Groundwater recharge in Menominee, Shawano, Waupaca, and Waushara Counties, Wisconsin, estimated by a GIS-based water-balance model

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Contents

Introduction

Purpose

Groundwater recharge is water that crosses the water table and is added to the groundwater system; recharge is thus the ultimate source of all groundwater. Understanding recharge and its distribution is important in making informed land-use decisions so that the groundwater needs of society and the environment can be met. This report describes the inputs, operation, and application of a soil-water balance (SWB) model used to estimate groundwater recharge in Menominee, Shawano, Waupaca, and Waushara counties, Wisconsin.

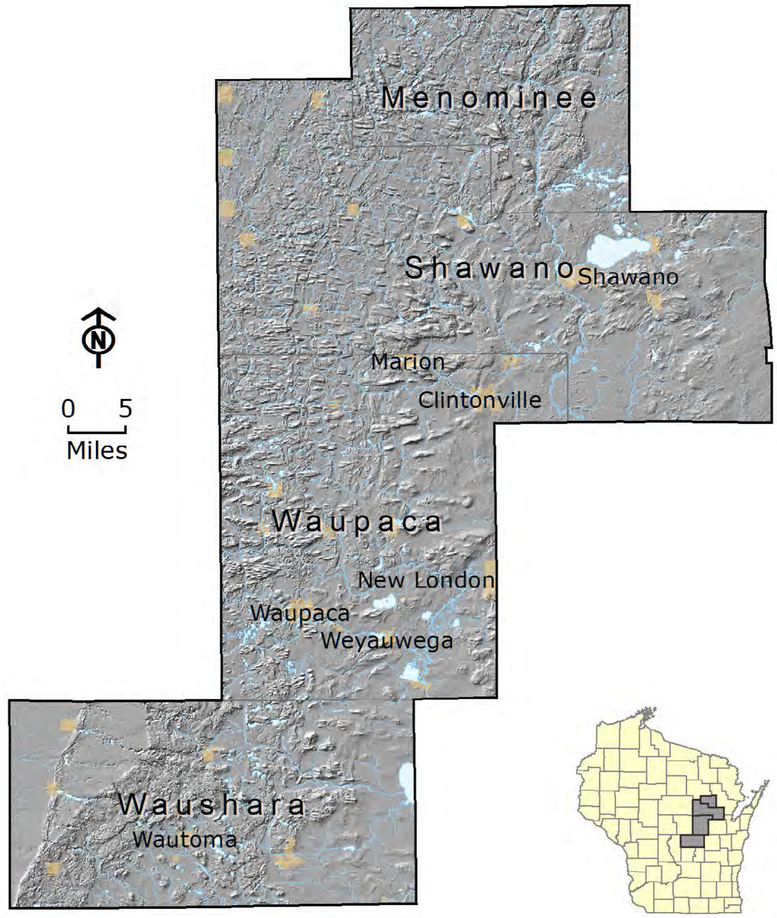
Groundwater recharge varies spatially and temporally. The spatial variation is due primarily to spatial differences in land use, soils, geology, and topography. Recharge also varies temporally with climate and precipitation. Local planning decisions cannot significantly alter the weather or geology, but can impact land use. Very often land use associated with development creates additional runoff and decreases recharge. The SWB model is a tool to understand the implications of different land uses to the groundwater flow system.

This recharge model provides a groundwater management tool to help guide land-use decisions and increase understanding of recharge in Menominee, Shawano, Waupaca, and Waushara counties. The recharge distributions produced by this technique represent an essential input for groundwater flow models in the three counties.

Objectives

The objective of this project was to delineate and categorize recharge to the shallow aquifers of Menominee, Shawano, Waupaca, and Waushara counties. These four counties are part of the East Central Wisconsin Regional Planning Commission (ECWRPC). A separate report, available from the ECWRPC, was prepared for Calumet, Outagamie, and Winnebago counties, also part of the ECWRPC. The resulting recharge map can be used to identify important groundwater recharge areas in the four counties and incorporate the areas into planning and land development decisions. For example, regions of high recharge in the four-county area are associated with an abundance of springs. A plan to maintain springflows must take these regions of high recharge into account. The methodology used was a soil-water balance model that estimates the spatial distribution of groundwater recharge for both present and past climate and land-use conditions. As input, the model uses readily available climate data and geographic information system (GIS) map data layers such as soil characteristics, land use, and topography.

Figure 1. Soil-water balance (SWB) model area: Menominee, Shawano, Waupaca, and Waushara Counties, Wisconsin.



Background and setting

Menominee, Shawano, Waupaca, and Waushara counties are located in east-central Wisconsin. The four counties are shown in figure 1. The counties are largely rural and share a physical geography that is strongly controlled by the glacial history of the area. During the last Ice Age, a large lobe of glacial ice covered all but the northwestern corner of Waushara County.

The four-county area is large enough to have significant differences in climate from north to south. For this reason, climate data from stations in Waupaca and Shawano, Wisconsin, were used in this study. The average annual precipitation at Shawano is 30.8 inches and at Waupaca is 31.96 inches. The mean annual air temperature is 45.0°F in Waupaca and 44.1°F in Shawano, with an average maximum in July of 83.5°F in Waupaca and 82.7°F in Shawano and an average minimum in January of 6.6°F in Waupaca and 5.9°F in Shawano. Nearly 60 percent of annual precipitation falls in the five months of highest precipitation, May through September.

Groundwater use in the four counties is primarily for domestic, agricultural, and irrigation uses. Table 1 shows the groundwater use for all categories for years 2000 and 2005. The large increases seen in Waupaca and Waushara counties are due to an increase in irrigation pumping in those counties. Between the years 2000 and 2005 irrigation use increased from 1.9 to 8.7 million gallons/day (mgd) in Waupaca County and from 27.1 to 49.1 mgd in Waushara County (Ellefson and others, 2002; Buchwald, 2009).

Recharge for the four-county area had been estimated previously by Gebert and others (2007) by using streamflow-gaging stations to estimate recharge for selected river and stream basins. The range of recharge values for the gaged basins located in part in the four-county area varied from 3.2 inches/year for the Pensaukee River basin in eastern Shawano County to 15.7 inches/year for the Big Roche a Cri Creek in western Waushara County.

Compared to basin-scale streamflow-based estimates, the SWB model has the advantages of finer scale resolution (less than 80 acres) with quantified estimates of recharge. The fine scale should be useful for land-use planning. For example, the impact of a new subdivision to recharge could be simulated by changing the land-use categories. The SWB model could also be used with a groundwater flow model to identify and potentially protect areas of very high recharge that are also source water areas for surface waters.

Acknowledgements

This project was funded by the East Central Wisconsin Regional Planning Commission. We thank Eric Fowle, Todd Verboomen, and Joe Huffman for facilitating the funding and dataset acquisition. The recharge model code was developed by W.R. Dripps (currently at Furman University) and modified by V.A. Kelson (Whitman Hydro Planning Associates) and S.U. Westenbroek of the USGS.

Table 1. Groundwater use in 2000 and 2005 for all categories.

County	Groundwater use (million gallons per day)	
	Year 2000	Year 2005
Menominee	0.7	0.8
Shawano	5.7	5.2
Waupaca	11.5	17.7
Waushara	31.8	52.0

Methodology

Recharge model description

The recharge model uses soil-water balance (SWB) accounting to determine the fate of precipitation on the land surface and within the soil zone. This method accounts for the various processes that divert precipitation from becoming recharge. The difference between the diverting processes, indicated by negative signs in the following equation, and precipitation represents estimated recharge.

