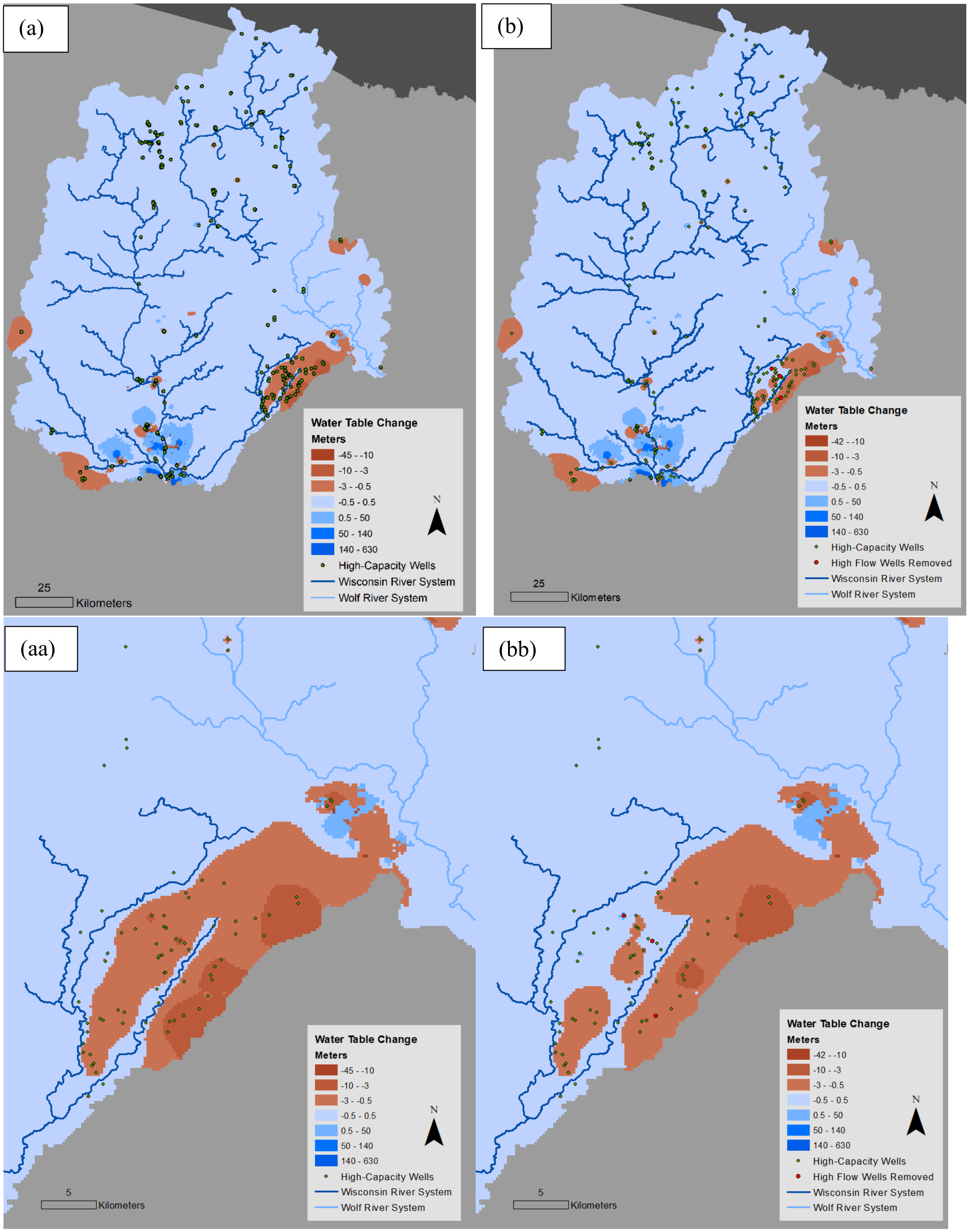


Figure 16 (a), (aa) Difference in hydraulic head measured in meters between the MODFLOW models 3 and 2, due to potential increases in groundwater withdrawal. **(b), (bb)** Difference in hydraulic head measured in meters between the MODFLOW models 4 and 2, due to potential increase in groundwater withdrawal and the closure of 3 high-capacity wells.

4.5 Discussion

This study combines the results of two hydrological models to predict the combined effects of climate change and predicted increases in agricultural irrigation. The results of the SWAT model which used climate change predictions to model future recharge rates were used as input data for the MODFLOW model which then used simulated increases in groundwater withdrawals to predict changes in hydraulic head.

The study found the predicted recharge rates in both the Wolf River basin and the Wisconsin River basin increased if only the predicted increases in precipitation were taken into consideration. But these increases were more than offset when the predicted increases in temperature were added to the SWAT model. The increased temperatures resulted in increased rates of ET in both basins which translated to decreased recharge rates which was expected. The finding that ET would increase with the predicted changes in the climate is consistent with the finding from Shaw et al. (2013) for New York and Illinois. Shaw et al. (2013) also found that the linkage between ET and baseflow was negligible, but this study suggests otherwise. However, the ET rate being lower (518.6 mm/year versus 528.3 mm/year) when using the RCP 8.5 scenario versus the RCP 4.5 scenario, was not expected for the Wolf River basin. The ET values for the Wisconsin River basin were slightly higher for the RCP 8.5 scenario as expected, but the recharge rate unexpectedly rose slightly despite the ET increase. A potential explanation for the unexpected results is that the RCP 8.5 temperature predictions were not downscaled for the state, nor were they broken down by season, therefore some assumptions had to be used in determining the values for daily minimum and maximum temperature increases per season.

The MODFLOW model then used the outputs from the SWAT model (recharge rates and stream segment elevations) to predict changes in hydraulic head due to both climate change and changes in the withdrawal rate from high-capacity wells. When the model was run using the predicted recharge rate after the predicted change in climate from the RCP 4.5 scenario, the hydraulic head decreased by ≈ 2.9 meters versus the MODFLOW model using the recharge rate which had used the current climate statistics. Both

runs before and after climate change used the current high-capacity withdrawal rates and all other variables also remained the same. This decline is in agreement with studies completed by Malekinezhad and Banadkooki (2018). The next MODFLOW model run incorporated an increase in the withdrawal rate of the high-capacity wells, the rate was increased 3-fold to mimic the increase that has been observed over the last three decades. The mean increase in hydraulic head of ≈ 0.4 meters was not expected, but the declines observed around the high-capacity wells, most notably in the Antigo flats area mimic those seen in the Central Sands (Weeks and Stangland 1971, Kraft et al. 2012). The mitigation of the maximum decline from 43.3 meters to 42.8 meters in the study basin when only three of the high-capacity wells were removed from the study suggests we can selectively reduce withdrawal rates to manage the groundwater resource (Malekinezhad and Banadkooki 2018). Additionally, the study suggests that the groundwater resource can be managed without having to implement an all-out ban on agriculture irrigation and that finding a stainable groundwater use rate is possible.

4.6 Conclusion

The study found recharge rate and groundwater elevation decreases due to predicted climate changes. The recharge rates decreased by an average of 18% (RCP4.5), and an average of 17% (RCP8.5). The reduced recharge rates translated to groundwater elevation decreases of approximately 3 meters across the study area. These decreases were larger around high-capacity wells when pumping rates were increased three times. The study also predicted that some of these decreases can be mitigated by abandoning just a select number of high withdrawing wells. This research yielded knowledge of the role of simultaneous hydrologic stresses, both natural and anthropogenic, on both streamflow and hydraulic head. More specifically the study showed that predicted increases in temperate due to climate change over the next several decades will lead to decreases in the available fresh water in the study area. These decreases to both groundwater and surface water are despite the predicted increases in precipitation over the same time frame. Further loses in the resource will be expected if the growth in the use of high-capacity wells continues at its current growth rate. The study also found that substantial savings of this

resource can be managed by selectively reducing the number of wells allowed to operate. This study highlights how rising temperatures along with an increased use of groundwater for agricultural irrigation could decrease Wisconsin's available groundwater resources despite increasing precipitation projected over the next several decades. The results will be useful for water resource managers and hydrologists interested in balancing the permitting of high-capacity wells for agricultural production and preserving streamflow, in a state where the climate is expected to change. This study highlights that a balance of the state's groundwater resources will need to be found between the state's agricultural, recreational, and environmental needs.

CHAPTER 5 CONCLUSIONS

5.1 Summary

Concerns have been raised from a variety of stake holders from environmentalists to agricultural growers about the diminished flows in many of the state's gauged streams. Although the stake holders and resource managers generally agree that groundwater withdrawal and climate variables affect both groundwater levels and streamflow, there is disagreement as to the degree each play. Studies have explored the relationship between high-capacity irrigation wells and declines in streamflow, studies have also found that environmental stresses are related to declines in groundwater levels. But these studies have concentrated on the effects, to the hydrological system, from either climate change or the groundwater withdrawals, not both simultaneously. This three-part study investigated how climate variables and human activity affect surface water and groundwater in Wisconsin at different spatial and temporal scales, using regression analysis and computer modeling. The study investigated the impact that climate change and high-capacity wells have on both groundwater levels and streamflows to better understand the groundwater-surface water system. The study further seeks to find a method to balance the interests between environmental protection and agricultural needs.

Chapter 2 of the study found that the baseflow trend over the study period (1984–2014) was spatially separated between declining baseflows in northern Wisconsin and increasing baseflows in the southern portion of the state; and that twenty out of thirty-five basins exhibited a deviation in the slope when the cumulative value of precipitation was plotted against the cumulative value of baseflow, suggesting an anthropogenic variable was affecting baseflows, most likely groundwater withdrawals. Chapter 3 adopted several regression methods (four different categories of panel data analysis (PDA) and simple linear regression) to determine the extent that groundwater withdrawals and climate variables affect streamflow and to determine if baseflows could be accurately predicted using analytic methods. The study found that the climate variables (precipitation and temperature) were significant in explaining

the temporal variability of baseflow, whereas land cover and the drainage conditions were important in explaining the spatial variability of baseflow but a reliable analytic model to predict baseflow was not found and it was suggested that a process-based modeling approach would be necessary. Lastly in chapter 4 this research employed two hydrological process-based computer modeling approaches to combine the effects of both climate change and groundwater withdrawals on groundwater elevations and stream baseflow. One model (SWAT) to model the surface water flow and the other (MODFLOW) to model the groundwater flow. The models looked at the relationship between surface water and groundwater in the WRB in northeastern Wisconsin. The study found recharge rate and groundwater elevation decreases due to both predicted climate changes and predicted increases in groundwater withdrawals.

Overall, the study showed that although analytically the most important variable in determining the variability of streamflow is the amount of annual precipitation, the modeling portion of the study showed that it was the predicted increases in temperate, due to climate change over the next several decades, which will ultimately lead to decreases in the available fresh water in the study area. Although analytically the study could not determine if high-capacity wells are affecting freshwater reserves, the computer models determined that if the escalating use of irrigation for Wisconsin's agriculture outpaces the increases in annual precipitation, declines in stream baseflow will result. The study also predicted that some of these decreases can be mitigated by abandoning just a select number of high withdrawing wells, therefore, a balance of this resource will need to be found.

5.2 Contributions

Knowledge from this study will both add to science's understanding of hydrological processes and provide scientific basis for policy makers to determine how the permitting of additional high-capacity irrigation wells will affect the baseflow of streams within basins across the state of Wisconsin. The study also found that climate variables such as precipitation and temperate affect groundwater differently in different locations for example the drainage condition is an important variable in determining baseflow

rate in basins over unconfined aquifers, while land use was an important variable in determining the baseflow rate in basins over unconfined aquifers. This knowledge will be useful for water resource managers and hydrologists interested in balancing the permitting of high-capacity wells for agricultural production and preserving streamflow, in a state where the climate is expected to change.

Secondly, this study highlights how rising temperatures along with an increased use of groundwater for agricultural irrigation could decrease Wisconsin's available groundwater resources despite increasing precipitation projected over the next several decades. By incorporating the use of two hydrological models this study was able to simulate changes in hydrology within a single basin from both predicted climate changes and potential increases to the groundwater withdrawal rate. The combined models will give policy makers the ability to project water resource saving that can be accomplished by selectively reducing the number of wells allowed to operate in select areas, while allowing others to potentially increase if necessary to insure the success of agriculture within the basin.

