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High Capacity Wells and Baseflow Decline in the Wolf River Basin, Northeastern Wisconsin

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HIGH CAPACITY WELLS AND BASEFLOW DECLINE IN THE WOLF RIVER BASIN, NORTHEASTERN WISCONSIN

by

Sue Borchardt

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ABSTRACT

HIGH CAPACITY WELLS AND BASEFLOW DECLINE IN THE WOLF RIVER BASIN, NORTHEASTERN WISCONSIN

by

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The University of Wisconsin-Milwaukee, 2016
Under the Supervision of Professor Woonsup Choi

The baseflow of the Wolf River (drainage area of 1,200 km^2) in northeastern Wisconsin has declined by over 30% during the last thirty years, whereas climatic, land cover, and soil characteristics of the basin have remained unchanged. Because groundwater basins do not always coincide with surface water basins, estimating groundwater discharge to streams using variables only pertinent to the surface water basin can be ineffective. The purpose of this study is to explain the decline in the baseflow of the Wolf River by developing a multiple regression model. To take into account variables pertaining to the groundwater basin, withdrawal rates from high capacity wells both inside the Wolf River basin and in two adjacent basins were included in the regression model. The other explanatory variables include annual precipitation and growing degree days. Groundwater discharge to the river was calculated using streamflow records with the computer program Groundwater Toolbox from the United States Geological Survey. Without the high capacity wells data, the model only explained 29.6% of the variability in the groundwater discharge. When the high capacity wells data within the Wolf River basin were included, r^2 improved to be 0.512. With the high capacity wells data in adjacent basins, r^2 improved to be 0.700. The study suggests that human activity taking place outside of the basin has had an effect on the baseflow, and should be taken into account when examining baseflow changes.

To

my husband who didn’t tell me

going back to school was a

crazy idea

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LIST OF ABBREVIATIONS

BFI	Base-Flow Index
BFIM	Base-Flow Index Modified
BFIS	Base-Flow Index Standard
DEM	Digital Elevation Model
DNR	Wisconsin Department of Natural Resources
GDD	Growing Degree Days
GIS	Geographical Information System
HYSEP	hydraulic separation method
HYSEP_F	hydraulic separation method-Fixed Interval
HYSEP_L	hydraulic separation methods-Local Minimum
HYSEP_S	hydraulic separation method-Sliding Interval
ID	Identification
Lat.	Latitude
Long	Longitude
n	number
N	North
NLCD	National Land Cover Database
NOAA	National Oceanic and Atmospheric Administration
OLS	ordinary least squares
p	probability
T_b	base Temperature (10^{o}C)
T_m	daily mean Temperature

VIF	Variance Inflation Factor
W	west
WI	Wisconsin
WICCI	Wisconsin Initiative on Climate Change Impacts
US	United States
USA	United States of America
USGS	United States Geological Survey

1. Introduction

Configurations of the groundwater table generally mimic the local surface topography, and groundwater divides generally coincide with local surface water divides. However, regional patterns of the groundwater table do not always coincide with surface water divides (Eberts and George 2000; Feinstein et al. 2004). This is particularly true in unconfined groundwater systems flowing through unconsolidated material (Winter et al. 2003). Furthermore, groundwater divides can move over time in response to external stresses that affect recharge and discharge of groundwater, such as climate change and overpumping from irrigated agriculture.

In northern Wisconsin (USA), shallow glacial aquifers are strongly connected to the surface water. Therefore high capacity wells used to irrigate agricultural land could significantly impact groundwater storage and associated interaction of surface and groundwater systems (Sophocleous 2002; Wahl and Tororelli 1997). In the state of Wisconsin, a high capacity well is defined as

One or more wells, drill holes or mine shafts on a property that have a combined approved pump capacity of 70 or more gallons (1 gallon = 3.78541 liter) per minute. A property is defined as contiguous or adjacent land having the same owner.” (WDNR, 2016).

High capacity wells affect the environment in previously glaciated areas of the United States, such as northern Wisconsin, differently from the western United States (Kraft et al. 2012). Irrigating crops was once almost exclusively practiced in the arid western portion of the United States, but the use of irrigation has accelerated in the last 30 years in the humid eastern half of the United States (Kraft et al. 2012). In northern Wisconsin irrigation is not required for crop production but is used in addition to rainfall to supplement when soil moisture is at a minimum. This supplement allows farmers to grow high-water demand crops and increase productivity. Farmers are able to produce these crops in coarse soils that have minimal moisture holding capacity (Kraft et al. 2012); coarse soils have a high porosity, which makes the soil an effective flow path for groundwater to be connected to the surface water (Todd and

Mays 2005). Since groundwater discharge makes up a majority of the streamflow in areas where the aquifer flows through highly permeable sand and gravel deposits (Barlow and Leake 2012), it is of great importance to be able to predict changes to baseflow in the stream.

The relationship between high capacity wells and baseflow decline has been well documented. Weeks et al. (1965) and Weeks and Stangland (1971) explored the relationship between high capacity wells and baseflow in Wisconsin. Wahl and Tororelli (1997) analyzed baseflow trends in the Oklahoma panhandle in relation to the decline of groundwater levels caused by high capacity wells. Barlow and Leake (2012) reported that the reduction of groundwater discharge to streams resulted from the pumping of high capacity wells. 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. The gradients are a result of the decline in groundwater surrounding the pumping wells (Sophocleous 2002). The studies above suggest that the decline of baseflow can be better understood when taking into account the withdrawal rate of high capacity wells. In the studies cited above, the wells were all located within the boundaries of the same surface water basin. However, because groundwater divides do not always coincide with the surface water divides, high capacity wells can be located in the same groundwater basin but outside the surface water basin boundary. Therefore wells outside, but adjacent to the basin boundary can possibly affect the baseflow of the basin.

Regression models have been developed to estimate recharge to the groundwater using the characteristics of the surface water basin such as climate, geomorphology, and land cover (Scanlon et al. 2002). Several different regression methods have been developed to estimate recharge at the basin level. Santhi et al. (2008) used variables such as relief, precipitation, potential evapotranspiration, and soil permeability to construct regression equations explaining the variability of baseflow across the United States. Lorenz and Delin (2007) developed an alternative regression model to predict recharge using growing degree days, precipitation, and specific yield across the state of Minnesota. Cherkauer and Ansari (2005) estimated recharge-precipitation ratios from soil conductivity, hill slope, depth to the water table, length of flow to the main channel, and percent of natural land cover at several catchments in southeastern Wisconsin. These studies suggest that the climate variables of both temperature (potential evapotranspiration and growing degree days) and precipitation are strongly related to the rate of recharge to the groundwater system, and thus influence baseflow rate of the river.