The governing equation for the model is as follows:

Recharge = precipitation – interception – runoff – evapotranspiration – (total soil moisture storage capacity of the root zone – antecedent soil moisture)

The terms of the equation are defined below. Each term has the same units as precipitation, amount/time period (for example, inches/year).

Recharge: The volumetric rate of water entering the groundwater flow system over an area.

Precipitation: The amount of water that falls to the earth as rain, sleet, snow, or hail.

Interception: The amount of water that falls on the plant canopy and is used by the plants or evaporates, never reaching the ground surface.

Runoff: The amount of water that flows across the land surface.

Evapotranspiration: The quantity of water that is either evaporated or taken up by plants and transpired through their leaves.

Total soil moisture storage capacity of the root zone: The amount of water that the soil can hold within its pore spaces.

Antecedent soil moisture: The amount of water already stored in the soil.

The difference between total soil moisture and antecedent soil moisture is the amount of water that must be added to the soil before recharge occurs.

The SWB recharge model operates on a geographic grid where the recharge for each cell of the grid is calculated daily. The model calculates inputs and outputs to this primary water-balance equation from input data grids that relate soil and land use to the terms in the equation. Daily precipitation is input and the negative terms on the right-hand side of the equation are calculated from the model inputs that vary in time and over the land surface. Recharge for that cell is calculated and stored in an output file. Runoff for the cell is added to the precipitation term of the next downslope cell and is subsequently partitioned between infiltration into that cell and runoff to be routed further downslope. The process is then repeated for each day of the model time period. An earlier version of the model is described in more detail in Dripps and Bradbury (2007) and the current model is described by Westenbroek and others (2009).

Model inputs and outputs

Input to the SWB recharge model consisted of daily climate records for the model period and four map data layers for the model extent: topography, soil hydrologic group, soil available water storage, and land use. The model domain covered Menominee, Shawano, Waupaca, and Waushara Counties and included small portions of surrounding counties. The spatial resolution of the model grid was 30 m (approximately 98 feet), corresponding to the resolution of the topographic input data.

Daily temperature and precipitation observations recorded at stations in Shawano and Waupaca were tabulated for model input. Although these climate parameters vary across the region, these two datasets are representative of the region on average. After review of the climate data, the period from 1981 through 2011 was chosen for input to the model. This recent period includes high-precipitation intervals, such as 1983–1984 and 2010, as well as low-precipitation intervals like 1988–1989, enabling analysis of the variability of groundwater recharge resulting from recent climate trends.

The recharge model uses topographic data to determine surface water flow direction and route runoff. A standard flow direction calculation was applied to a 30-meter digital elevation model (DEM) from the US Geological Survey's National Elevation Dataset (USGS 2003). While more detailed elevation data are available for the area, the 30-meter resolution was appropriate given the regional scale of the study. Because DEMs typically include erroneous depressions that can adversely influence surface flow routing, a standard fill routine was applied to the DEM before the final calculation of the flow direction input grid. Several tests of fill thresholds were conducted, and a complete fill was determined to be the most appropriate. A shaded-relief depiction of the DEM is shown in figure 2.

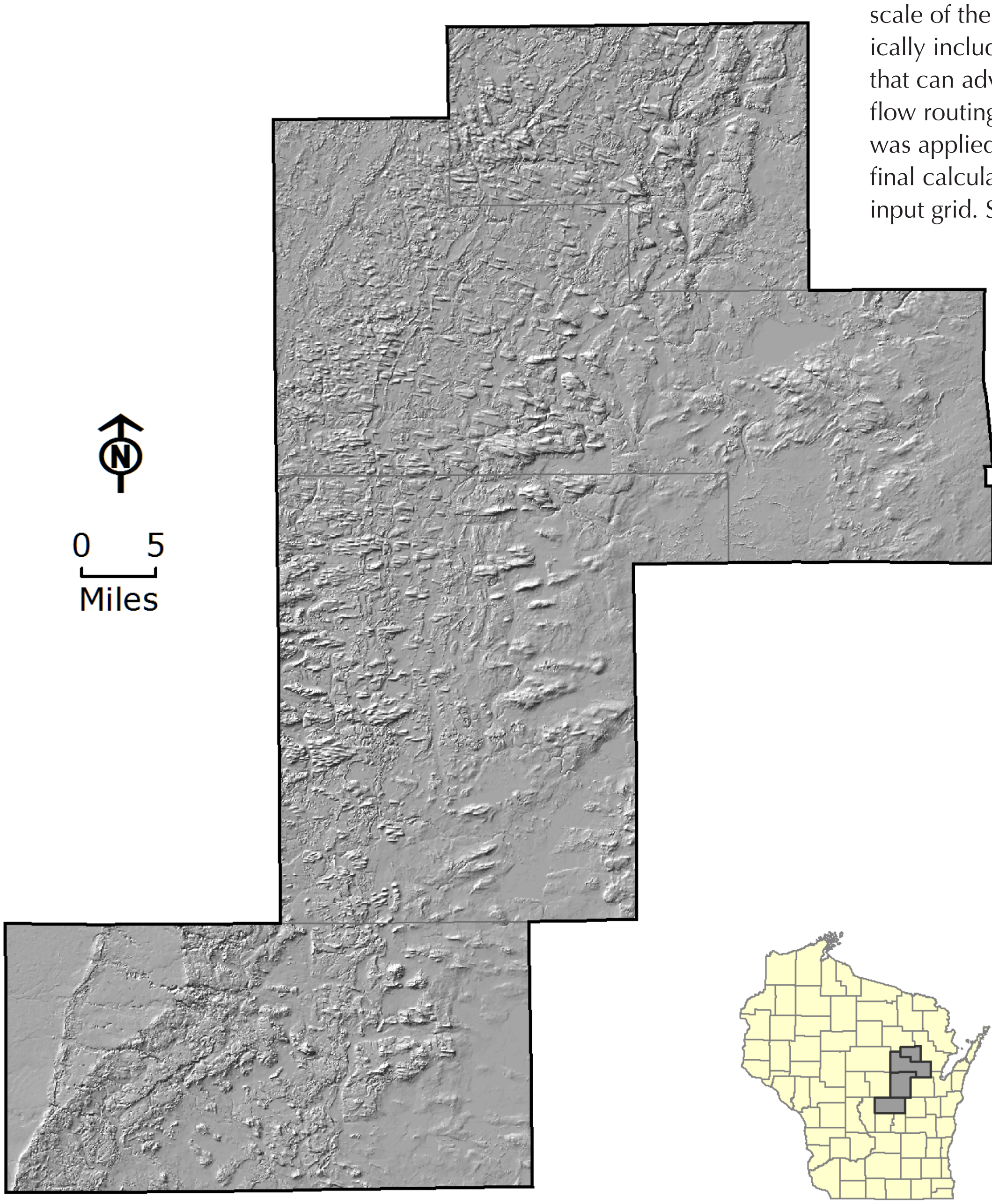
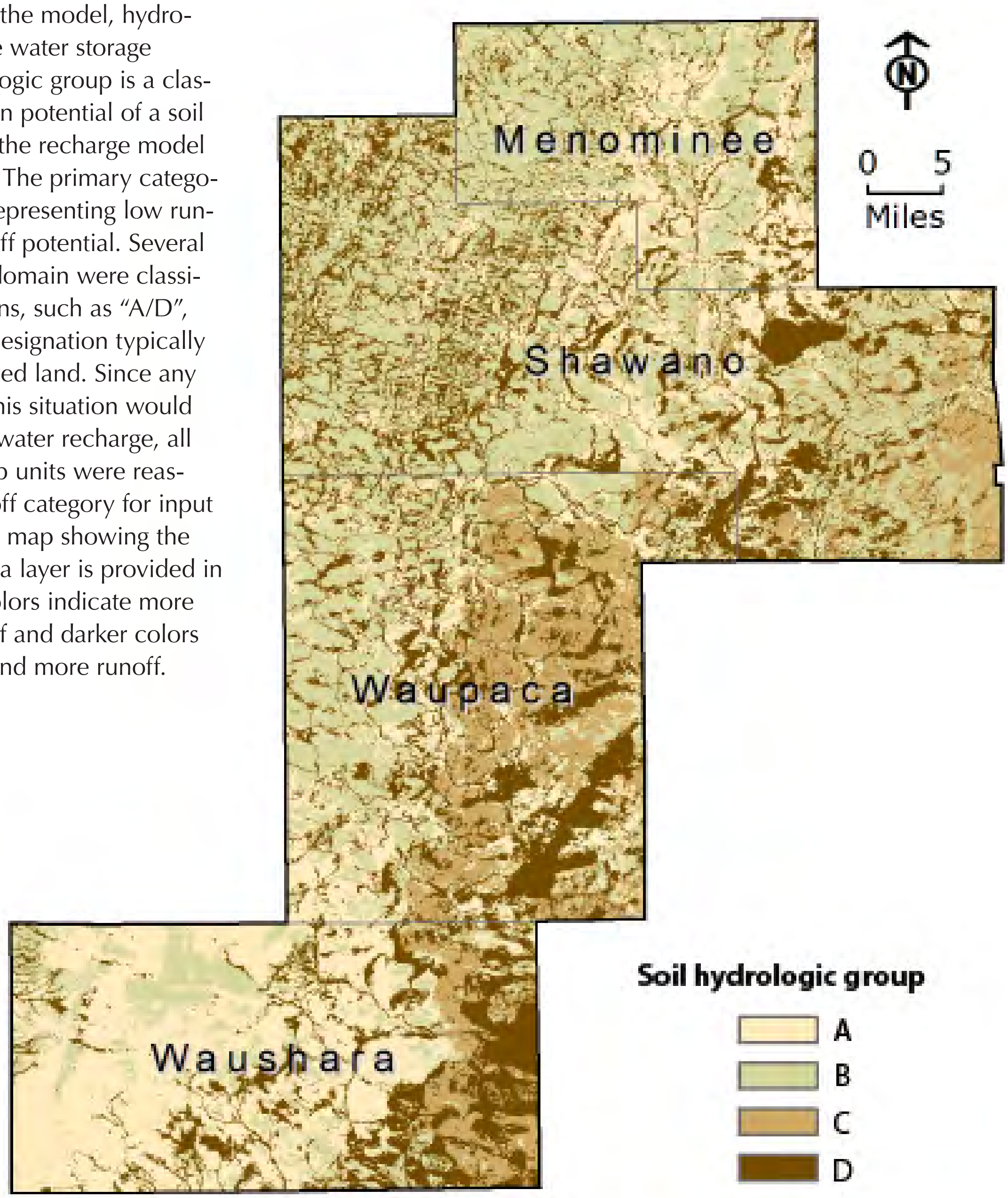