5.3 Future Research

Future research should include the simultaneous stresses to the groundwater-surface water system from both environmental and anthropogenic sources. As seen in this study the environmental variables, more specifically Wisconsin's predicted climate changes of greater annual precipitation and greater mean temperatures put stresses on the hydrological system in two different directions, and the effects differ further based on the land information variables. Additionally, the withdrawal rate affects the basin differently based on well location in respect to the land information and proximity to each other.

The predictive ability of both the analytic and computer simulation models should improve in reliability as land information such as land use, drainage class, available storage, and slope become available in a greater and greater resolution; and the availability of historical withdrawal data becomes more extensive. Additionally, improvements in predictive ability will be achieved when the study data is broken down into small time units. The current study used annual data for a preliminary look at the future

trend of freshwater availability. By refining the data into seasonal or monthly time frames, the data should reveal a more refined view of how the variables affect groundwater stores.

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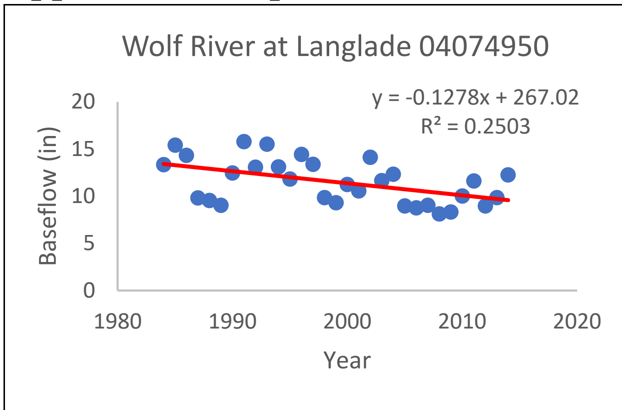
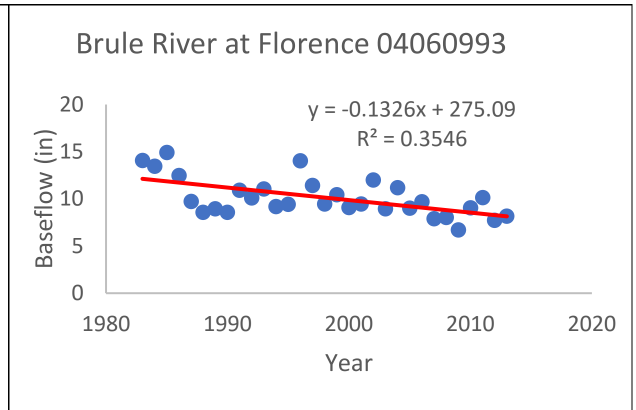
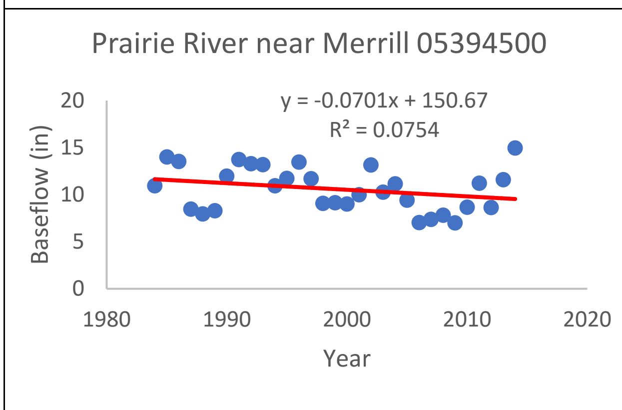
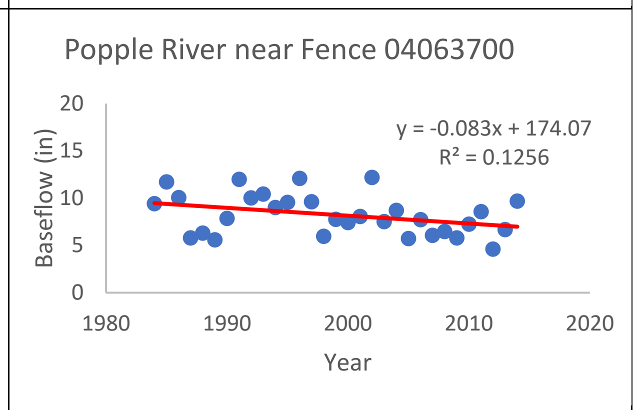
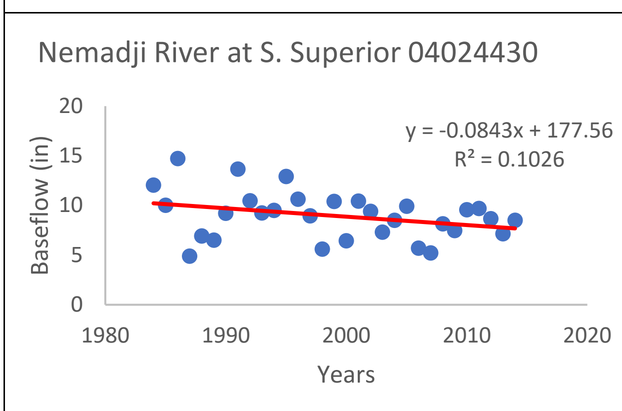
Appendix A Graphs of 36 Basin Baseflows Across Years 1984–2014

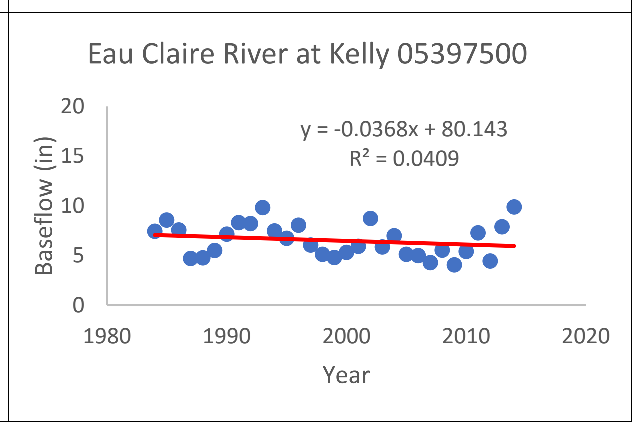


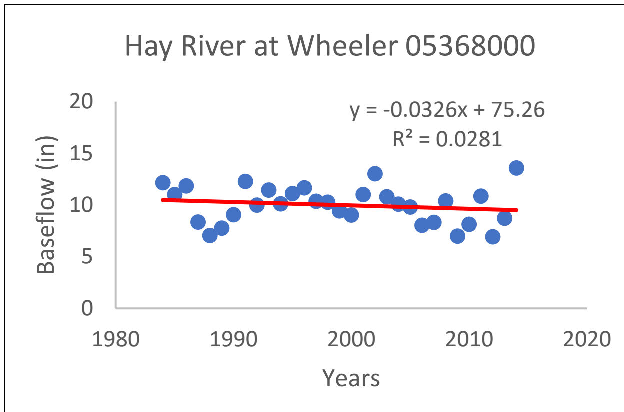


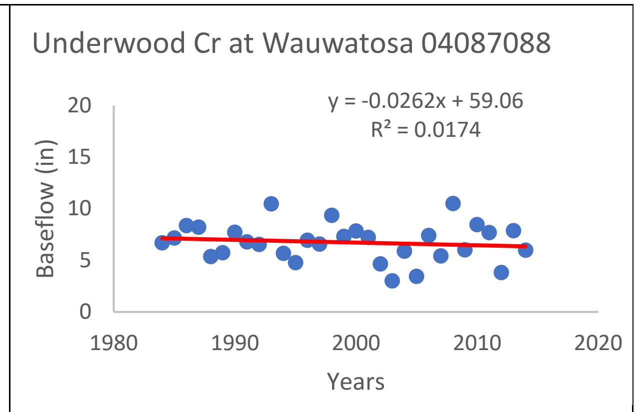


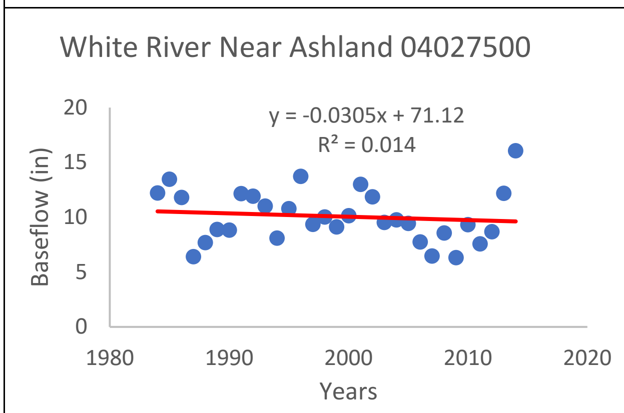


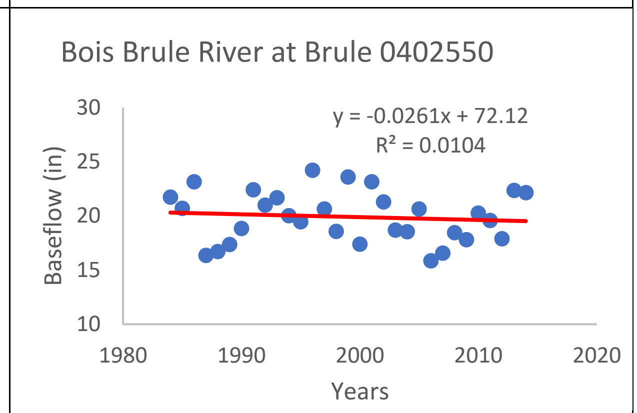


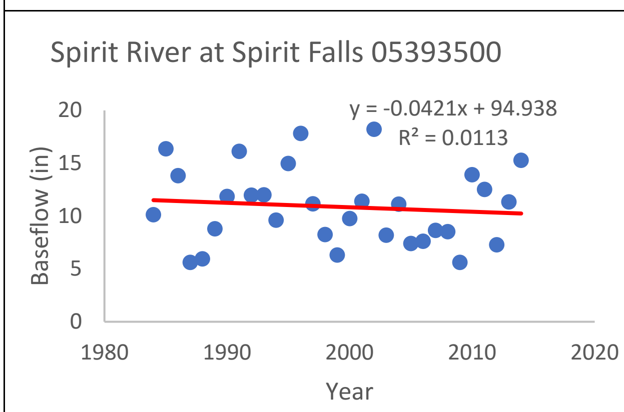


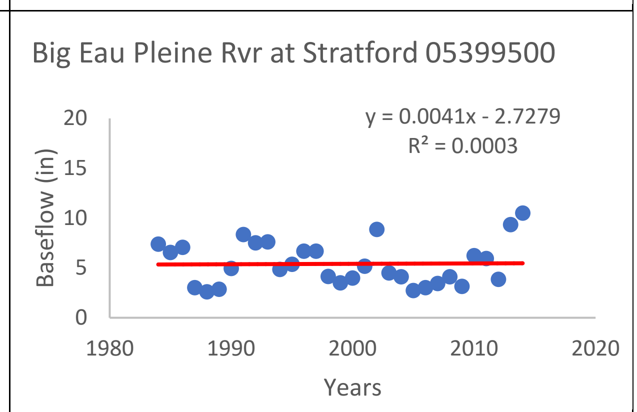

Hay River at Wheeler 05368000
y = -0.0326x + 75.26
R² = 0.0281
Baseflow (in)
0
5
10
15
20
1980
1990
2000
2010
2020
Years

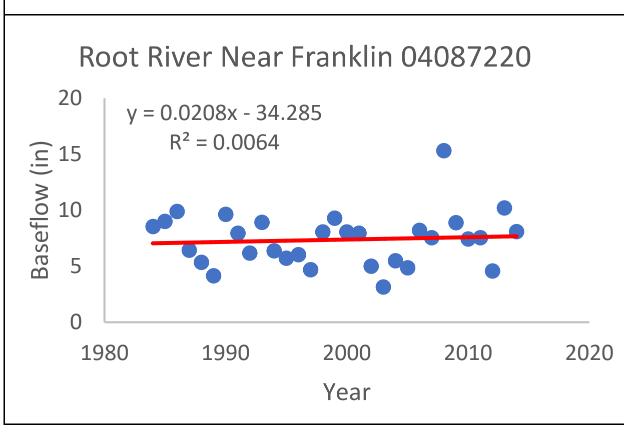

Underwood Cr at Wauwatosa 04087088
y = -0.0262x + 59.06
R² = 0.0174
Baseflow (in)
0
5
10
15
20
1980
1990
2000
2010
2020
Years