This study aims to determine the variability of annual baseflow using a regression model that takes into account the withdrawal rate of high capacity wells outside of the basin. It focuses on the Wolf River basin in northeastern Wisconsin where mean annual streamflow has declined over the last three decades, and hypothesizes that the decline is largely due to the high capacity wells located outside of the basin. The study has three main components. First, the groundwater divide is identified for the Wolf River basin. Second, the baseflow is determined for the Wolf River from the observed streamflow data. Third, a regression model is built to predict baseflow using both climatic and anthropogenic variables. The results of the study can be useful for estimating future changes in baseflow as a result of either the approval of additional well permits or the abandonment of existing high capacity wells.

2. Study Area

The study area is the Wolf River basin (drainage area of 1,200 km^2) located in Langlade County in northeast Wisconsin (Fig. 1). 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). The glacial melt formed an area of outwash called the Antigo Flats, where irrigated agriculture is used to produce potatoes.

Elevations vary in the Wolf River basin from approximately between 330 and 575 m above sea level. The two other adjacent basins, the Springbrook Creek and the Upper Eau Clair River basins, vary less, with elevations ranging from 435 to 575 m above sea level. The United States Geological Survey (USGS) gauging station for the Wolf River (USGS site number 04074950) is located at latitude 45°11'24" and longitude 88°44'00", approximately in the center of the Wolf River basin (green star in Fig. 1(a)). There are a few more gauging stations outside of the basins with intermittent data.

Land use and land cover in the Wolf River basin has changed very little during the study period. Forest, wetlands, and lakes make up approximately 90% of the land cover (Fig. 2(a), 2(b), and Table 1). The Enhanced Historical land use map (Fig. 2(a)) depicts land use and land cover that was previously published in other formats from 1970 to 1985 by the USGS. The USGS has reformatted this information in digital format (http://water.usgs.gov/GIS/dsdl/ds240/index.html , last accessed 28 April 2016). The 2011 land use data was downloaded from the National Land Cover Database (NLCD). The NLCD data is derived from Landsat satellite imagery (http://www.mrlc.gov/index.php , last accessed 30 April 2016). By comparing the Enhanced Historical land use map to the 2011 NLCD land use map (Table 1) it can be determined that agriculture and developed land make up only about 10% of the land use in both maps.

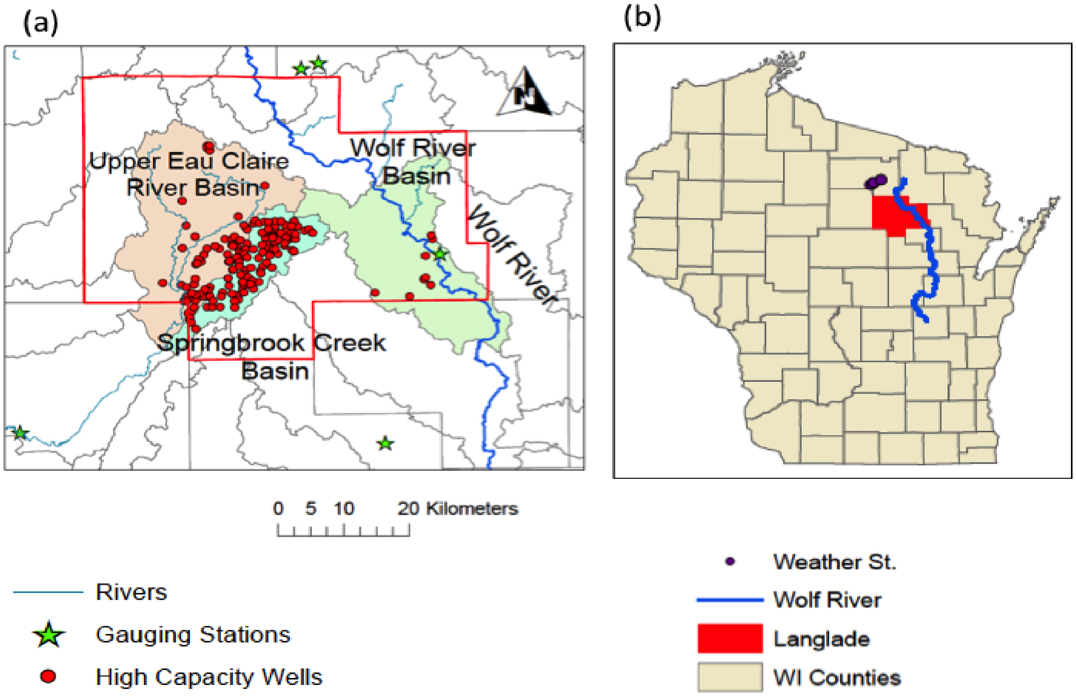

Fig. 1 (a) Boundaries of the Wolf River basin, Upper Eau Claire River basin, and Springbrook Creek basin. The watershed boundaries were obtained from the Wisconsin Department of Natural Resources. **(b)** The Wisconsin state map includes the approximate location of the weather stations (red circles) and the Wolf River

The Wolf River basin has eight high capacity wells upstream of the gauging station. The total recorded withdrawal from these wells was 0.22×10^6 m^3 in 2013. On the other hand, densely populated high capacity wells, primarily used to irrigate the agriculture land, are located in the Springbrook Creek and the Upper Eau Clair River basins. The 166 high capacity wells in these two basins withdrew a recorded 8.24×10^6 m^3 in 2013.