Figure 2. Digital elevation model (showing shaded relief) input to the SWB model, Menominee, Shawano, Waupaca, and Waushara Counties, Wisconsin (USGS 2003).

Digital soil data from the Natural Resources Conservation Service (NRCS) Soil Survey Geographic (SSURGO) Database were used for two input datasets to the model, hydrologic group and available water storage (NRCS 2010). The hydrologic group is a classification of the infiltration potential of a soil map unit, and is used in the recharge model input to calculate runoff. The primary categories range from A to D, representing low runoff potential to high runoff potential. Several map units in the model domain were classified with dual designations, such as "A/D", where the lower-runoff designation typically indicates artificially drained land. Since any infiltration occurring in this situation would not contribute to groundwater recharge, all dual-designation soil map units were reassigned to the higher-runoff category for input to the recharge model. A map showing the soil hydrologic group data layer is provided in figure 3, where lighter colors indicate more infiltration and less runoff and darker colors indicate less infiltration and more runoff.

Figure 3. Soil hydrologic group input to the SWB model, Menominee, Shawano, Waupaca, and Waushara Counties, Wisconsin, Wisconsin (NRCS 2010).



Available water storage, a measure of the amount of water-holding potential in a specified soil thickness, is used by the model for root zone moisture accounting. A map showing the available water storage data layer is provided in figure 4. Darker colors show higher soil water storage capacity; lighter show lower soil water storage capacity.