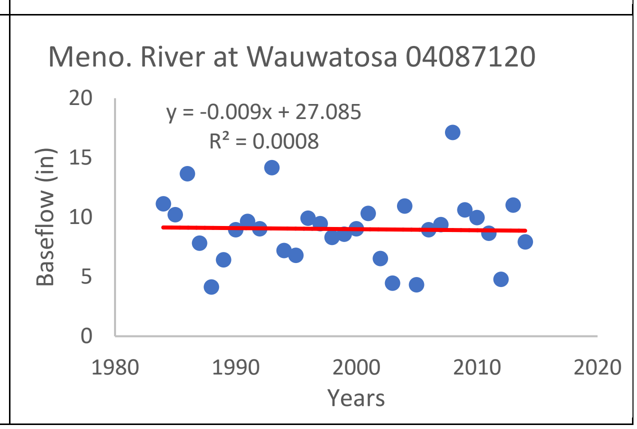

White River Near Ashland 04027500
y = -0.0305x + 71.12
R² = 0.014
Baseflow (in)
0
5
10
15
20
1980
1990
2000
2010
2020
Years

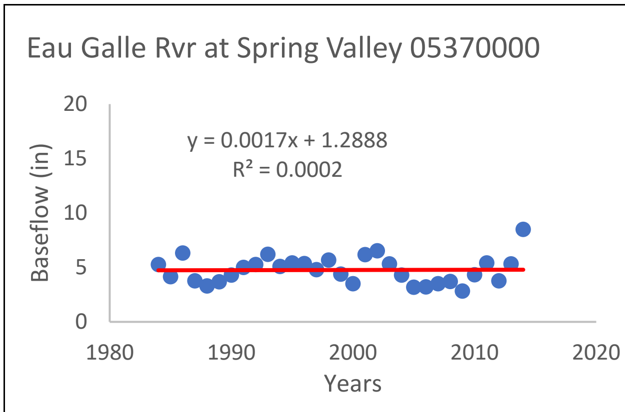

Bois Brule River at Brule 0402550
y = -0.0261x + 72.12
R² = 0.0104
Baseflow (in)
10
15
20
25
30
1980
1990
2000
2010
2020
Years

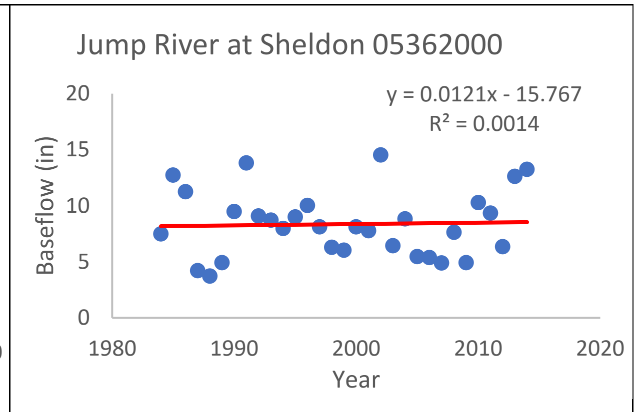

Spirit River at Spirit Falls 05393500
y = -0.0421x + 94.938
R² = 0.0113
Baseflow (in)
0
5
10
15
20
1980
1990
2000
2010
2020
Year

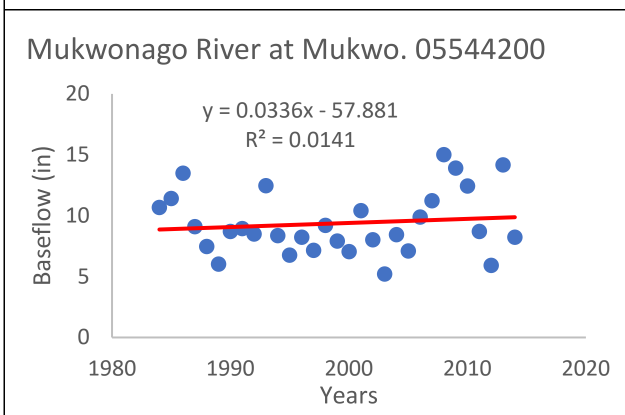

Big Eau Pleine Rvr at Stratford 05399500
y = 0.0041x - 2.7279
R² = 0.0003
Baseflow (in)
0
5
10
15
20
1980
1990
2000
2010
2020
Years

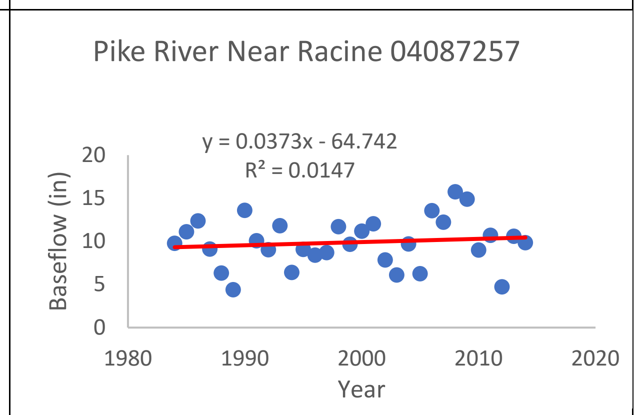

Root River Near Franklin 04087220
y = 0.0208x - 34.285
R² = 0.0064
Baseflow (in)
0
5
10
15
20
1980
1990
2000
2010
2020
Year

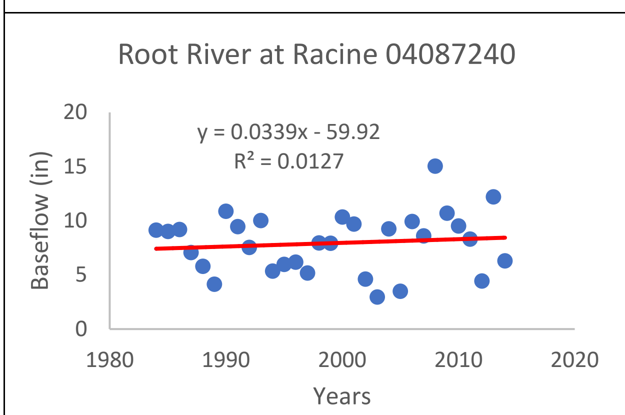

Meno. River at Wauwatosa 04087120
y = -0.009x + 27.085
R² = 0.0008
Baseflow (in)
0
5
10
15
20
1980
1990
2000
2010
2020
Years

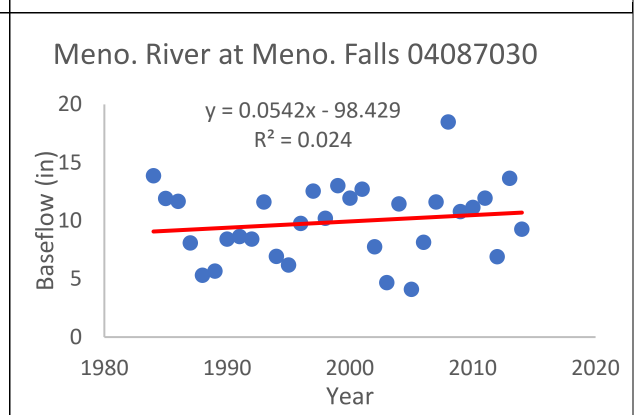

Eau Galle Rvr at Spring Valley 05370000
y = 0.0017x + 1.2888
R² = 0.0002
Baseflow (in)
0
5
10
15
20
1980
1990
2000
2010
2020
Years

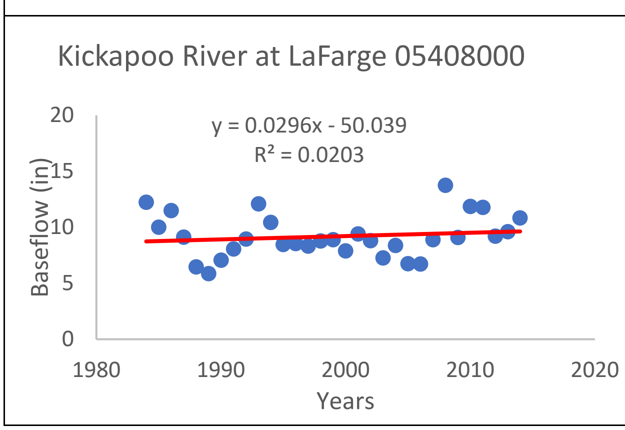

Jump River at Sheldon 05362000
y = 0.0121x - 15.767
R² = 0.0014
Baseflow (in)
0
5
10
15
20
1980
1990
2000
2010
2020
Year

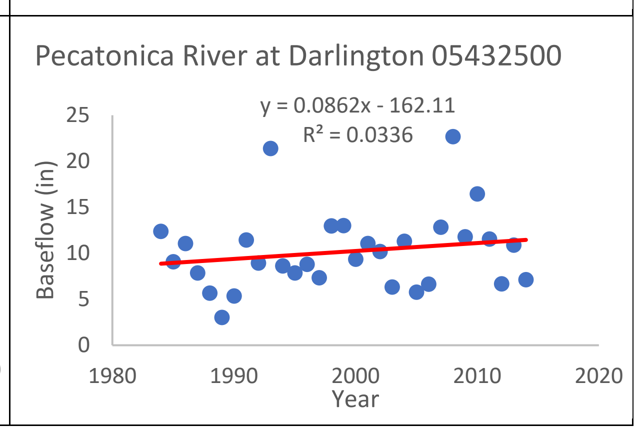

Mukwonago River at Mukwo. 05544200
y = 0.0336x - 57.881
R² = 0.0141
Baseflow (in)
0
5
10
15
20
1980
1990
2000
2010
2020
Years

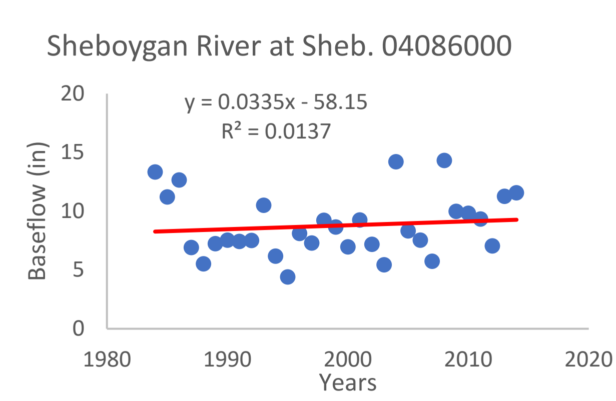

Pike River Near Racine 04087257
y = 0.0373x - 64.742
R² = 0.0147
Baseflow (in)
0
5
10
15
20
1980
1990
2000
2010
2020
Year

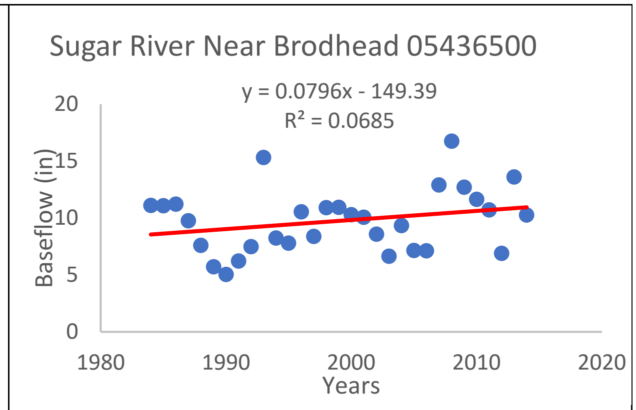

Root River at Racine 04087240
y = 0.0339x - 59.92
R² = 0.0127
Baseflow (in)
0
5
10
15
20
1980
1990
2000
2010
2020
Years