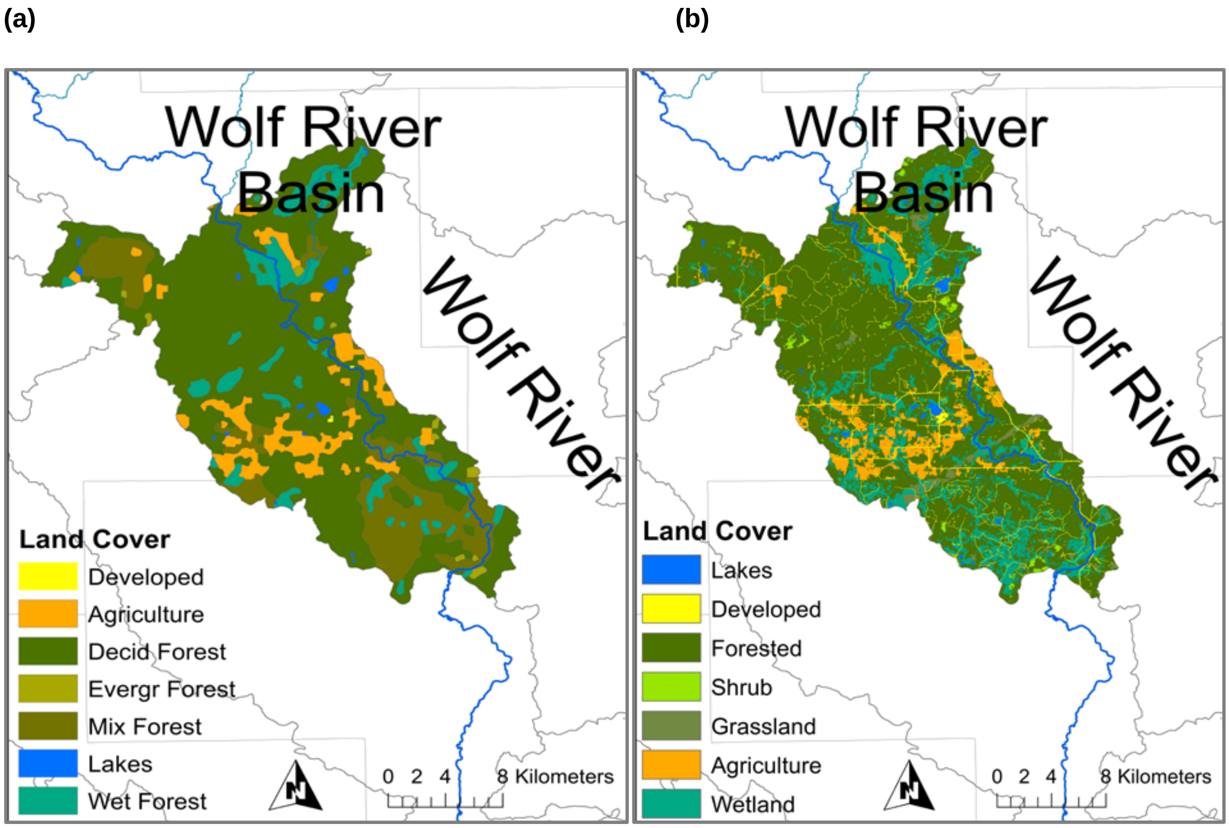

Fig. 2 **(a)** Enhanced Historical land use map data from the USGS, **(b)** 2011 land use map data from the NLCD

Table 1 Land Use in the Wolf River Basin

Land Use Class	Land Use % Enhance Historical	Land Use % 2011 NLCD
Forest	82.5	69.864
Wetland	8.55	18.151
Crops	8.318	6.992
Developed	0.049	3.548
Lakes	0.583	1.434

3. Materials and Methods

3.1. Identification of the Groundwater Divide

To get better understanding of the groundwater flow system, a groundwater table elevation map was drawn to determine whether the groundwater divide coincides with the surface water basin divides. The groundwater table map was constructed from a GIS layer compiled by the Wisconsin Department of Natural Resources (DNR), containing static depth data of groundwater wells drilled in the state (Smail, Robert A. Email correspondence, 6 January 2015). The well data was sorted to contain only 111-screened wells, which had been drilled in Langlade County since 2012. Screened wells were chosen because they are more likely to only extend into the unconfined aquifer and not into the bedrock aquifer below. The digital elevation model (DEM) dataset was obtained from the USGS. The elevation of the groundwater table was identified by subtracting the static depth of 111-screened wells from the DEM dataset. The 111-point data of the groundwater table was then used to create a contour map of the groundwater table.

3.2. Baseflow Determination

Annual mean baseflow was calculated from the streamflow data, collected during 1983-2013 at the Langlade gauging station in the Wolf River, using the USGS computer program, Groundwater Toolbox (http://water.usgs.gov/ogw/gwtoolbox/, last accessed on 9 March 2016). The gauge has been continuously recording daily stream flow since March 1966 to September 1979, and October 1980 to the present (http://waterdata.usgs.gov/usa/nwis/uv?04074950, last accessed on 12 March 2016).

The Groundwater Toolbox program includes six hydrograph-separation methods, the Base-Flow Index (BFI; Standard and Modified), HYSEP (Fixed Interval, Sliding Interval, and Local Minimum), and PART methods and one recession-curve displacement method, the RORA method, for baseflow separation (Barlow et al. 2015). Each method uses a slightly different calculation to identify the baseflow component of streamflow. The hydrograph-separation methods are based on formalized algorithms and not on mathematical solutions. The baseflow hydrographs are created by connecting the turning points (low points) in the hydrograph. The recession-curve displacement method is based on a mathematical solution. A recession index is specified for the basin based on the time required for groundwater to discharge to the surface water. It 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).

3.3. Regression Model

Lorenz and Delin (2007) and Santhi et al. (2007) used climatic and physiographical variables as explanatory variables for the regression models. In this study, precipitation and growing degree days (GDD) were selected to represent climatic variables. The GDD was selected because GDD is a primary factor in estimating evapotranspiration (Lorenz and Delin 2007) and is more easily available than evapotranspiration data. The Wolf River basin is approximately 90% forest and wetland forest (Fig. 2(a) and 2(b), Table 1), and the soil characteristics and topography did not change during the study period. Therefore, these variables were not used in the regression model. The withdrawal rates from high capacity wells were used in the regression model because of the relationship between withdrawal rate and baseflow decline (Weeks et al. 1965; Weeks and Stangland 1971). The withdrawal rate of low capacity wells was not used in the model. Low capacity wells are used in residential applications where on site wastewater treatment is also present; therefore what is pumped is put back into the ground. In summary, this study premised on Equation (1):

$$\text{Baseflow} = f\,(\text{precipitation, GDD, groundwater withdrawal}) \tag{1}$$

Data sources and processing for each of the variables are described in the following subsections.

3.3.1. Precipitation

The precipitation data was ordered from the National Centers for Environmental Information for the counties of Langlade, Oneida, and Forest (https://www.ncei.noaa.gov/, last accessed on 11 March 2016). It was determined that the Rhinelander Water Works weather station (Table 2), to the northwest of the study area and upstream of the gauging station, had the most complete data set for precipitation (Fig. 1(b)). Two other weather stations (Rhinelander WJFW TV12 and Rhinelander 4 NE station) were used to fill in missing data as needed. Annual total precipitation varied from 45.1 cm to 109.7 cm (Fig. 3(a)), with the mean of 80.8 cm. The linear trend over the study period indicates an increase of 7.5%. This increase is in agreement with studies completed by the Wisconsin Initiative on Climate Change Impacts (WICCI) (WICCI 2011). The WICCI reported an increase in precipitation over the state of Wisconsin during 1950-2006 of ~8 cm annually.

Table 2 Weather stations selected for the study.