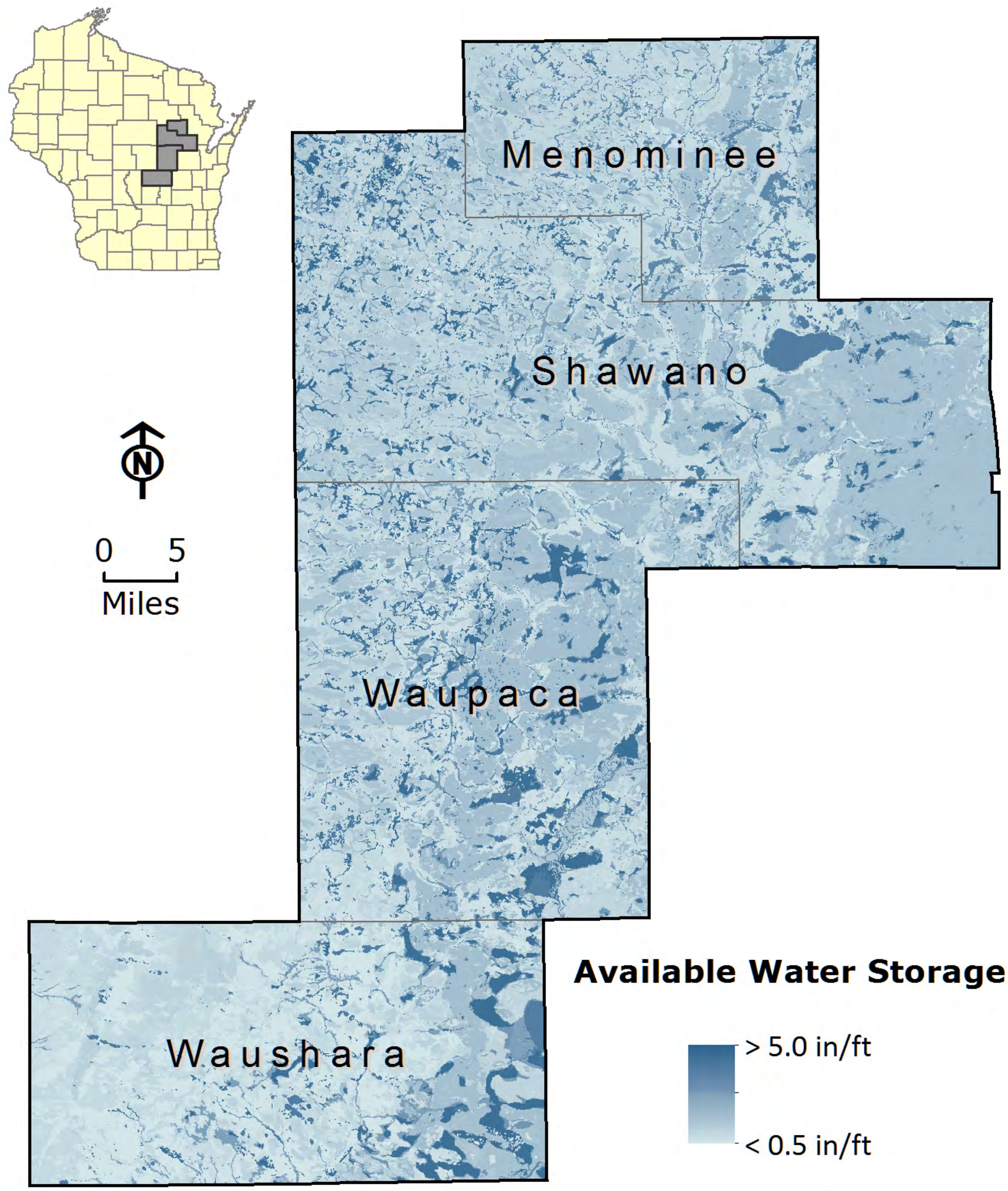
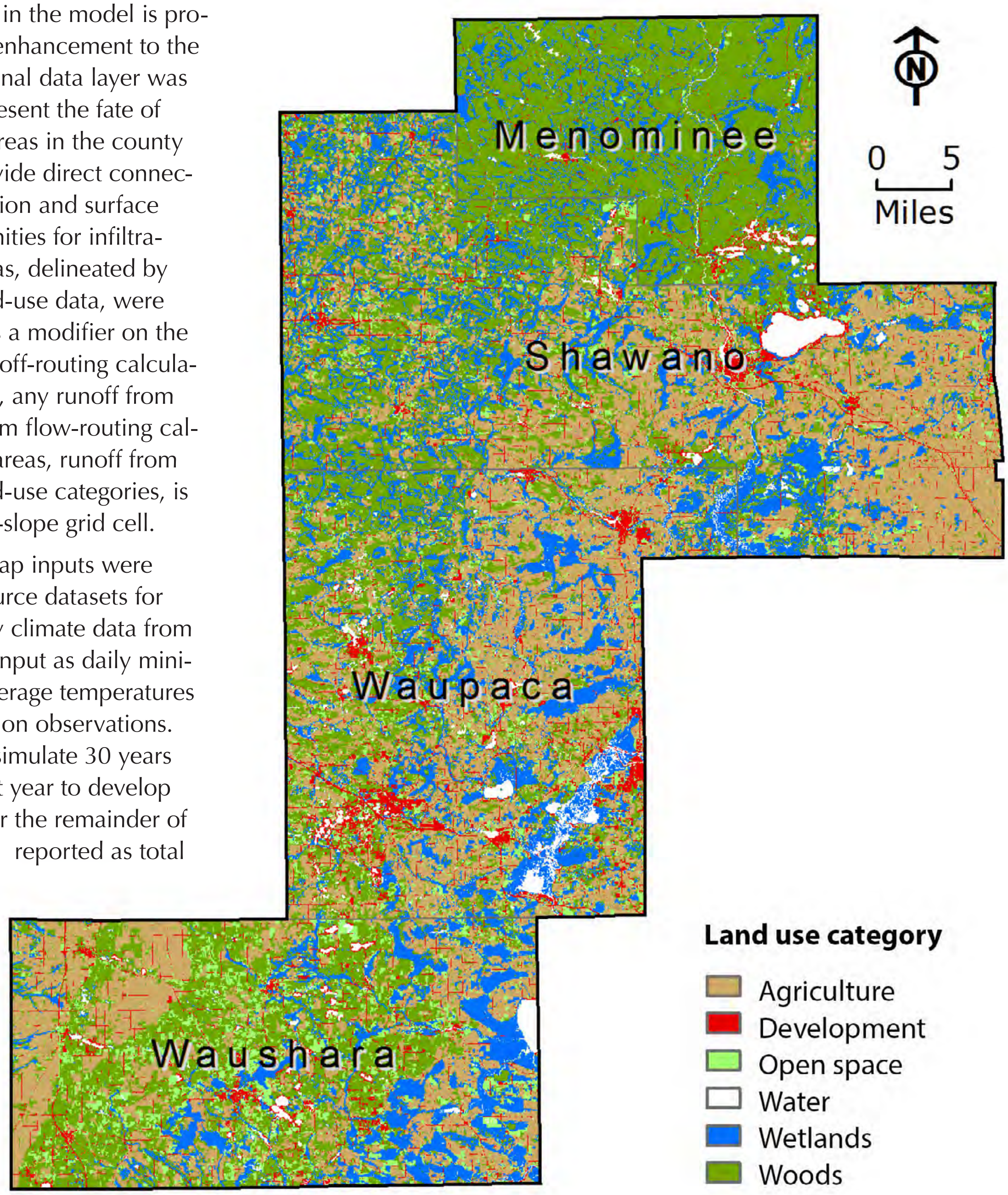


Figure 4. Soil available water storage input to the SWB model, Menominee, Shawano, Waupaca, and Waushara Counties, Wisconsin, Wisconsin (NRCS 2010).

Land-use data are used in calculations of interception, runoff, evapotranspiration, and for determination of root zone depth. Land-use data for 2000 were provided by the East-Central Wisconsin Regional Planning Commission (ECWRPC, 2010). The data also specified runoff curve numbers for each land-use category. These values are used in the standard NRCS TR-55 rainfall-runoff method within the SWB model. A map showing the land-use data layer used in the model is provided in figure 5. As an enhancement to the land-use data, an additional data layer was developed to better represent the fate of runoff from roadways. Areas in the county where storm sewers provide direct connection between transportation and surface water eliminate opportunities for infiltration of runoff. These areas, delineated by ECWRPC within the land-use data, were included in the model as a modifier on the land-use data for the runoff-routing calculations. Within these areas, any runoff from roadways is removed from flow-routing calculations; outside these areas, runoff from roadways, like other land-use categories, is routed to the next down-slope grid cell.

Data grids for the four map inputs were generated from these source datasets for input to the model. Daily climate data from 1981 through 2011 was input as daily minimum, maximum, and average temperatures and total daily precipitation observations. The model was used to simulate 30 years of recharge, with the first year to develop antecedent conditions for the remainder of the period, with output reported as total annual recharge in inches/year. The land-cover category of water was removed from further processing and labeled as undefined. The model output was then smoothed using a focal median method with a 19-cell (approximately 80-acre) area.

Figure 5. Land-use data input to the SWB model, Menominee, Shawano, Waupaca, and Waushara Counties, Wisconsin (ECWRPC, 2010).



Model limitations

The SWB model is a difference model. It subtracts interception, evapotranspiration, runoff, and available moisture storage from precipitation. Error in the modeling of those processes is carried into error of the recharge. The difference is also not strictly recharge but is more properly called deep infiltration since that water has not yet entered the water table. There is a lag time between the deep infiltration simulated by the SWB model and actual recharge. This lag is not as important when using the model to evaluate average recharge distributions over an area since the average represents recharge over all time. The lag time is more important when considering variation of recharge with time and climate since there might be significant differences between the deep infiltration and recharge.

The accuracy of the recharge predicted by this model is limited by the uncertainty and limited resolution of the input parameter grids and by the model itself. The SWB model was developed to make use of readily available data. The resolution of that data limits the resolution of the recharge output. In this model, the physical resolution was limited to 30 meters or more (approximately 98 feet), based on the digital elevation model, the land-use records, and the soils data. The precision and accuracy of the input data is also an issue. The demarcation between the categories of inputs, land uses, and soil types is drawn as a sharp line in the input data, but the actual locations may vary or gradually transition. For example, the dimensions of an infiltration basin might be less than 30 meters and so would not be included in the model as a closed basin. Finer-scale inputs would lead to finer-scale outputs.