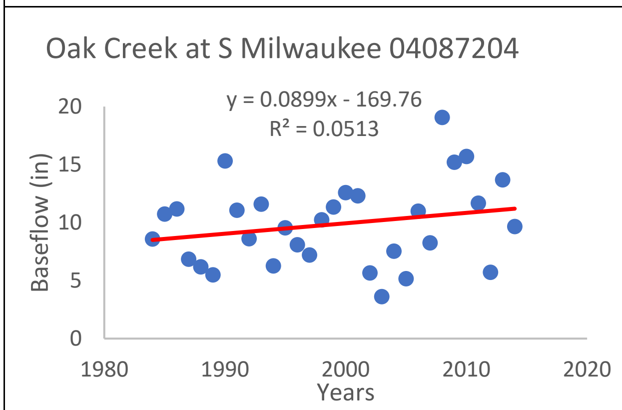

Meno. River at Meno. Falls 04087030
y = 0.0542x - 98.429
R² = 0.024
Baseflow (in)
0
5
10
15
20
1980
1990
2000
2010
2020
Year

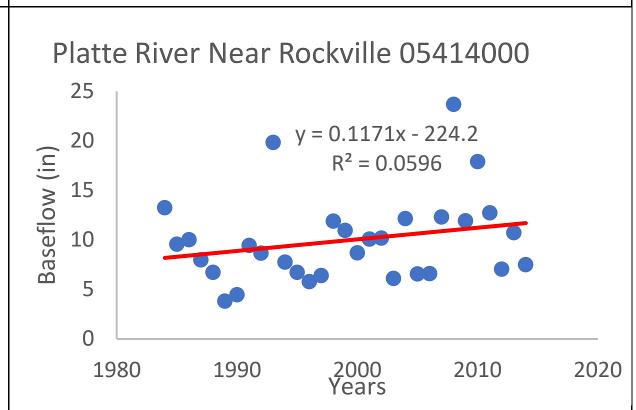

Kickapoo River at LaFarge 05408000
y = 0.0296x - 50.039
R² = 0.0203
Baseflow (in)
0
5
10
15
20
1980
1990
2000
2010
2020
Years

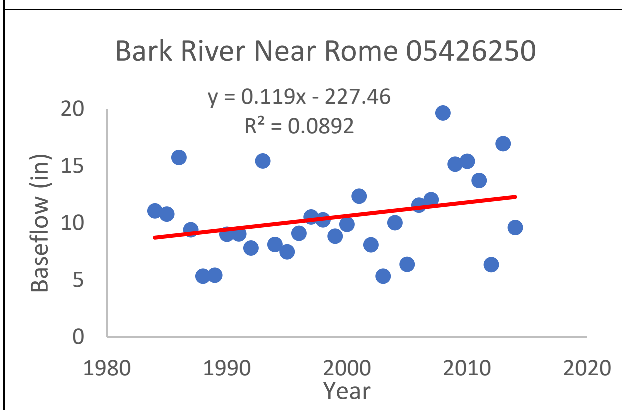

Pecatonica River at Darlington 05432500
y = 0.0862x - 162.11
R² = 0.0336
Baseflow (in)
0
5
10
15
20
25
1980
1990
2000
2010
2020
Year

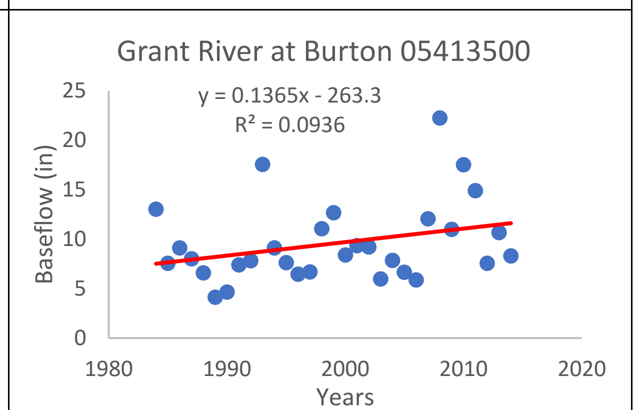

Sheboygan River at Sheb. 04086000
y = 0.0335x - 58.15
R^2 = 0.0137
Baseflow (in)
Years
0
5
10
15
20
1980
1990
2000
2010
2020

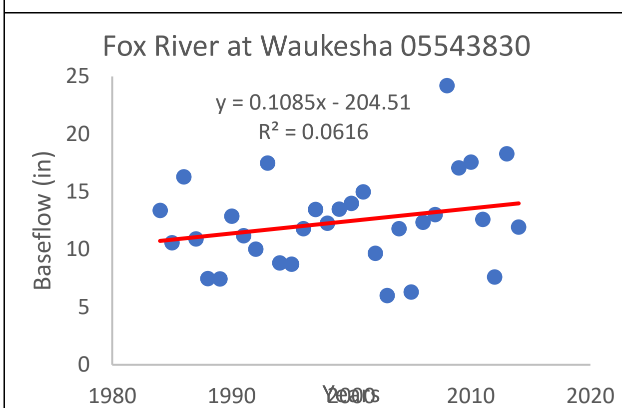

Sugar River Near Brodhead 05436500
y = 0.0796x - 149.39
R^2 = 0.0685
Baseflow (in)
Years
0
5
10
15
20
1980
1990
2000
2010
2020

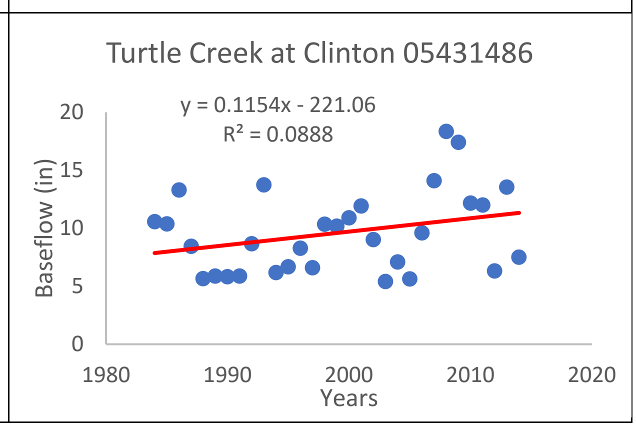

Oak Creek at S Milwaukee 04087204
y = 0.0899x - 169.76
R^2 = 0.0513
Baseflow (in)
Years
0
5
10
15
20
1980
1990
2000
2010
2020

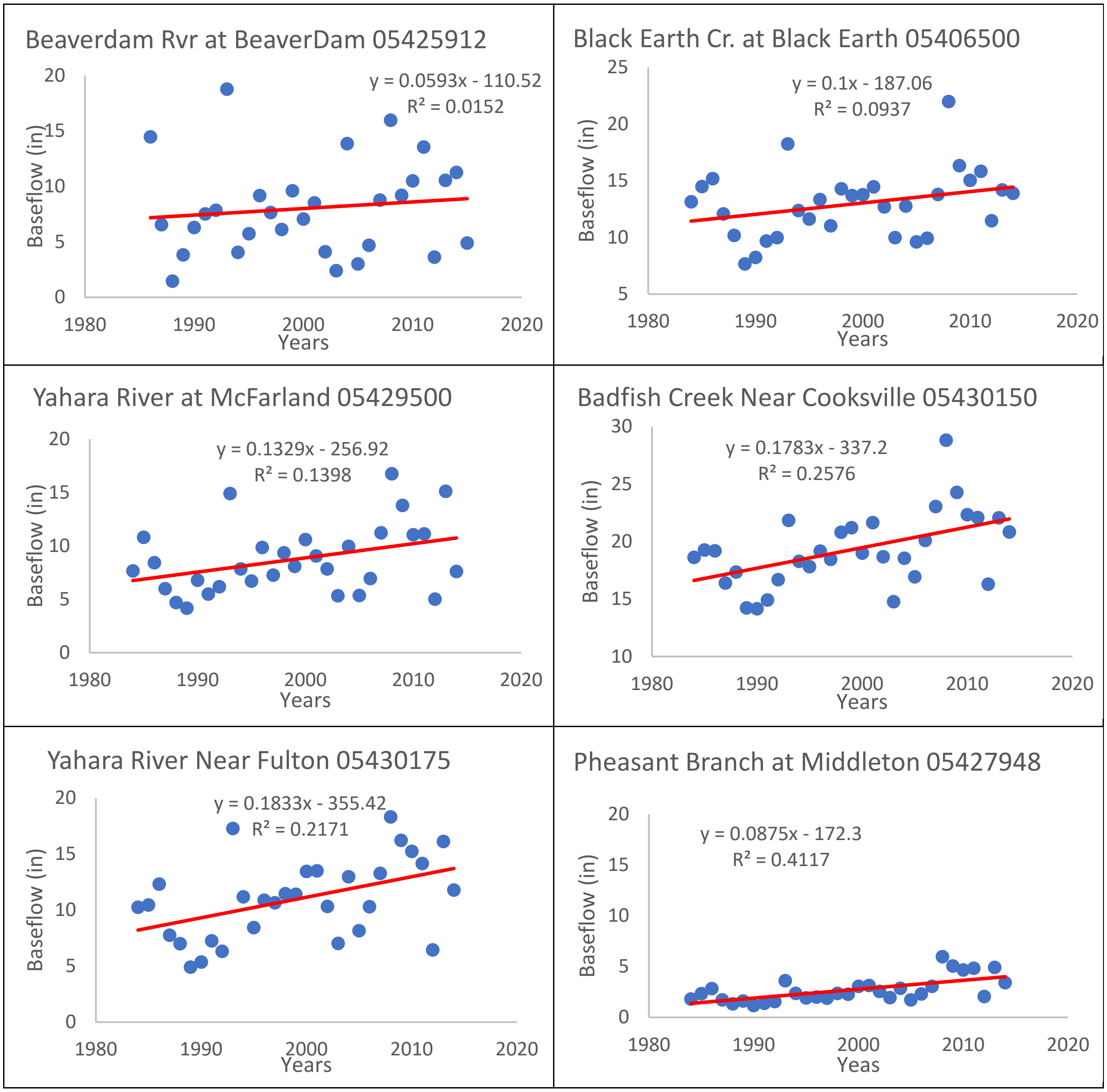

Platte River Near Rockville 05414000
y = 0.1171x - 224.2
R^2 = 0.0596
Baseflow (in)
Years
0
5
10
15
20
25
1980
1990
2000
2010
2020


Bark River Near Rome 05426250
y = 0.119x - 227.46
R^2 = 0.0892
Baseflow (in)
Year
0
5
10
15
20
1980
1990
2000
2010
2020


Grant River at Burton 05413500
y = 0.1365x - 263.3
R^2 = 0.0936
Baseflow (in)
Years
0
5
10
15
20
25
1980
1990
2000
2010
2020


Fox River at Waukesha 05543830
y = 0.1085x - 204.51
R^2 = 0.0616
Baseflow (in)
Years
0
5
10
15
20
25
1980
1990
2000
2010
2020


Turtle Creek at Clinton 05431486
y = 0.1154x - 221.06
R^2 = 0.0888
Baseflow (in)
Years
0
5
10
15
20
1980
1990
2000
2010
2020