Station Name	Station ID	Lat/Long	Data Obtained
Rhinelander Water Works, WI US	477113	45.599^{o}N / 89.451^{o}W	Precipitation, growing degree days
Rhinelander WJFM TV12, WI US	477118	45.622^{o}N / 89.410^{o}W	Precipitation
Rhinelander 4 NE, WI US	477115	45.653^{o}N / 89.307^{o}W	Precipitation

3.3.2. Growing Degree Days (GDD)

The GDD was used as the temperature variable in lieu of evapotranspiration. The GDD is a measure of the mean temperature above the base temperature for each day (Equation (2)).

$$GDD = \begin{cases} T_m - T_b \text{ for } T_m > T_b, \\ T_b \quad \text{otherwise} \end{cases} \tag{2}$$

Where T_m is the daily mean temperature (°C) and T_b is the base temperature (10°C). GDD base 10 was used because deciduous trees nearly stop transpiring when the leaves have dropped, and evergreen trees transpire slowly in the winter. The majority of the land cover in the Wolf River basin is deciduous trees

(Fig. 2(a) and 2(b)). Annual GDD data (annual sum of daily GDD) was obtained for Rhinelander at the Rhinelander Water Works from the Midwestern Regional Climate Center (http://www.wrcc.dri.edu/cgi-bin/cliMONtg50.pl?wi7113, last accessed on 12 March 2016). The weather station was chosen due to its complete data record and to be consistent with the precipitation data. Annual GDDs ranged from the minimum of 800.5°C in 1984 to the maximum of 1,366.1°C in 2005, and the mean was 1,064.7°C. During the study period GDD presented an increasing linear trend of 3.9% (Fig. 3(b)). This trend is also in agreement with the WICCI finding of an increase in mean annual temperature during 1950-2006 of 0.6°C (WICCI 2011).

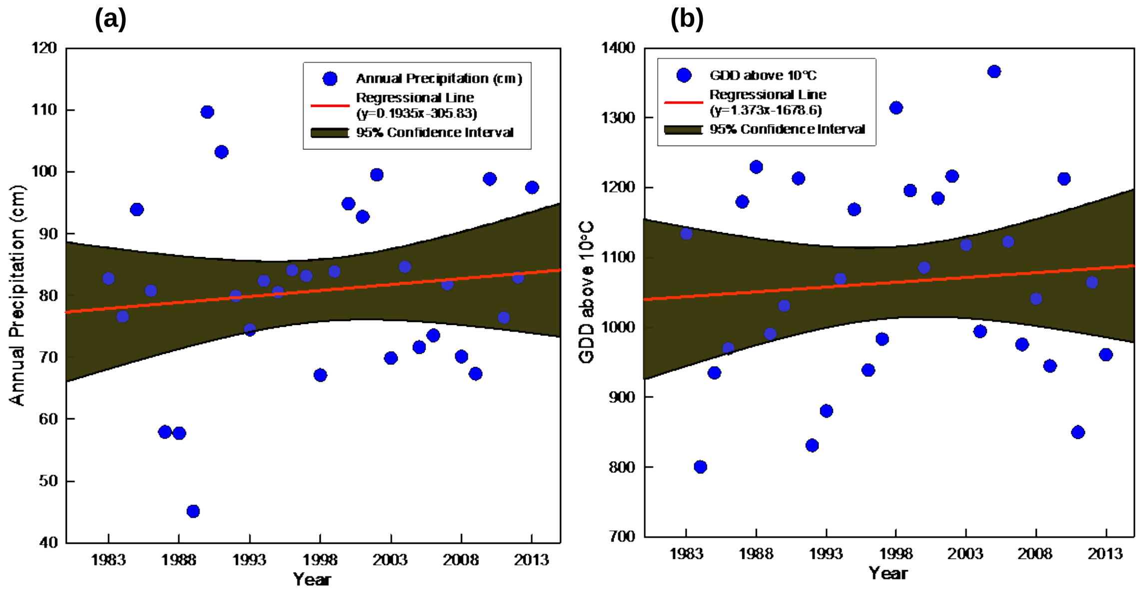

Fig. 3 **(a)** Total annual precipitation (cm) and **(b)** annual GDD above 10°C during 1983-2013.

3.3.3. Groundwater Withdrawal

High capacity well data for Langlade County was acquired from the DNR (Smail, Robert A. email correspondence 6 January 2015). The well data has the reported annual pumping rates for each high capacity well for the years 2011, 2012, and 2013, along with the date the wells were permitted. Wisconsin has only required annual pumping reports since 2011, so an average of the three reporting years was used as the annual pumping rate for each well. The wells were divided into two groups. The first group included eight wells within the Wolf River drainage basin (Fig. 1(a)). The eight wells combined had an average pumping rate of 0.285×10^6 m^3/year in 2013. The second group of 166 wells was within the two adjacent basins (Upper Eau Claire River and Springbrook Creek basins). They had a combined average pumping rate of 8.02×10^6 m^3/year in 2013.

4. Results

4.1. Groundwater Divide

Fig. 4 portrays the elevation of the groundwater table delineated for the study area. Fig. 4(a) shows that the groundwater moves in general from the northwest corner of the county where the head is approximately 510 m to the southeast with the head below 370 m. The estimated regional gradient for groundwater is 0.3%. The contour lines change direction along the boundary between Upper Eau Clair and Springbrook, suggesting a groundwater divide between them. The contour lines for 420-440 m and below are almost straight, suggesting the same groundwater basin.

Fig. 4(b) and Fig. 4(c) compare the surface topography and the groundwater table elevation along the cross-sections A-A' and B-B' respectively shown in Fig. 4(a). They indicate that the groundwater divide extends beyond the boundaries of the surface water basin of the Wolf River. The cross-sections also demonstrate that wells in the Springbrook creek basin and the eastern portion of the Upper Eau Claire basin are in the same groundwater basin as the Wolf River.