The temporal resolution also limits the accuracy of the model. In this model, the precipitation data were input as daily total values, so the model cannot differentiate between a steady rainfall and a 30-minute storm event. This temporal resolution also impacts how runoff is routed. The runoff is routed over the entire model in a single time step. The runoff would be allowed to move the same distance whether the time step was 1 hour or 1 month.

This SWB model had to be altered to avoid introducing error into calculations of recharge through its handling of runoff and infiltration. The digital elevation model was used to route any precipitation that was not infiltrated or intercepted in a single cell. If a basin contained a closed depression along a flow path, large amounts of the runoff could be counted as recharge, resulting in unreasonably large recharge. To correct for this, the digital elevation model was altered to eliminate all closed depressions, thus forcing the digital elevation model to slope to a surface water body that could accept the runoff. Snowmelt timing also adds another possible error. The snowmelt timing is set by surface temperatures with a built-in lag time, but that timing is unlikely to always be correct.

Another issue was that the model limited infiltration by assuming a value of hydraulic conductivity and a unit gradient for each of the four soil hydrologic groups. In reality, the variation within the groups could be significant and so infiltration might be overestimated or underestimated under unit gradient or saturated conditions. The variation will be less than an order of magnitude and will be most important only when the soils are completely saturated. The largest error in total recharge is likely to come from soil groups A and B because they allow the most water. For this reason the upper limit for infiltration was capped at 50 inches/day.

Uncertainty in land-use categories and evapotranspiration (ET) represents another potential model error. The amount of ET for the different land-use categories depends on values of rooting depths for the different soil types for assumed vegetation in the specified land-use category. The model has been shown to be sensitive to rooting depth parameters (Westenbroek and others, 2009) and it is likely that significant variation exists within land-use categories. For example, residential vegetation can vary from trees to grass.

However, in the model both would be treated the same and assigned the same rooting depths in the residential land-use category.

This model also assumes that the soil types in the NRCS SSURGO database are representative of the subsurface from the ground surface to the water table. This assumption may be violated if, for example, an outwash sand overlies a lake clay. However, lithologies found at the surface are most likely the same as those beneath the surface, so the assumption should usually hold.

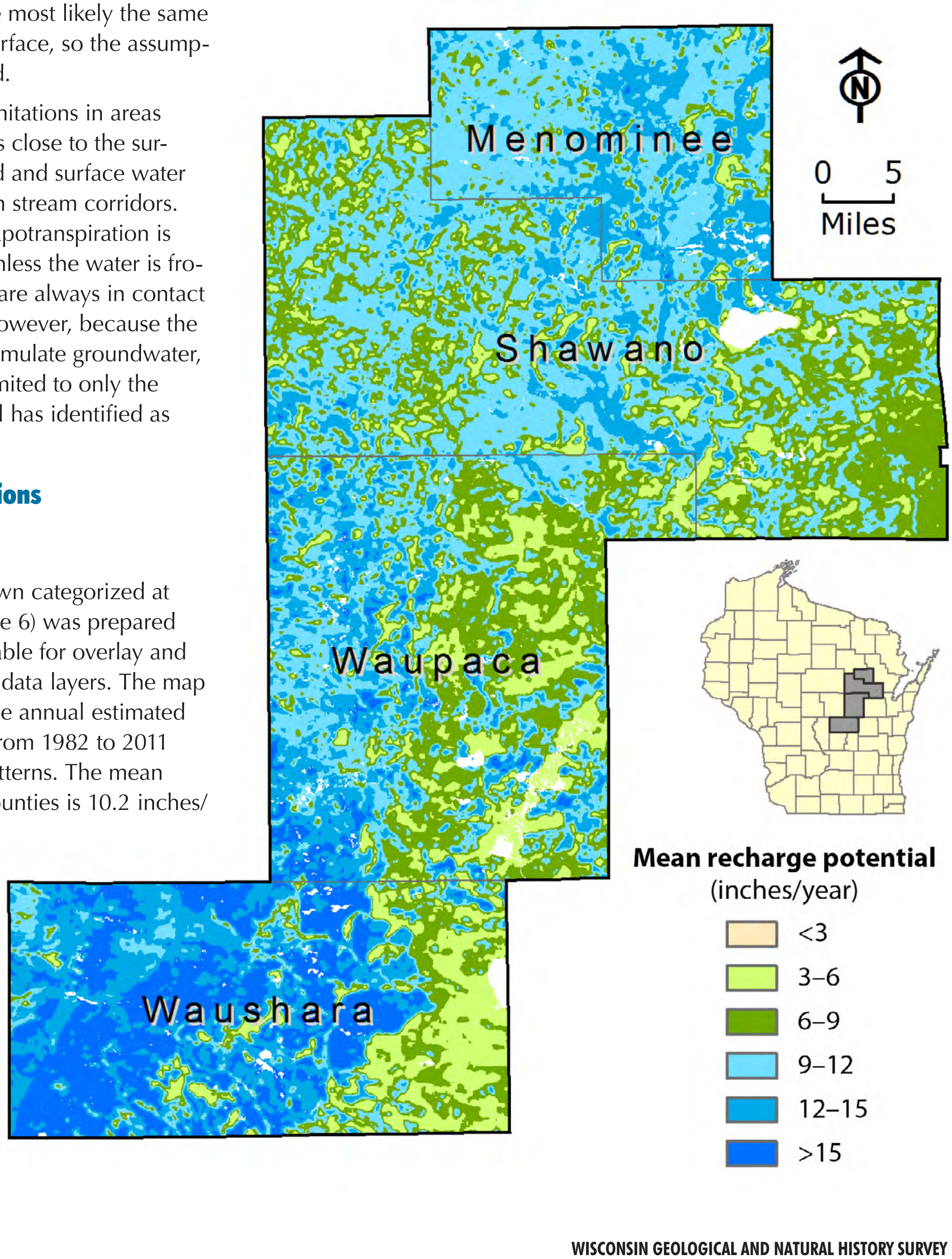
The SWB model has limitations in areas where the water table is close to the surface, such as in wetland and surface water areas and along riparian stream corridors. In these conditions, evapotranspiration is constantly occurring (unless the water is frozen) because the roots are always in contact with the water table. However, because the SWB model does not simulate groundwater, evapotranspiration is limited to only the moisture that the model has identified as infiltration.

Results and applications

Regional recharge

The recharge map (shown categorized at a reduced scale in figure 6) was prepared as a raster dataset, suitable for overlay and analysis with other GIS data layers. The map represents a mean of the annual estimated recharge for the years from 1982 to 2011 using 2000 land use patterns. The mean recharge for the four counties is 10.2 inches/

Figure 6. Recharge in Menominee, Shawano, Waupaca, and Waushara Counties.



year. Table 2 shows the mean, minimum, and maximum recharge for each county averaged over the years from 1982 to 2011. The minimum and maximum values are the smallest and largest in the area of each county for the averaged recharge from 1982 to 2011. Using individual years with their different precipitation patterns and antecedent moisture conditions will result in different recharge estimates but in general, the pattern of recharge remained similar to the mean recharge.

We can combine the estimates of recharge and pumping rates to give an indication of the percentage of water being diverted from the natural flow system to pumping wells. The recharge entering the flow system in gallons/day is calculated by multiplying the area of each county by the recharge rate over that county and converting that volumetric rate to millions of gallons/day (mgd). Those values for the mean recharge rates are shown in table 3 along with the pumping rates from table 1 for Year 2005 and the ratios of pumping rates to recharge.