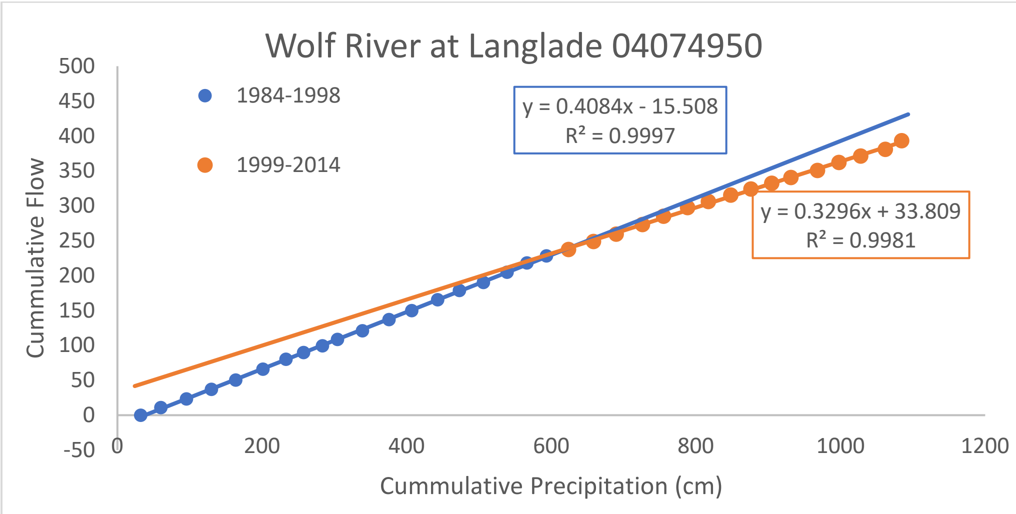

Beaverdam Rvr at BeaverDam 05425912
y = 0.0593x - 110.52
R² = 0.0152
Baseflow (in)
Years
Black Earth Cr. at Black Earth 05406500
y = 0.1x - 187.06
R² = 0.0937
Baseflow (in)
Years
Yahara River at McFarland 05429500
y = 0.1329x - 256.92
R² = 0.1398
Baseflow (in)
Years
Badfish Creek Near Cooksville 05430150
y = 0.1783x - 337.2
R² = 0.2576
Baseflow (in)
Years
Yahara River Near Fulton 05430175
y = 0.1833x - 355.42
R² = 0.2171
Baseflow (in)
Years
Pheasant Branch at Middleton 05427948
y = 0.0875x - 172.3
R² = 0.4117
Baseflow (in)
Yeas

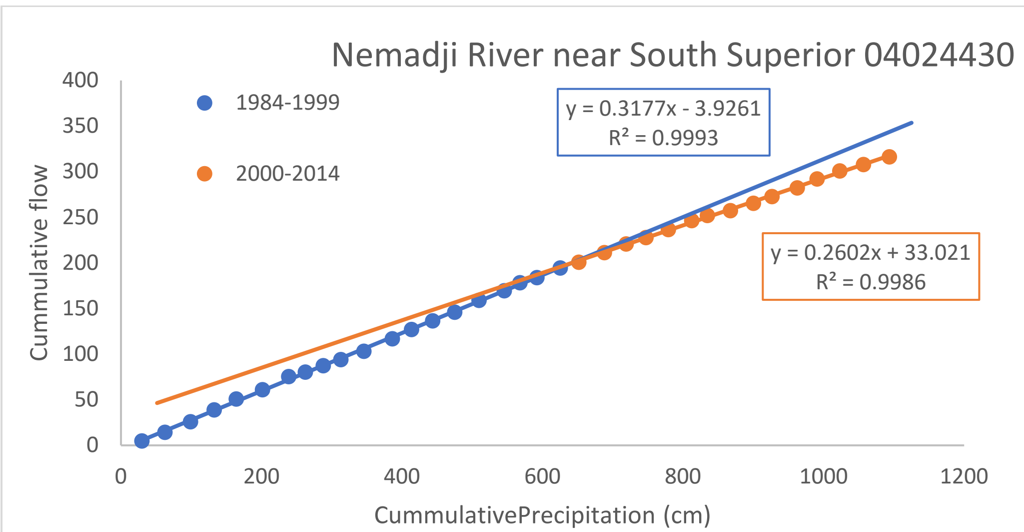
Appendix B Percent Slope of Regression Line Between Baseflow and Years

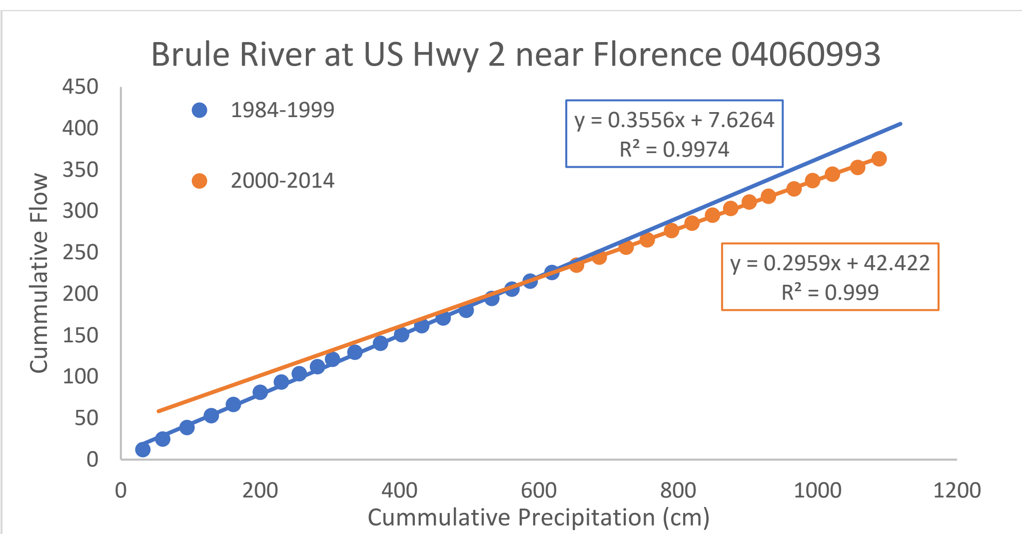
Percent slope of regression line between annual baseflow and time in years, Kendall's Tau and Pearson's correlation and their significance as calculated by the statistical computer program SPSS by IBM.

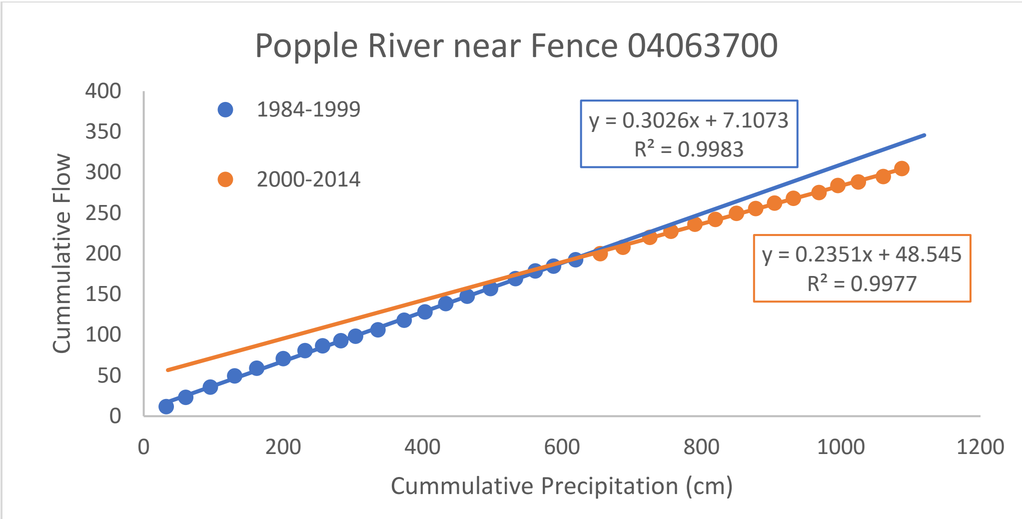
Station ID	Station Name	Percent Change	Kendall Tau	Sig.	Pearson	Sig.	Levene Sig.
04074950	WOLF RIVER AT LANGLADE, WI	−28.47	−0.355	0.005	−0.5	0.004	0
04060993	BRULE RIVER AT US HWY 2 FLORENCE, WI	−27.54	−0.306	0.016	−0.511	0.003	0
05394500	PRAIRIE RIVER NEAR MERRILL, WI	−18.14	−0.23	0.069	−0.275	0.135	0
04063700	POPPLE RIVER NEAR FENCE, WI	−0.79	−0.23	0.069	−0.354	0.05	0
04024430	NEMADJI RIVER NEAR SOUTH SUPERIOR,	−24.53	−0.213	0.092	−0.32	0.079	0
05397500	EAU CLAIRE RIVER AT KELLY, WI	−15.48	−0.202	0.169	−0.174	0.275	0
05368000	HAY RIVER AT WHEELER, WI	−9.24	−0.168	0.179	−0.17	0.368	
04087088	UNDERWOOD CREEK AT WAUWATOSA, WI	−11.10	−0.132	0.671	−0.054	0.479	0
04027500	WHITE RIVER NEAR ASHLAND, WI	−8.63	−0.118	0.215	−0.157	0.527	
04025500	BOIS BRULE RIVER AT BRULE, WI	−3.85	−0.102	0.475	−0.09	0.585	
05393500	SPIRIT RIVER AT SPIRIT FALLS, WI	−11.07	−0.084	0.507	−0.106	0.57	0
05399500	BIG EAU PLEINE RIVER AT STRATFORD,	2.28	−0.052	0.683	0.017	0.927	
04087220	ROOT RIVER NEAR FRANKLIN, WI	8.94	−0.032	0.799	0.08	0.669	
04087120	MENOMONEE RIVER AT WAUWATOSA, WI	−2.93	−0.029	0.932	−0.011	0.877	
05370000	EAU GALLE RIVER AT SPRING VALLEY, WI	1.09	−0.022	0.865	0.013	0.946	0
05362000	JUMP RIVER AT SHELDON, WI	4.41	−0.017	0.892	0.037	0.842	
05544200	MUKWONAGO RIVER AT MUKWONAGO, WI	11.48	0.011	0.932	0.119	0.524	
04087257	PIKE RIVER NEAR RACINE, WI	12.08	0.054	0.671	0.121	0.515	
04087240	ROOT RIVER AT RACINE, WI	13.86	0.067	0.598	0.113	0.547	
04087030	MENOMONEE RIVER AT MENO. FLS, WI	17.86	0.082	0.518	0.155	0.405	
05408000	KICKAPOO RIVER AT LA FARGE, WI	10.22	0.105	0.405	0.142	0.444	
05432500	PECATONICA RIVER AT DARLINGTON, WI	29.02	0.105	0.405	0.183	0.323	.072
04086000	SHEBOYGAN RIVER AT SHEBOYGAN, WI	12.09	0.117	0.308	0.129	0.531	
05436500	SUGAR RIVER NEAR BRODHEAD, WI	27.97	0.131	0.3	0.262	0.155	0
04087204	OAK CREEK AT SOUTH MILWAUKEE, WI	30.78	0.14	0.269	0.226	0.221	
05414000	PLATTE RIVER NEAR ROCKVILLE, WI	43.23	0.166	0.191	0.244	0.186	0
05426250	BARK RIVER NEAR ROME, WI	41.34	0.177	0.163	0.299	0.103	0
05413500	GRANT RIVER AT BURTON, WI	54.48	0.177	0.163	0.306	0.094	.001
05543830	FOX RIVER AT WAUKESHA, WI	30.27	0.178	0.158	0.248	0.178	0
05431486	TURTLE CREEK AT CLINTON, WI	43.86	0.196	0.122	0.298	0.103	0
05425912	BEAVERDAM RIVER AT BEAVER DAM, WI	24.95	0.202	0.124	0.178	0.357	
05406500	BLACK EARTH CREEK AT BLACK EARTH,	26.46	0.207	0.103	0.306	0.094	0
05429500	YAHARA RIVER AT MC FARLAND, WI	59.04	0.258	0.041	0.374	0.038	0
05430150	BADFISH CREEK NEAR COOKSVILLE, WI	32.33	0.342	0.007	0.508	0.004	0
05430175	YAHARA RIVER NEAR FULTON, WI	66.68	0.342	0.007	0.466	0.008	.002
05427948	PHEASANT BRANCH AT MIDDLETON, WI	201.92	0.463	0	0.642	0	