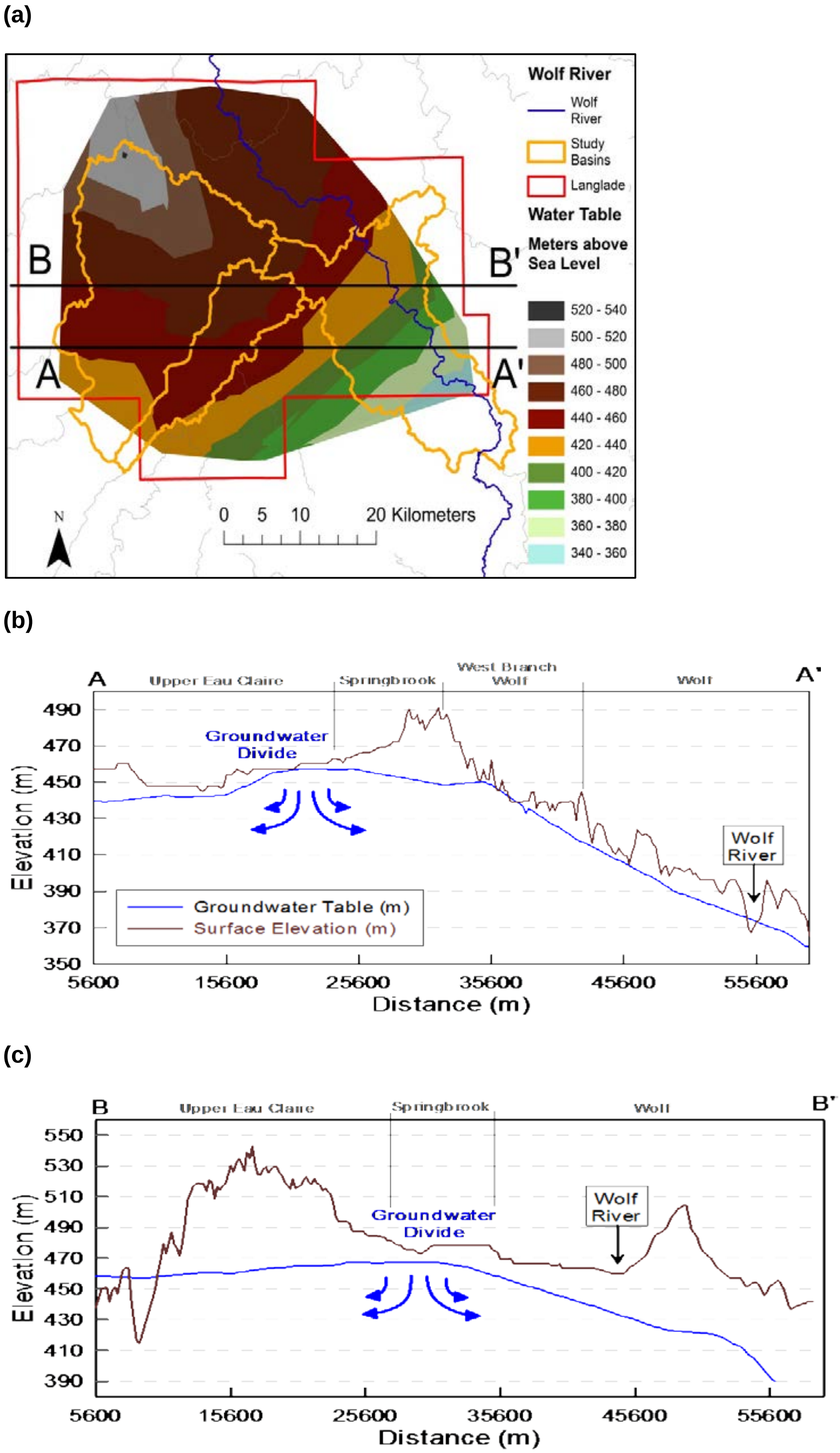

Fig. 4 (a) Elevation of groundwater table interpolated from static well depths and surface elevations; **(b)** Elevation profile of the land surface and aquifer for the transect A-A' and **(c)** Same for transect B-B'

4.2. Baseflow Separation

All seven hydrograph-analysis methods described in Section 3.2 were used to separate baseflow from the observed streamflow data, and the resulting outputs were compared (Fig. 5 and Table 3). All seven methods compare favorably with each other, revealing a declining trend (~30%) over the study period (1983-2010). Particularly low flow years of 1989, 1998, and 2009 were also very low precipitation years, with 1989 being the lowest precipitation year of the study (Fig. 3(a)). The GDD for the same years do not appear to be correlated to the low flow, with two years (1989 and 2009) having lower that average GDD, and 1998 having higher than average GDD (Fig. 3(b)).

For most years the BFIM method, a hydrograph-separation method, produced the lowest rate and the RORA method, a recession-curve displacement method, produced the highest rate. On average, the BFIM produced and the RORA produced rates were different by 19.1%, and the difference varied between 2.5% and 28.9% over the years. This study investigates the interannual variability of the baseflow, and the graph shows that although each method is slightly different, the variability is consistent between the methods (Fig. 5). The results from the RORA method were chosen for use in the regression model for this study because of its more realistic assumption of the recharge process. The RORA program creates estimates of net recharge. Net recharge is recharge minus leakage to deeper aquifers and losses caused by groundwater evapotranspiration (Rutledge 2000). It assumes that groundwater discharge to streams is an episodic response to storms, unlike the hydrograph-separation methods which assume a continuous process (Rutledge 2007). Batton (1987) reported the rise in groundwater elevation after precipitation events in Langlade County; therefore the RORA method is the more reasonable method for this study area. The RORA method is appropriate for basins between 2.5 km^2 and 1,300 km^2 (Rutledge 2000 and 2007), the Wolf River basin sized at 1,200 km^2 fits within this range.

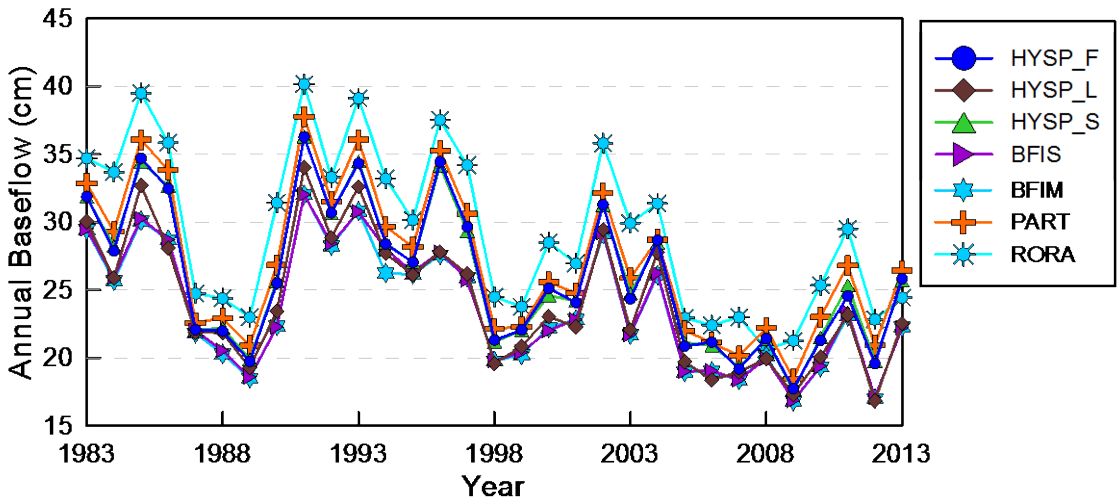

Fig. 5 Annual baseflow (cm) during 1983-2013 from seven different baseflow separation methods in USGS Groundwater Toolbox