The percentages of groundwater being diverted to pumping wells in the four counties varies widely, from less than 1 percent in Menominee County to more than 14 percent in Waushara County. In the absence of pumping, this diverted water would discharge to streams, lakes, springs, or wetlands in the region. Evaluating the impacts of this diversion is beyond the scope of this study, but there is a point at which the natural systems that depend on groundwater will show degradation from too much water being diverted. More sophisticated tools such as groundwater flow models, data analysis of pumping over time and with climate, and data collection of groundwater water levels and flows in streams would need to be applied to answer "how much is too much." The value of 14.2 percent in Waushara County indicates the need for further application of these tools and more discussion of water use and how water is valued in that region of the state.

Table 2. Recharge by county.

	Recharge by county (inches/year)		
County	**Mean**	**Minimum**	**Maximum**
Menominee	11.2	3.2	17.3
Shawano	9.2	2.3	16.4
Waupaca	9.5	3.2	18.2
Waushara	12.0	3.1	18.9

Table 3. Comparison of estimated recharge to groundwater pumping.

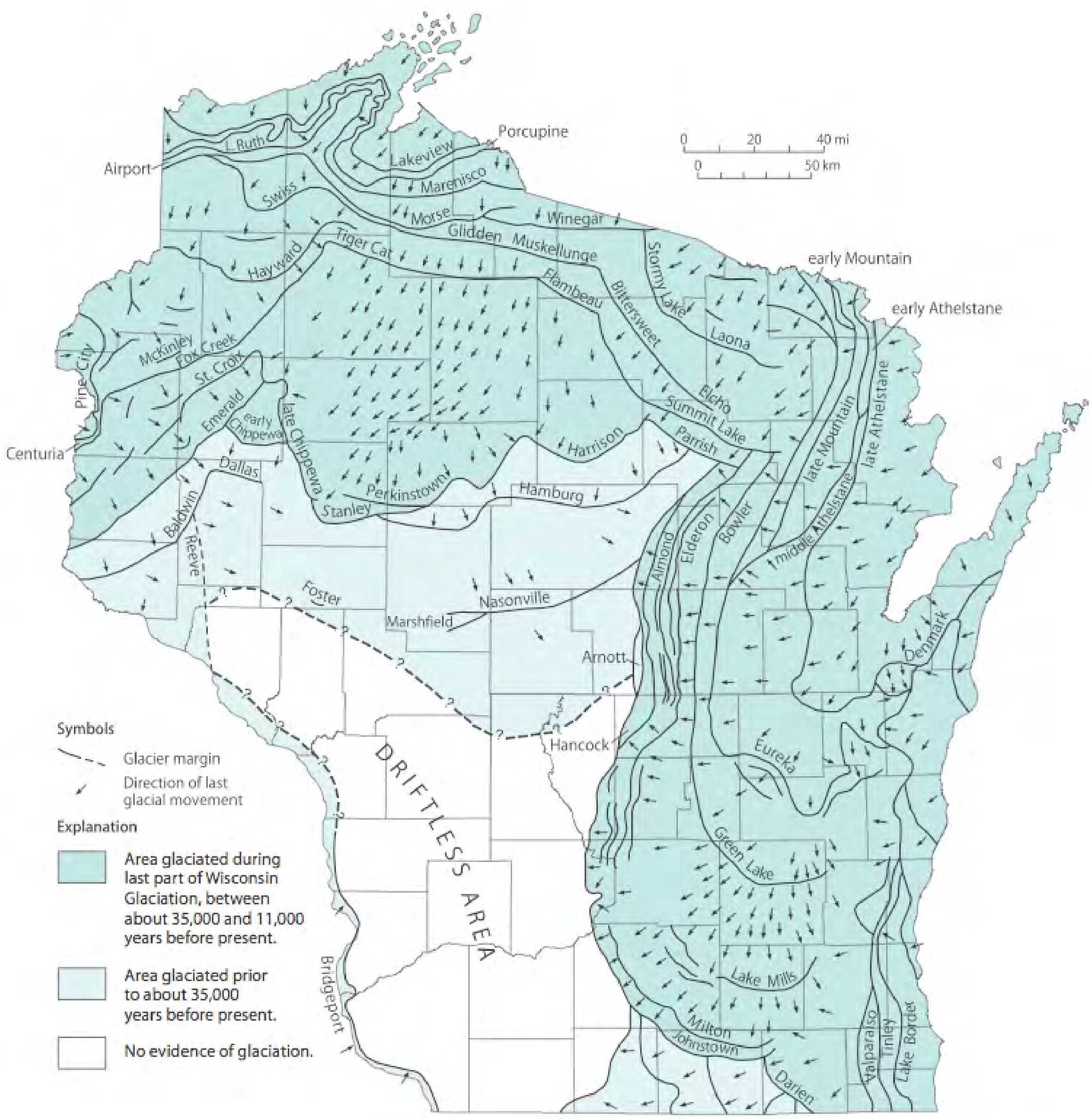
County	Year 2005 pumping (mgd)	Mean recharge (mgd)	Ratio of 2005 pumping to mean recharge (%)
Menominee	0.8	195	0.4
Shawano	5.2	398	1.3
Waupaca	17.7	346	5.1
Waushara	52.0	364	14.2

Glacial geology and recharge

The surficial and glacial geology of the four-county area provides the greatest control on recharge. Other factors such as land use and topography play a secondary role.

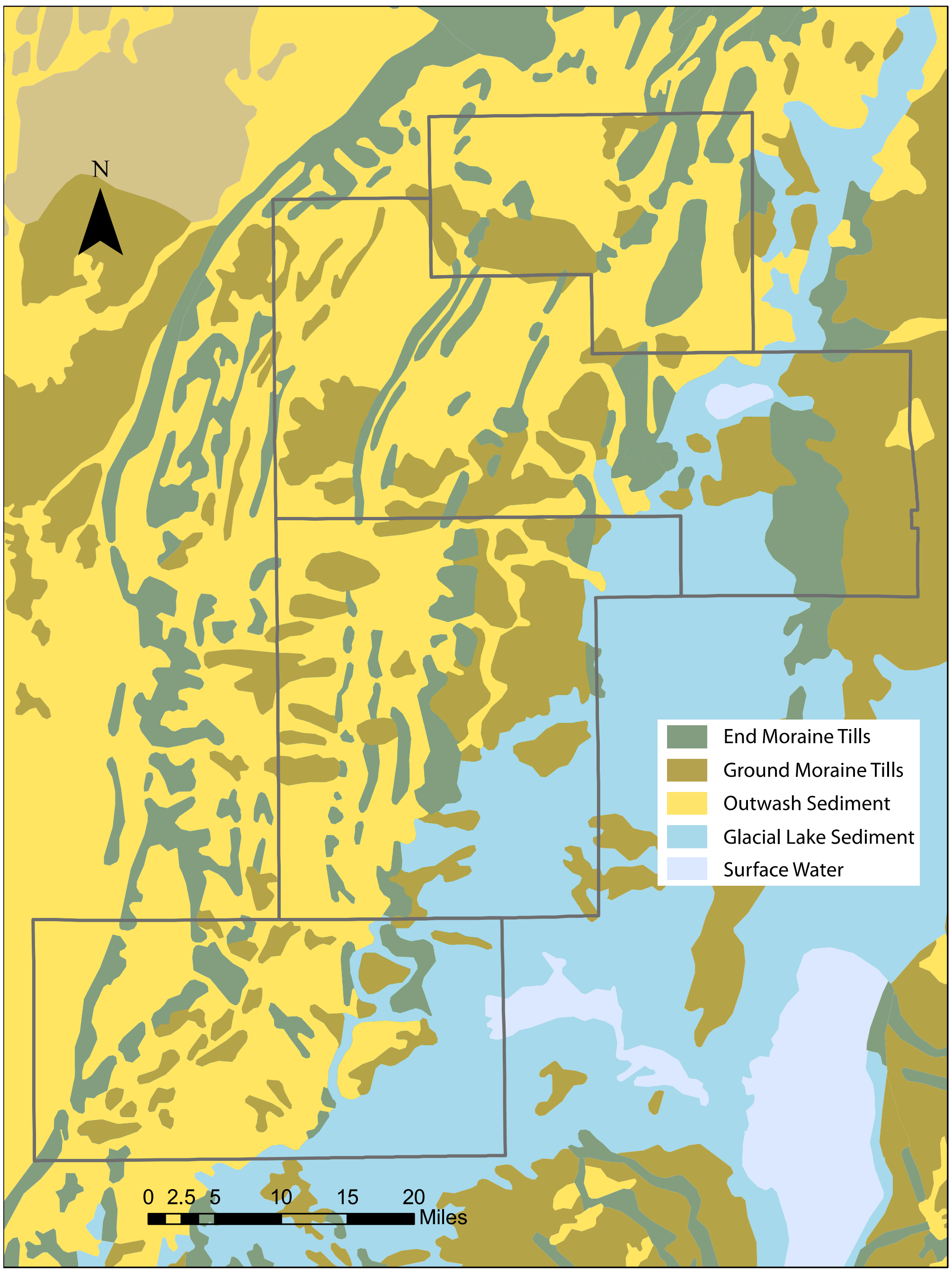
Figure 7 shows the glaciation in Wisconsin. The arrows show the direction of ice flow and the lines show the glacial margins or edge of the glacier at various times. The series of lines mark locations where the glaciers halted during retreat. During the last glaciation, a lobe of glacial ice covered nearly all the four-county area. This glacial ice was called the Green Bay lobe because it flowed out of Green Bay up the present day Fox River valley. As it flowed, it spread and covered most of east-central Wisconsin. Only the northwest corner of Waushara County was not beneath this glacial ice. The advance and retreat of the Green Bay lobe left the soils and sediments that we see today.