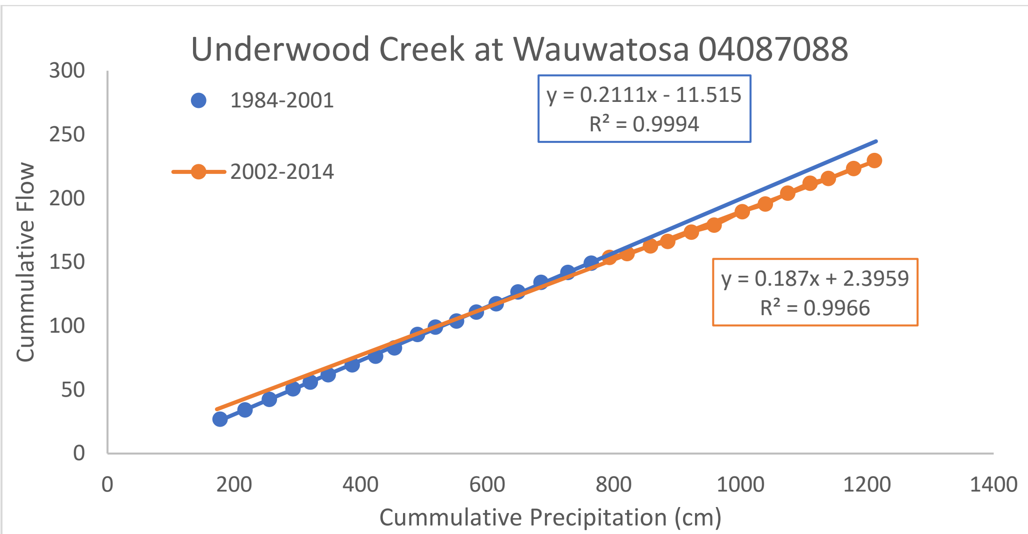
Appendix C Double Mass Curve Analysis Graphs for 20 Wisconsin Basins

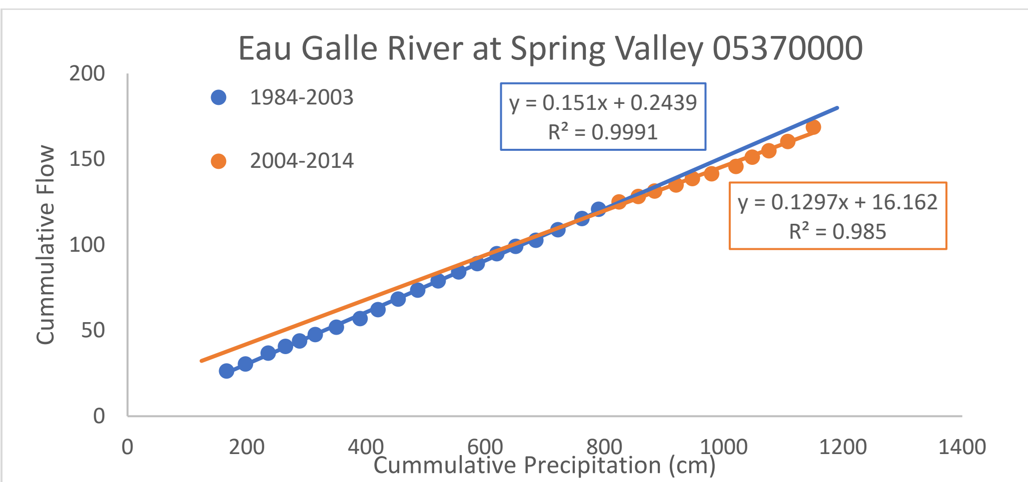


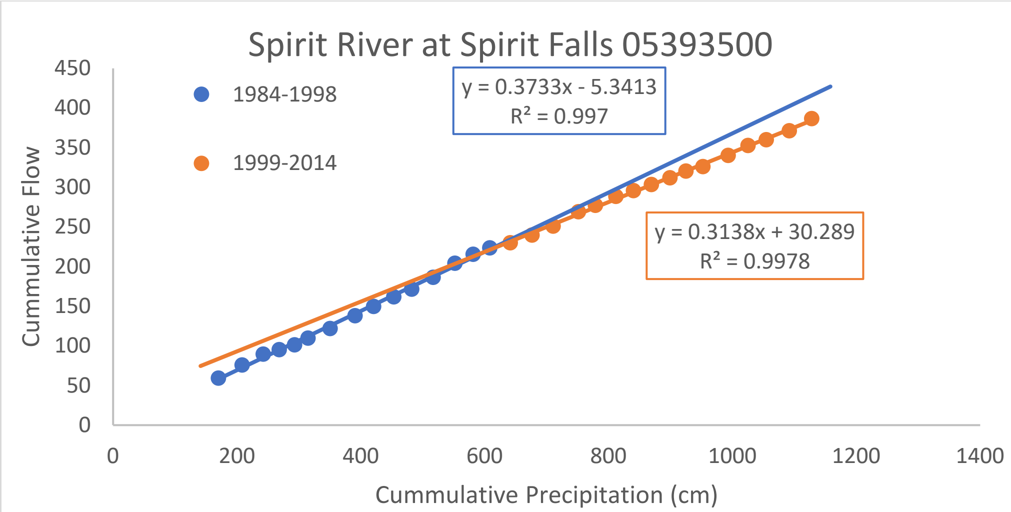


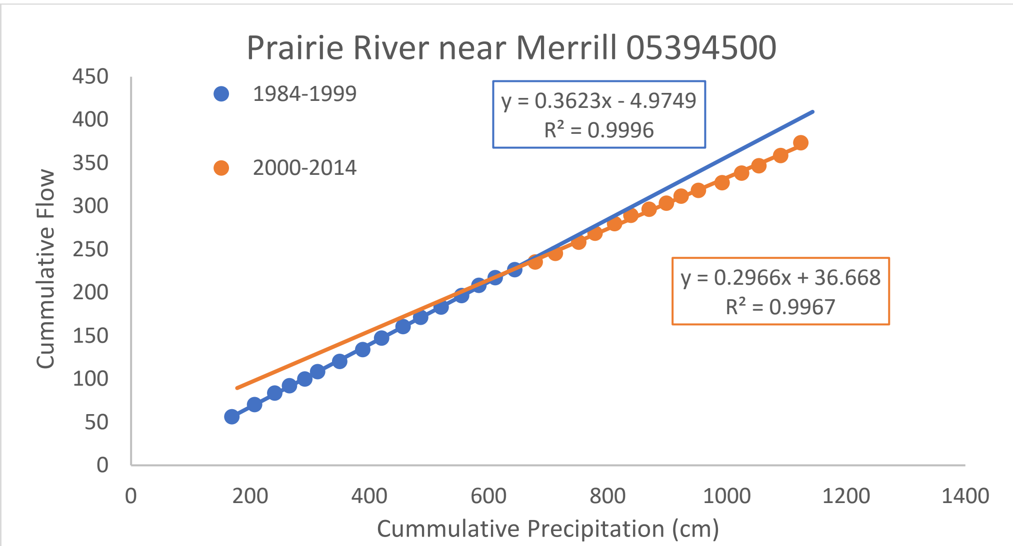


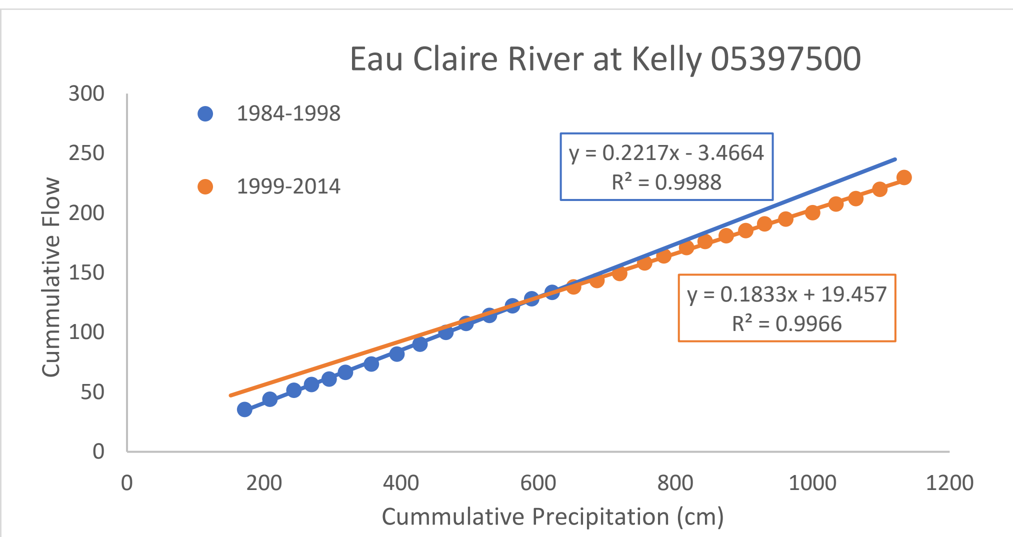

Popple River near Fence 04063700
1984-1999
2000-2014
y = 0.3026x + 7.1073
R² = 0.9983
y = 0.2351x + 48.545
R² = 0.9977
Cummulative Flow
Cummulative Precipitation (cm)
0
50
100
150
200
250
300
350
400
0
200
400
600
800
1000
1200

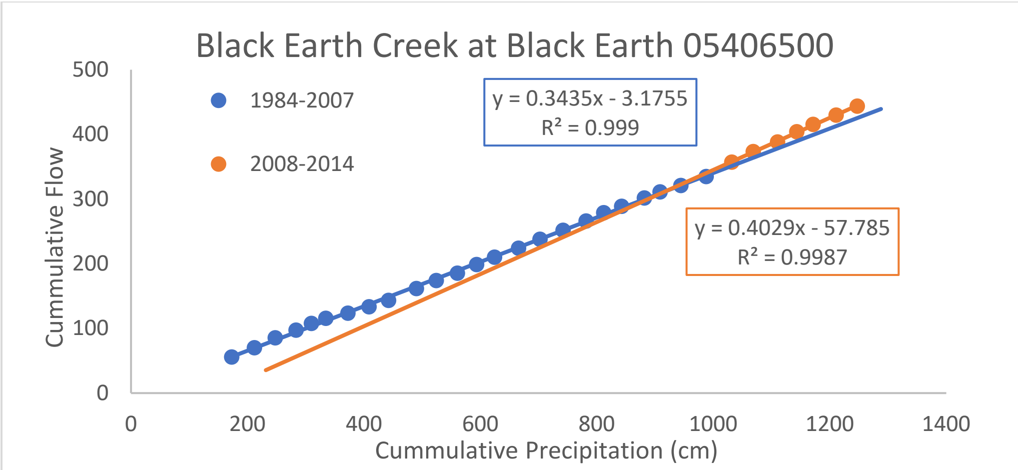

Underwood Creek at Wauwatosa 04087088
1984-2001
2002-2014
y = 0.2111x - 11.515
R² = 0.9994
y = 0.187x + 2.3959
R² = 0.9966
Cummulative Flow
Cummulative Precipitation (cm)
0
50
100
150
200
250
300
0
200
400
600
800
1000
1200
1400

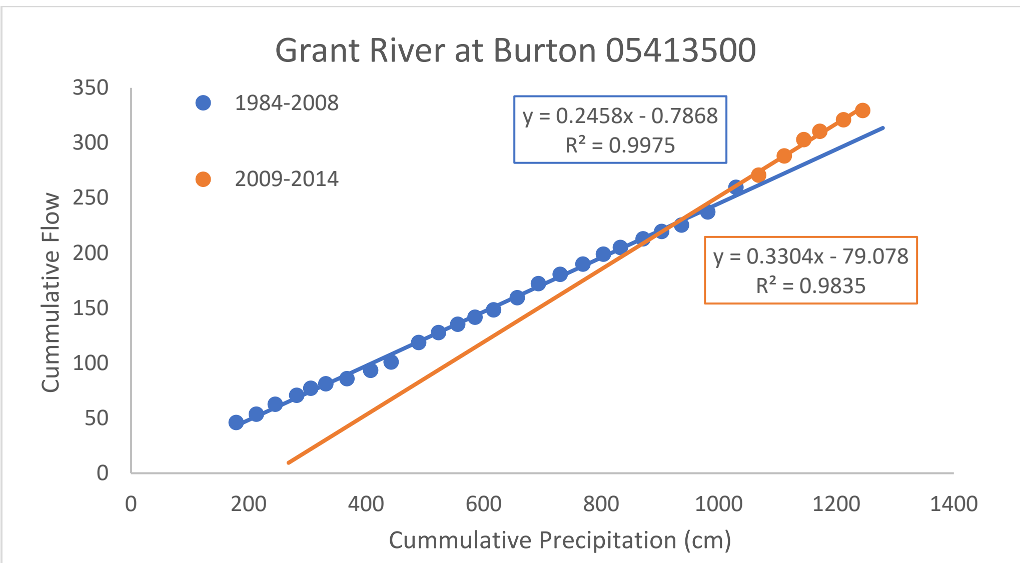

Eau Galle River at Spring Valley 05370000
1984-2003
2004-2014
y = 0.151x + 0.2439
R² = 0.9991
y = 0.1297x + 16.162
R² = 0.985
Cummulative Flow
Cummulative Precipitation (cm)
0
50
100
150
200
0
200
400
600
800
1000
1200
1400