Table 3 Summary statistics of annual baseflow (cm) during 1983-2013 from seven different baseflow separation methods in USGS Groundwater Toolbox

	HYSP_F	HYSP_L	HYSP_S	BFIS	BFIM	PART	RORA
Max	36.27	34.01	36.30	32.03	32.03	37.77	40.16
Min.	17.73	16.84	17.60	16.87	16.81	18.44	20.65
SD	5.31	4.78	5.26	4.49	4.43	5.45	5.99
Mean	25.98	24.14	26.01	23.69	23.57	27.00	29.29

4.3. Regression Model

Ordinary least squares (OLS) regression was run three times using different sets of explanatory variables for the years 1983-2013 (n = 31, Table 4). The first run used the climatic variables of annual GDD and annual total precipitation (cm), and the resulting r^2 was 0.296. In the second run, the annual withdrawal rates (10^6 m^3) from the wells located in the Wolf River basin alone were added to the existing variables and the resulting r^2 improved to be 0.512. The large improvement in the r^2 score indicates that the withdrawal rate is significantly affecting the baseflow. Finally, the third run of OLS adds the withdrawal rate of the wells in the two adjacent basins to the withdrawal variable. The addition of the withdrawal rate from the high capacity wells in these two basins brings the r^2 up to 0.700. The model now explains 70% of the variability in the baseflow of the Wolf River.

Each of the OLS models indicates that all of the explanatory variables are significant to the model ($p < 0.01$ except for one), and that there is no redundancy in the variables indicated by the small (~1) variance inflation factor (VIF) values (Table 5). The *p*-value is 0.054 for GDD in Model 1, suggesting the GDD is marginally significant in this model. In the models, precipitation has positive coefficient whereas both GDD and withdrawal rates have negative coefficients. Table 5 also shows the standardized coefficients (β), whose absolute values indicate the sensitivity of the model to the explanatory variable. In Model 2, precipitation has the highest absolute value by a small margin over both GDD and withdrawal rates. In Model 3, the withdrawal rate has the highest absolute value by a greater margin over either GDD or precipitation; therefore the withdrawal rate from the three basins has the most influence on the baseflow rate.

Table 4 Variables entered in each regression model and resulting r^2

Model	Explanatory variables	R^2	Adjusted R^2
1	Precipitation GDD	0.2955	0.2452
2	Precipitation GDD Withdrawal rate of Wolf River basin wells	0.512057	0.457842
3	Precipitation GDD Withdrawal rate of Wolf River basin wells and Adjacent basin wells	0.699835	0.666483

Table 5 Regression coefficients of each model

Model	Variable	Coefficient	Std Coefficient	Probability	VIF
1	Intercept	28.187545	N/A	0.003641	N/A
	Precipitation	0.186694	0.4406977	0.009649	1.000000
	GDD	-0.013359	-0.3184034	0.054467	1.000000
2	Intercept	63.511812	N/A	0.000029	N/A
	Precipitation	0.210917	0.4978769	0.001035	1.015096
	GDD	-0.016976	-0.4046123	0.006347	1.034322
	Withdrawal	-139.101093	-0.4767418	0.001801	1.049399
3	Intercept	46.227724	N/A	0.000000	N/A
	Precipitation	0.208533	0.4922494	0.000076	1.006572
	GDD	-0.015002	-0.3575633	0.002194	1.003793
	Withdrawal	-3.016398	-0.6391799	0.000002	1.010361

Fig. 6 portrays the correlation between the residuals and the explanatory variables, and between the residuals and the estimated baseflow from Model 3. All the graphs show no correlation between the residuals and the variables. Residuals appear to be somewhat larger with lower withdrawal rates than with higher rates, suggesting better explanatory power of withdrawal rates when they were high.

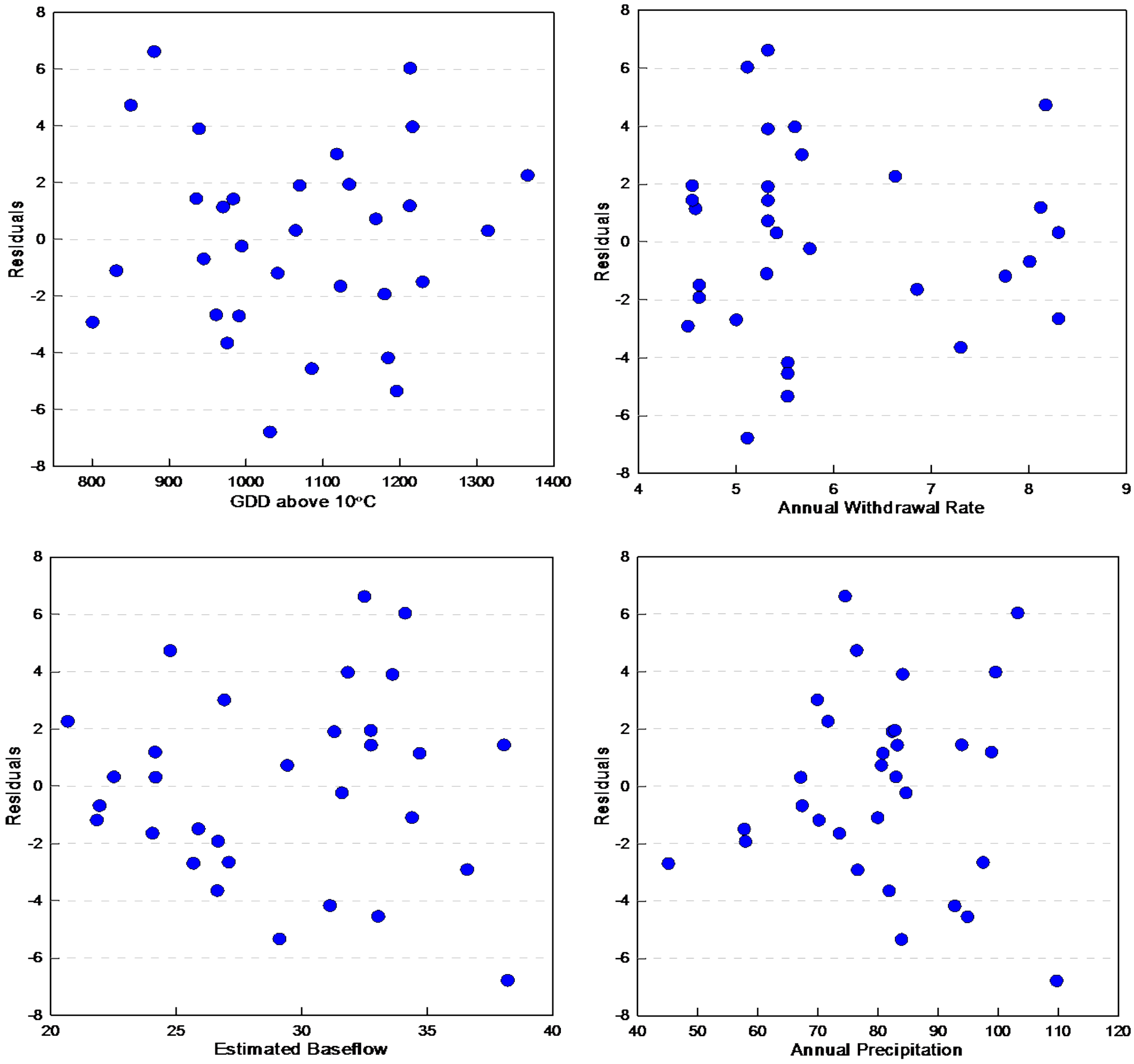

Fig. 6 GDD above 10°C, withdrawal rate (10^6 m^3), estimated annual baseflow (cm), and annual precipitation (cm) versus the residual