Figure 7. Glaciation in Wisconsin (Attig and others, 2011).



In the four-county area, glaciers deposited three general types of sediment: tills, outwash, and lake sediments. These sediments are shown in figure 8. Till, consisting of ground-up rock and sediment, is deposited beneath the glacier as it flows over the land surface to form ground moraines or at the front of glaciers at the ice margin to form end moraines. Outwash sediments are deposited in front of glaciers. As the ice melts, the meltwater deposits the sands and gravels near the front of the glacier, the silts and clays much farther away. These sediments filled in the low areas as the glacier retreated and

Figure 8. Glacial sediments in Menominee, Shawano, Waupaca, and Waushara Counties (after Farrand and others, 1984, and Lineback and others, 1983).



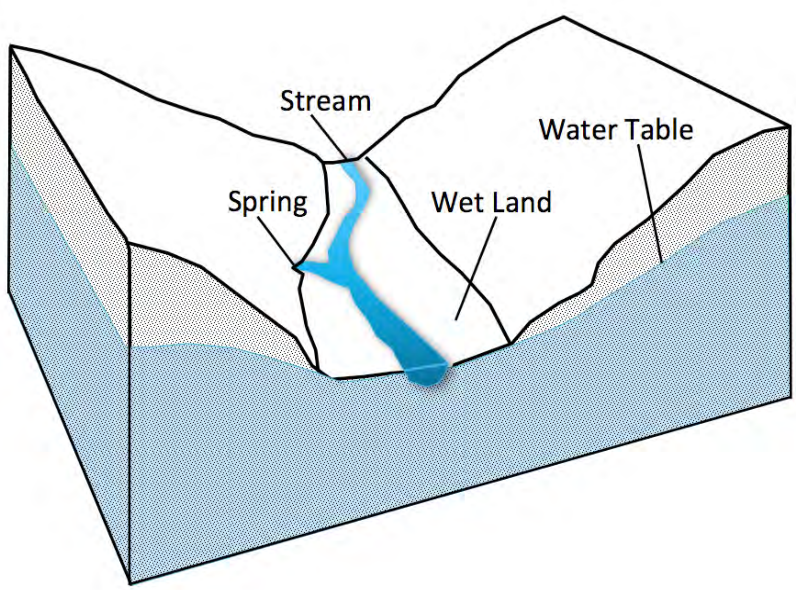
sometimes lie on top of end and ground moraine tills. Lake sediments form when the meltwater can't flow away and a lake forms at the front of the glacier. Because the clays and silts aren't carried away, glacial lake sediments are often fine grained. The lake sediments shown in the map are fine grained and are in the glacial Lake Oshkosh basin (Hooyer and Mode, 2008). This glacial lake formed in front of the glacier that extended up the Fox River Valley from Green Bay. It periodically drained as the glacier retreated. Lake Winnebago is a remnant of this glacial lake. In general, the areas of outwash correspond to higher recharge values, tills to intermediate recharge values, and glacial lake sediments to lower recharge values.

A comparison of the recharge in figure 6 and the glacial sediments in figure 8 shows how recharge and the sediments are related. The lower recharge areas along the eastern edge of Shawano, Waupaca, and Waushara counties corresponds to the locations of fine-grained lake sediments. The intermediate recharge corresponds to the locations of tills in all four counties and the higher recharge areas correspond to the locations of outwash.

Springs and recharge

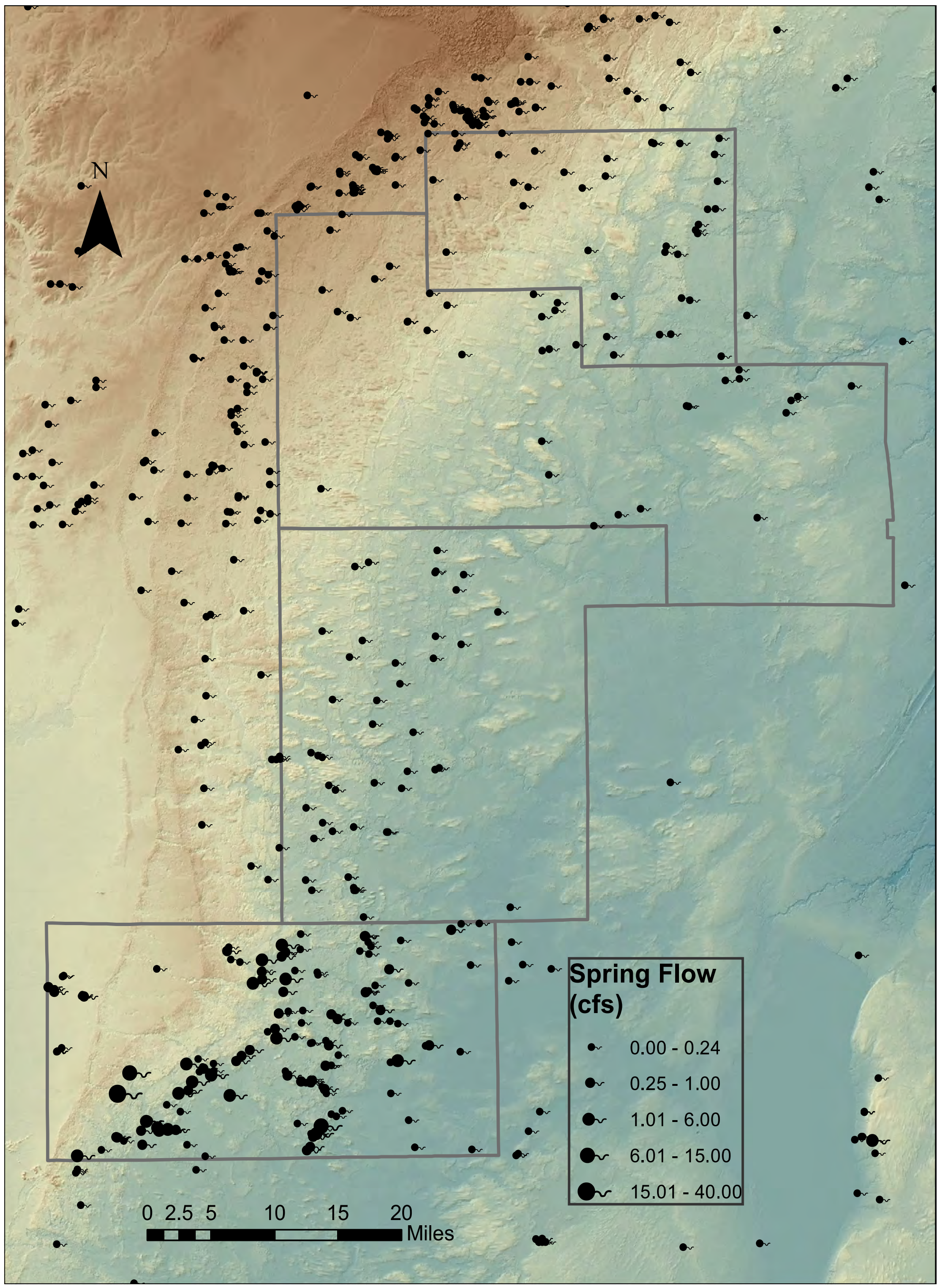
Springs are points or areas of localized discharge of groundwater and are often one of the more prominent components of a groundwater flow system. Springs are sensitive to changes in the flow system and as such are good indicators of groundwater quality and quantity. In this region of Wisconsin, springs commonly form where the water table intersects the land surface. A spring can form initially as a small seep on the hillside. If that seep has enough flow, it can erode sediment, forming a small cut back into the hillside. When that happens more of the water table is intersected by the land surface which in turn increases flow and potential erosion. After a time, the seep will become a spring and form a spring pool or channel into the hill slope. Figure 9 is a diagram showing a spring with a small channel into the hillside, the shallow water table, wetland area, and a stream.