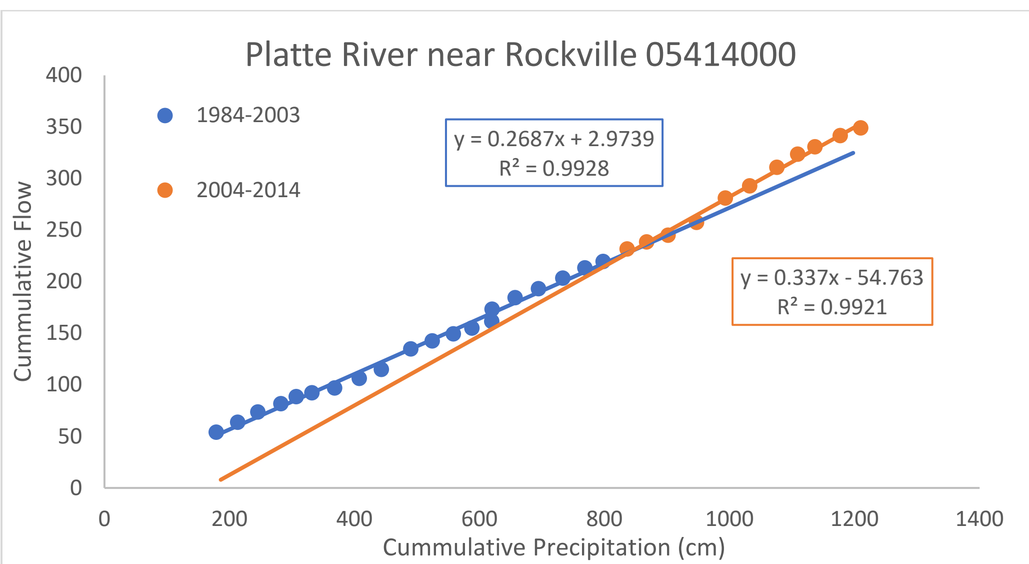

Spirit River at Spirit Falls 05393500
1984-1998
1999-2014
y = 0.3733x - 5.3413
R² = 0.997
y = 0.3138x + 30.289
R² = 0.9978
Cummulative Flow
Cummulative Precipitation (cm)
0
50
100
150
200
250
300
350
400
450
0
200
400
600
800
1000
1200
1400

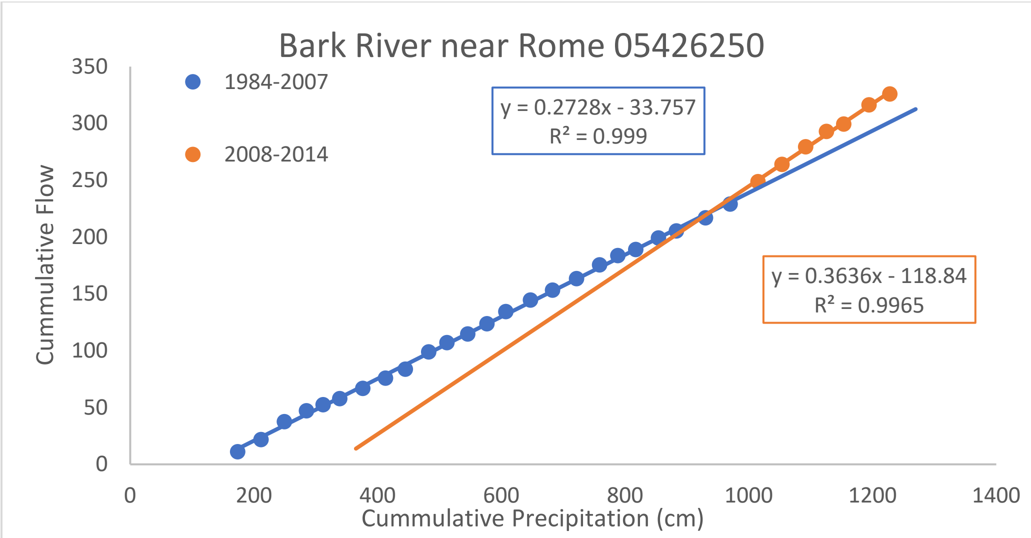

Prairie River near Merrill 05394500
1984-1999
2000-2014
y = 0.3623x - 4.9749
R² = 0.9996
y = 0.2966x + 36.668
R² = 0.9967
Cummulative Flow
Cummulative Precipitation (cm)
0
50
100
150
200
250
300
350
400
450
0
200
400
600
800
1000
1200
1400

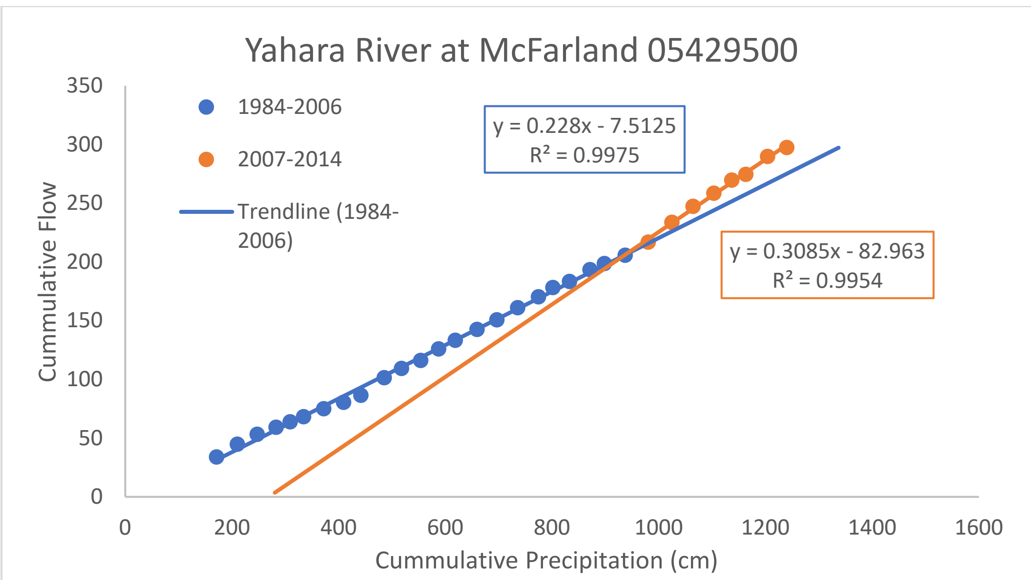

Eau Claire River at Kelly 05397500
1984-1998
1999-2014
y = 0.2217x - 3.4664
R² = 0.9988
y = 0.1833x + 19.457
R² = 0.9966
Cummulative Flow
Cummulative Precipitation (cm)
0
50
100
150
200
250
300
0
200
400
600
800
1000
1200

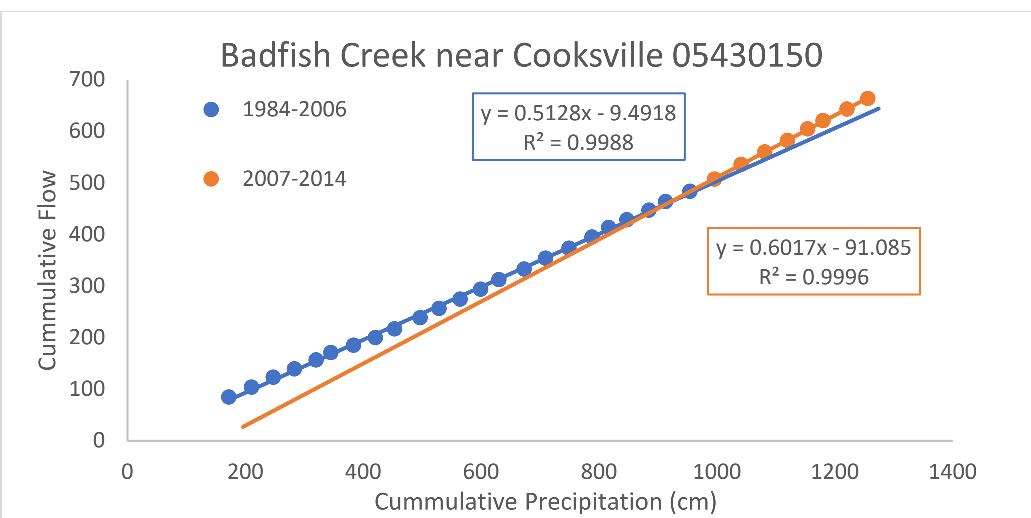

Black Earth Creek at Black Earth 05406500
1984-2007
2008-2014
y = 0.3435x - 3.1755
R² = 0.999
y = 0.4029x - 57.785
R² = 0.9987
Cummulative Flow
Cummulative Precipitation (cm)
0
100
200
300
400
500
0
200
400
600
800
1000
1200
1400

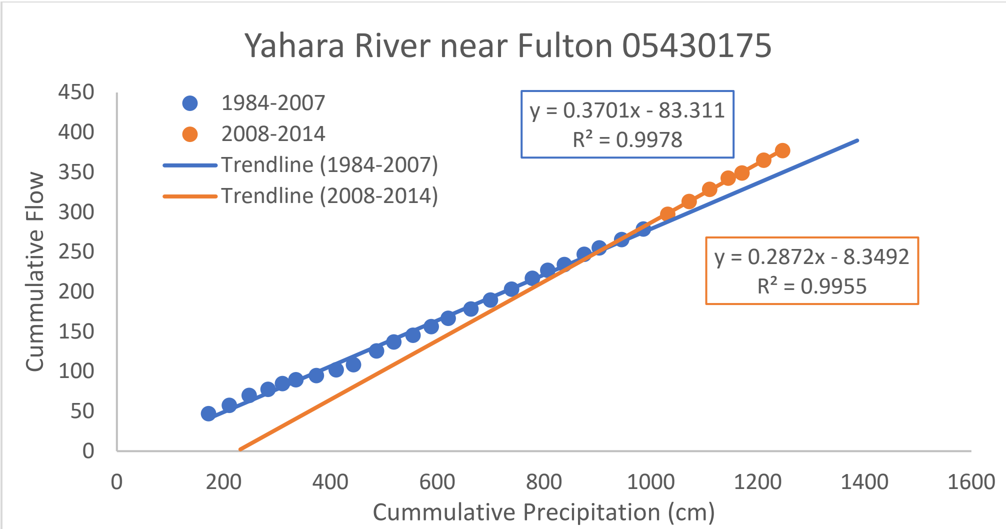

Grant River at Burton 05413500
1984-2008
2009-2014
y = 0.2458x - 0.7868
R² = 0.9975
y = 0.3304x - 79.078
R² = 0.9835
Cummulative Flow
Cummulative Precipitation (cm)
0
50
100
150
200
250
300
350
0
200
400
600
800
1000
1200
1400