Fig. 7 portrays the correlation between the observed baseflow from the RORA method and the baseflow estimated by Model 3, along with the 45-degree (1:1) line and regression line between the observed and estimated baseflow. As mentioned before, the baseflow tends to be smaller in more recent decades, and residuals have a decreasing trend as well. Residuals (horizontal distance of each case from the 1:1 line in the scatterplot) during 1983-1992 were between −6.78 and 6.04, but the maximum and minimum are vastly different from the rest. The residuals were between −5.33 and 6.62 during 1993-2002, and then between −3.65 and 4.73 during 2003-2013. Standardized residuals have a smaller range during 2003-2013 than previous decades (not shown), suggesting better predictability in more recent decades. All the residuals are within 22.4% of the observed baseflow, and standardized residuals are within ± 2. The trend line generally follows the 1:1 line with baseflow decreasing with time. A couple of very unusual years were found that could not be explained by the climate variables. Large positive residuals were found in 1993 which was cold and wet, and in 1991 which was warm and dry. Large negative residuals were found in 1999 when it was warm with average precipitation, and in 1990 which had an average temperature but higher than average precipitation.

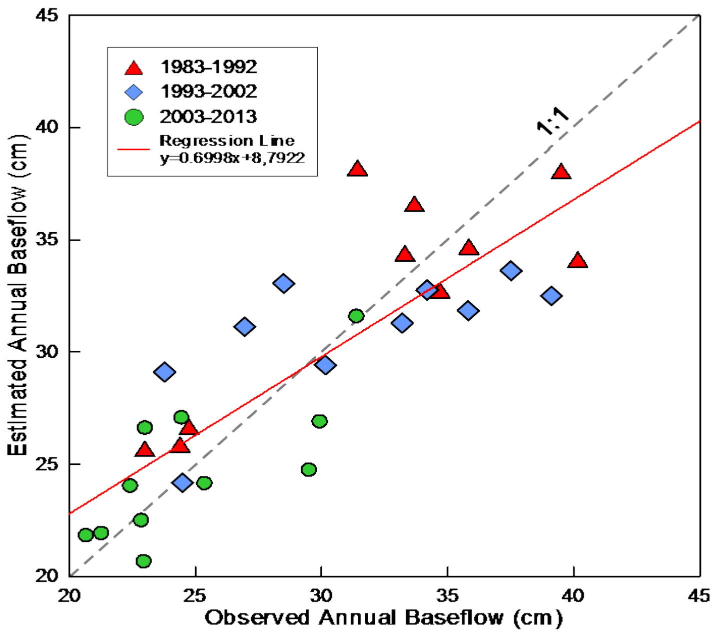

Fig. 7 Observed and predicted annual baseflow (cm) during 1983-2013, grouped by decade. The straight is the regression line and the dashed line is the 45-degree line.

5. Discussion

In this study, a regression model was developed to explain the variability of the annual baseflow of the Wolf River in Langlade County in northeast Wisconsin. This was done by first determining whether the groundwater basin divides extended beyond the divides of the surface water basin. Secondly the baseflow was estimated for 30 years (1983-2013) using the USGS Groundwater Toolbox. The final step was to use ordinary least squares to develop the regression model.

The regression model in this study found that baseflow is a function of precipitation, growing degree days, and the withdrawal rate from high capacity wells. These findings are in agreement with previous studies (e.g. Lorenz and Delin 2007; Santhi et al. 2007) that climate variables such as precipitation and temperature affect baseflow rates. In this study both the precipitation and the temperature variables are trending upward slightly, and are in agreement with climate studies by WICCI. While increasing temperatures would suggest a decreasing trend in baseflow, the increasing precipitation totals would counteract this trend with increasing baseflows. These counteracting trends may help explain why the first model was only able to explain approximately 29% of the variability. The low r^2 result suggested another variable was required to explain the declining trend in the baseflow.

The introduction of the withdrawal variable into the model is in agreement with Wahl and Tortorelli (1997), Barlow and Leake (2012), Sophocleous (2002), Weeks et al. (1965), and Weeks and Stangland (1971) suggesting that high capacity wells play a significant role in baseflow decline. The study highlights that human activity, i.e. groundwater withdrawal from high capacity wells outside but adjacent to the surface water basin, is affecting the baseflow rate of the Wolf River. Most importantly, high capacity wells outside the boundaries of the surface water basin can have an effect on the baseflow rate. For example, the regression Model 2 was only able to explain approximately 50% of the variation in baseflow when the withdrawal rate of only the wells within the boundaries of the surface water basin was used in the model. When the withdrawal rate of the wells from the adjacent basins were added to the withdrawal variable, the model’s ability to predict variations in baseflow rate jumped up to 70% (Model 3).

The water table map along with the cross section graphs (Fig. 4) are in agreement with Winter et al. (2003) who found that groundwater basins can extend beyond surface water divides, and that the groundwater divides do not always coincide with the surface water divides (Eberts and George 2000; Feinstein et al. 2004). In particular the cross section shows that the high capacity wells located in the Springbrook Creek basin and the eastern portion of the Upper Eau Claire river basin are within the same groundwater basin as the Wolf River. Since these wells are in the same groundwater basin as the Wolf River they are drawing ground water that would have eventually discharged to the river, thus causing a decline in the river’s baseflow (Barlow and Leake 2012).

This study created a model using baseflow data from just one basin, and it is anticipated that future studies of other basins with declining baseflows could corroborate these findings. It is also anticipated that the model prediction will improve as more actual withdrawal data becomes available. Although an average of the three recording years worked as a substitute for actual values, rates vary from year to year. This annual variation in withdrawal rate may be able to explain some of the larger residuals. There is also a lack of historical streamflow data in the adjacent basins. The gauges to the north at Swamp Creek (USGS site numbers 04074548 and 04074538) have intermittent data and have not recorded since 2009. The gauge to the southeast at the Red River (USGS site number 04077630) has only been recording since 1992. The next closest gauging station (USGS 05397500 Eau Claire River at Kelly, WI) is southwest of the basins (southwest corner of Fig. 1(a)). This gauging station is directly downstream from the wells and has had a decline of approximately 27% over the study period suggesting high capacity wells maybe affecting other adjacent basins, and further analysis of stream baseflow near clusters of high capacity wells is warranted.

6. Conclusions

This study examined the annual baseflow of the Wolf River basin in northeastern Wisconsin using groundwater table maps and regression models taking high capacity wells into account. The study found that in the area surrounding the Wolf River basin, the groundwater basin extends beyond the boundaries of the surface water basin and the baseflow of the Wolf River has been declining over the last three decades. It was also 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. The regression model's explanatory power improved statistically significantly when the withdrawal data from adjacent basins were included.

Water resources managers need to look beyond surface water divides when determining if additional high capacity well permits will adversely affect surface water resources. Previous studies as well as the present study have shown that groundwater divides do not always coincide with surface water divides. Groundwater divides can also move due to changing climate conditions or anthropogenic stresses such as overpumping. This study developed a regression model that shows strong effects of the increasing withdrawal rates of high capacity wells outside the surface water basin on the baseflow within the basin. Further research including more basins is expected to corroborate the conclusion that high capacity wells in close proximity to surface water divides can have an adverse effect on the baseflow of surface waters.

Bibliography

Barlow, P. M., Cunningham, W. L., Zhai, T., & Gray, M. (2015*)*. US Geological Survey Groundwater Toolbox, a Graphical and Mapping Interface for Analysis of Hydrologic Data (Version 1.0): User Guide for Estimation of Base Flow, Runoff, and Groundwater Recharge From Streamflow Data: United States Geological Survey Techniques and Methods 3-B10, 27p., http://dx.doi.org/10.3133/tm3B10 (Last accessed 1 May 2016)

Barlow, P. M., & Leake, S. A. (2012). Streamflow Depletion by Wells--Understanding and Managing the Effects of Groundwater Pumping on Streamflow (No. 1376, pp. i-84). United States Geological Survey.

Batten, W. G. (1987). Water Resources of Langlade County, Wisconsin (No. 58). Wisconsin Geological and Natural History Survey.

Cherkauer, D. S., & Ansari, S. A. (2005). Estimating Ground Water Recharge From Topography, Hydrogeology, and Land Cover. *Groundwater,* 43(1), 102-112.

Eberts, S. M., & George, L. L. (2000). Regional Ground-Water Flow and Geochemistry in the Midwestern Basins and Arches Aquifer System in Parts of Indiana, Ohio, Michigan, and Illinois (Vol. 1423). United States Geological Survey.

Feinstein, D. T., Hart, D. J., Eaton, T. T., Krohelski, J. T., & Bradbury, K. R. (2004). Simulation of Regional Groundwater Flow in Southeastern Wisconsin. Wisconsin Geological and Natural History Survey Open-File Report, 1(2004), 134.

Kraft, G. J., Clancy, K., Mechenich, D. J., & Haucke, J. (2012). Irrigation Effects in the Northern Lake States: Wisconsin Central Sands Revisited. *Groundwater,* 50(2), 308-318.

Lorenz, D. L., & Delin, G. N. (2007*)*. A Regression Model to Estimate Regional Ground Water Recharge. *Groundwater*, 45(2), 196-208.

Mickelson, D. M. (1987). Pleistocene Geology of Langlade County: Wisconsin Geological and Natural History Survey. *Information Circular,* 52, 32.

Rutledge, A. T. (2007). Update on the Use of the RORA Program for Recharge Estimation. *Groundwater,* 45(3), 374-382.

Rutledge, A. T. (2000). Considerations for Use of the RORA Program to Estimate Groundwater Recharge From Streamflow Records (No. USGS-OFR-00-156). United States Geologic Survey, Reston VA.

Santhi, C., Allen, P. M., Muttiah, R. S., Arnold, J. G., & Tuppad, P. (2008). Regional Estimation of Base Flow for the Conterminous United States by Hydrologic Landscape Regions. *Journal of Hydrology*, 351(1), 139-153.

Scanlon, B. R., Healy, R. W., & Cook, P. G. (2002). Choosing Appropriate Techniques for Quantifying Groundwater Recharge. *Hydrogeology Journal*, 10(1), 18-39.

Smail, Robert A. - Wisconsin Department of Natural Resources (WDNR). (2015) Robert.Smail@Wisconsin.Gov, Subject: Well Data, 6 January 2015.

Sophocleous, M. (2002). Interactions Between Groundwater and Surface Water: the State of the Science. *Hydrogeology Journal*, 10(1), 52-67.

Todd, D. K., & Mays, L. W. (2005). *Groundwater Hydrology*. Wiley, New Jersey.

Wahl, K. L., & Tortorelli, R. L. (1997). Changes in Flow in the Beaver-North Canadian River Basin Upstream From Canton Lake, Western Oklahoma. United States Department of the Interior, United States Geological Survey.

United States Geological Survey (USGS). (2016). GW Toolbox - http://water.usgs.gov/ogw/gwtoolbox/ (last accessed 28 April 2016)

United States Geological Survey (USGS). (2016). Land Use Data http://water.usgs.gov/GIS/dsdl/ds240/index.html (last accessed 28 April 2016)

United States Geological Survey (USGS). (2016). Stream Flow Data http://waterdata.usgs.gov/usa/nwis/uv?04074950 (last accessed 28 April 2016)

Weeks, E. P., Ericson, D. W., & Holt, C. L. R. (1965). Hydrology of the Little Plover River Basin, Portage County, Wisconsin and the Effects of Water Resource Development. United States Government Printing Office.

Weeks, E. P., & Stangland, H. G. (1971). Effects of Irrigation on Streamflow in the Central Sand Plain of Wisconsin. United States Department of the Interior, United States Geological Survey, Water Resources Division.

Winter, T. C., Rosenberry, D. O., & LaBaugh, J. W. (2003). Where Does the Ground Water in Small Watersheds Come From?. *Groundwater*, 41(7), 989-1000.

Wisconsin Department of Natural Resources (WDNR). (2016). High Capacity Wells. http://dnr.wi.gov/topic/wells/highcapacity.html (last accessed 20 January 2016)

Wisconsin Initiative on Climate Change Impacts (WICCI). (2011). Wisconsin's Changing Climate: Impacts and Adaptation 2011. Nelson Institute for Environmental Studies, University of Wisconsin-Madison and the Wisconsin Department of Natural Resources, Madison, Wisconsin.