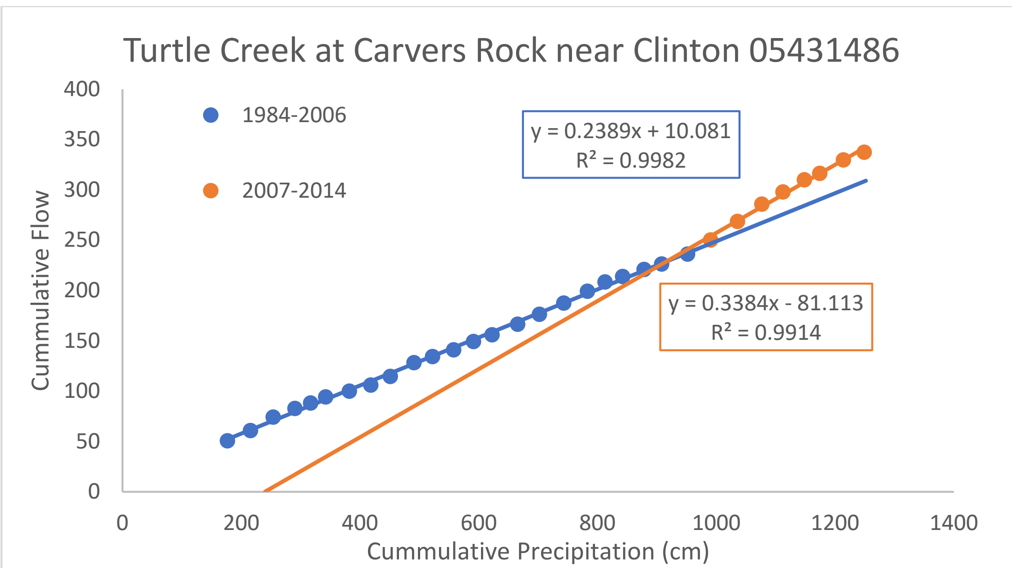

Platte River near Rockville 05414000
1984-2003
2004-2014
y = 0.2687x + 2.9739
R² = 0.9928
y = 0.337x - 54.763
R² = 0.9921
Cummulative Flow
Cummulative Precipitation (cm)
0
50
100
150
200
250
300
350
400
0
200
400
600
800
1000
1200
1400

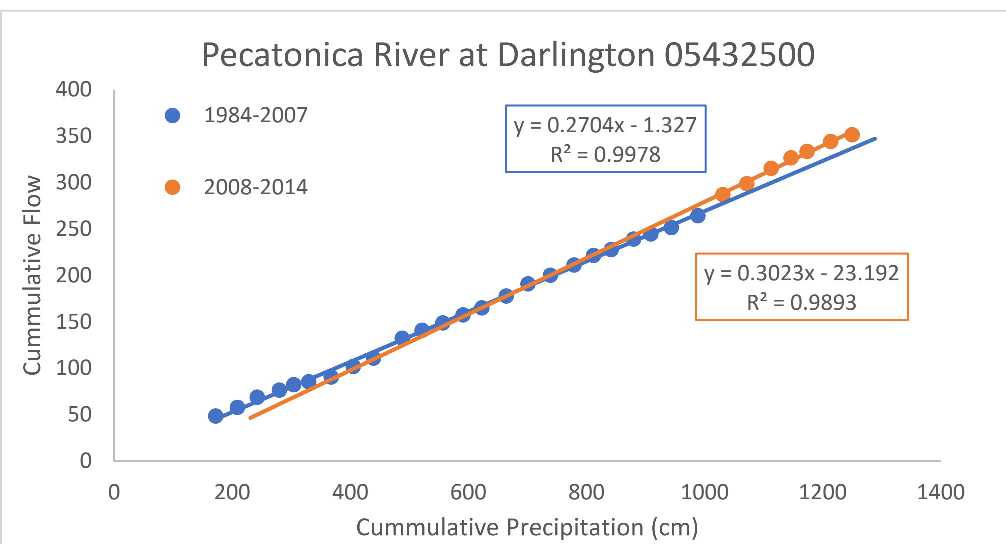

Bark River near Rome 05426250
1984-2007
2008-2014
y = 0.2728x - 33.757
R² = 0.999
y = 0.3636x - 118.84
R² = 0.9965
Cummulative Flow
Cummulative Precipitation (cm)
0
50
100
150
200
250
300
350
0
200
400
600
800
1000
1200
1400

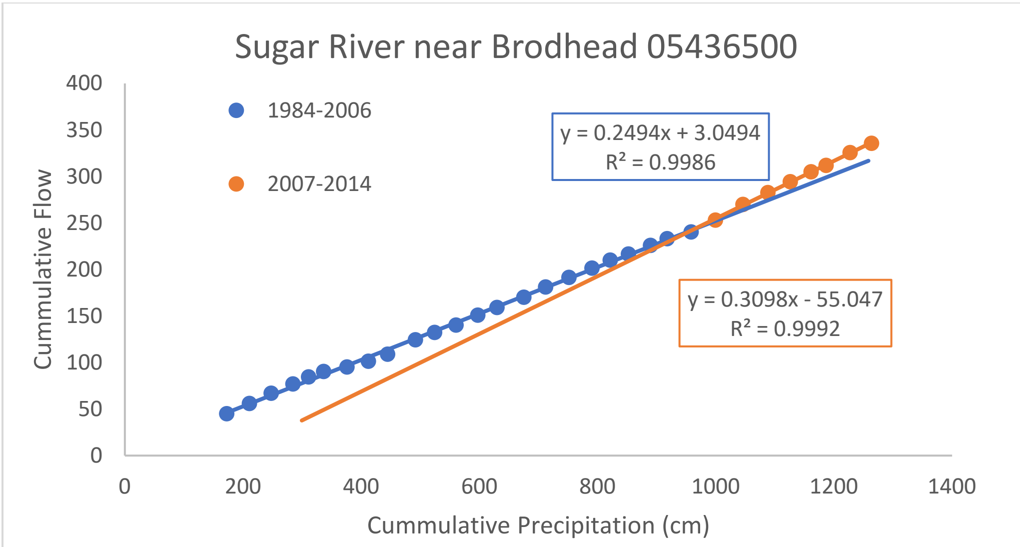

Yahara River at McFarland 05429500
1984-2006
2007-2014
Trendline (1984-2006)
y = 0.228x - 7.5125
R² = 0.9975
y = 0.3085x - 82.963
R² = 0.9954
Cummulative Flow
Cummulative Precipitation (cm)
0
50
100
150
200
250
300
350
0
200
400
600
800
1000
1200
1400
1600

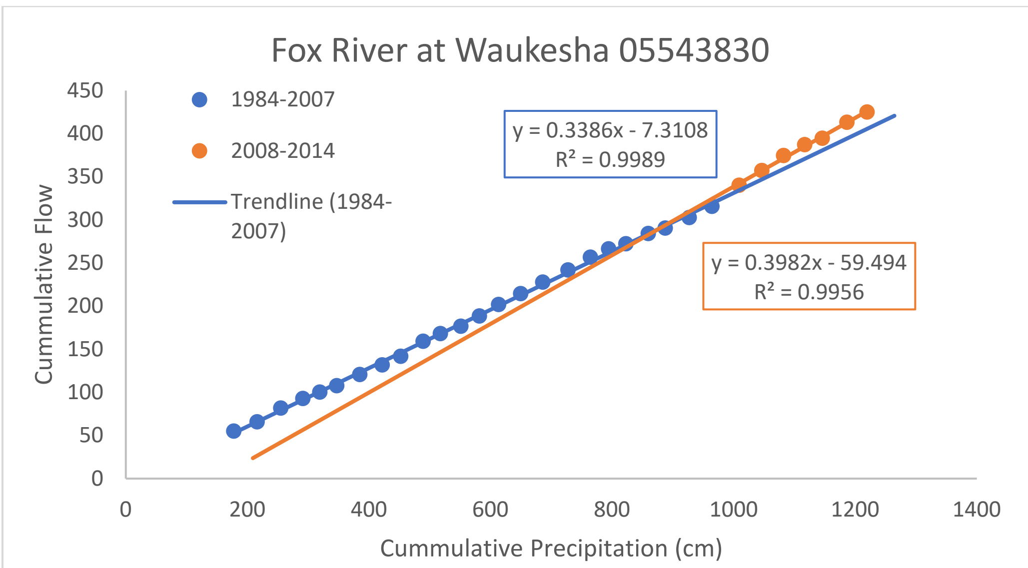

Badfish Creek near Cooksville 05430150
1984-2006
2007-2014
y = 0.5128x - 9.4918
R² = 0.9988
y = 0.6017x - 91.085
R² = 0.9996
Cummulative Flow
Cummulative Precipitation (cm)
0
100
200
300
400
500
600
700
0
200
400
600
800
1000
1200
1400


Yahara River near Fulton 05430175
1984-2007
2008-2014
Trendline (1984-2007)
Trendline (2008-2014)
y = 0.3701x - 83.311
R² = 0.9978
y = 0.2872x - 8.3492
R² = 0.9955
Cummulative Flow
Cummulative Precipitation (cm)
0
50
100
150
200
250
300
350
400
450
0
200
400
600
800
1000
1200
1400
1600


Turtle Creek at Carvers Rock near Clinton 05431486
1984-2006
2007-2014
y = 0.2389x + 10.081
R² = 0.9982
y = 0.3384x - 81.113
R² = 0.9914
Cummulative Flow
Cummulative Precipitation (cm)
0
50
100
150
200
250
300
350
400
0
200
400
600
800
1000
1200
1400


Pecatonica River at Darlington 05432500
1984-2007
2008-2014
y = 0.2704x - 1.327
R² = 0.9978
y = 0.3023x - 23.192
R² = 0.9893
Cummulative Flow
Cummulative Precipitation (cm)
0
50
100
150
200
250
300
350
400
0
200
400
600
800
1000
1200
1400


Sugar River near Brodhead 05436500
1984-2006
2007-2014
y = 0.2494x + 3.0494
R² = 0.9986
y = 0.3098x - 55.047
R² = 0.9992
Cummulative Flow
Cummulative Precipitation (cm)
0
50
100
150
200
250
300
350
400
0
200
400
600
800
1000
1200
1400


Fox River at Waukesha 05543830
1984-2007
2008-2014
Trendline (1984-2007)
y = 0.3386x - 7.3108
R² = 0.9989
y = 0.3982x - 59.494
R² = 0.9956
Cummulative Flow
Cummulative Precipitation (cm)
0
50
100
150
200
250
300
350
400
450
0
200
400
600
800
1000
1200
1400

Appendix D Horizontal Hydraulic Conductivity of Glacial Deposits and Average Values for Selected Soil Water Retention and Hydraulic Conductivity

Horizontal Hydraulic Conductivity of Glacial Deposits in Langlade County from Batten (1987)

Lithostratigraphic unit and location	**Lithology**	**Hydraulic conductivity (ft/d)**	**Landform and remarks**
Mapleview supraglacial till Sec.18,T30N.,R11E	Medium sand, trace silt and gravel lenses	14.4	Hummocky end moraine area
Mapleview supraglacial Sec.13,T30N.,R11E	Medium sand, trace silt and gravel lenses	24.1	Hummocky end moraine area
Mapleview basal till Sec.,33,T31N.,R13E	Very fine sand, silty	4.6	Streamlined ridge area
Mapleview basal till Sec.12,T31N.,R13E	Medium to coarse sand, very silty and some gravel	3.7	Streamlined ridge area
Nashville basal till Sec.7,T34N.,R10E	Mixed sand, very silty and some gravel	7.4	Streamlined ridge area
Nashville basal till Sec.25,T34N.,R10E	Mixed sand, very silty and gravel, trace clay	1.0	Rolling topography
Nashville basal till Sec.18,T33N.,R14E	Mixed sand, very silty	1.2	Streamlined ridge area
Nashville basal till Sec.,11,T34N.,R12E	Mixed sand, silty and some gravel	0.7	Streamlined ridge area
Merrill till Sec.36,T32N.,R9E	Mixed sand, silty, clay and some gravel	16.4	Rolling topography
Lacustrine sand in Nashville till area Sec. 12,T34N.,R12E	Fine sand, very silty	4.2	Flat low-lying area
Antigo sand and gravel Sec.5,T31N.,R11E Sec.14,T31N.,R11E Sec.19,T32N.,R12E	Stratified sand and gravel	145	Gently sloping glacial outwash

Average values for selected soil water retention and hydraulic conductivity parameters for 12 major soil textural groups according to Carsel and Parrish [1988]

Texture	K cm/d	K m/d
Sand	712.8	7.13
Loamy Sand	350.2	3.50
Sandy Loam	106.1	1.06
Loam	24.96	0.25
Silt	6.00	0.06
Silt Loam	10.80	0.11
Sandy Clay Loam	31.44	0.31
Clay Loam	6.24	0.06
Silty Clay Loam	1.68	0.02
Sandy Clay	2.88	0.03
Silty Clay	0.48	0.005
Clay	4.80	0.05