Figure 9. Diagram of a spring and its relationship to the water table, the ground surface, and surface waters (modified from Dean and others, 1976).



Most of the springs in the region discharge to lowland area wetlands and are located near the base of the hills and ridges left by the glaciers. Figure 10 shows the relationship between spring locations (Macholl, 2007) and surface topography.

Figure 10. Topography and spring locations (Macholl, 2007).



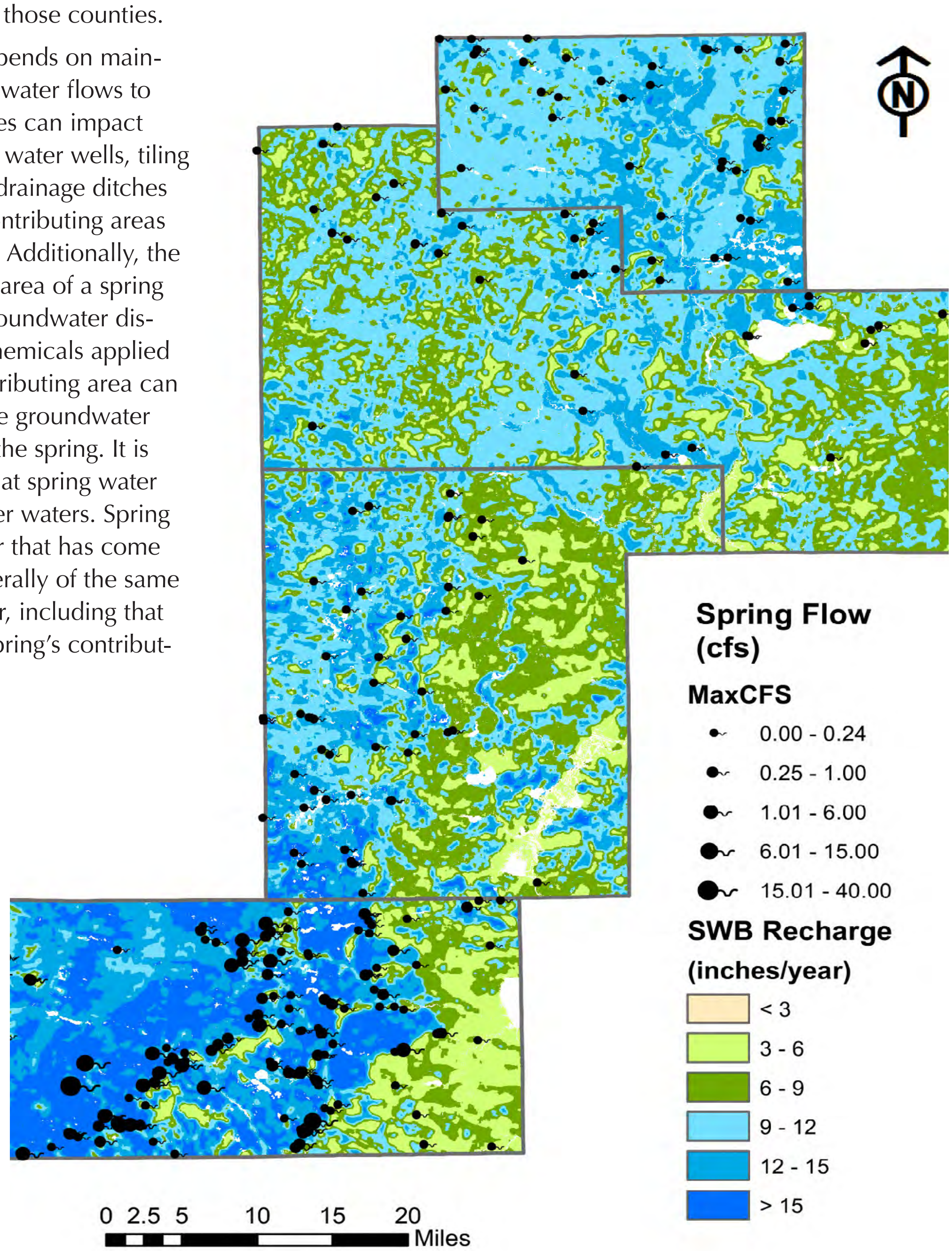
Recharge also plays a large role in the location and size of springs in the region. Figure 11 shows recharge and the spring location and flows. In this region springs are located where recharge is high and there is a change in topography so that the water table is at or very near the land surface. Waushara County has the highest concentration of springs and springs with the largest flows, followed by Menominee County and western Waupaca County, reflecting the high recharge areas and the hilly nature of those counties.

A plan to protect springs depends on maintaining recharge and groundwater flows to the springs. Land use changes can impact recharge and pumping from water wells, tiling of fields, or construction of drainage ditches can divert flows from the contributing areas of springs and reduce flows. Additionally, the land use in the contributing area of a spring can impact the quality of groundwater discharging from the spring. Chemicals applied to the land surface in a contributing area can be carried by recharge to the groundwater and ultimately discharge to the spring. It is a common misperception that spring water is of higher quality than other waters. Spring water is merely groundwater that has come to the surface and so is generally of the same quality as other groundwater, including that from wells installed in the spring's contributing area.

Comparison of SWB and baseflow recharge estimates

The SWB recharge model was compared to USGS baseflow measurements (Gebert and others, 2007). Unlike the USGS baseflow measurements, the SWB model does not include any direct measurements of flow in the hydrologic system and so a comparison

Figure 11. Recharge and spring locations (Macholl, 2007).



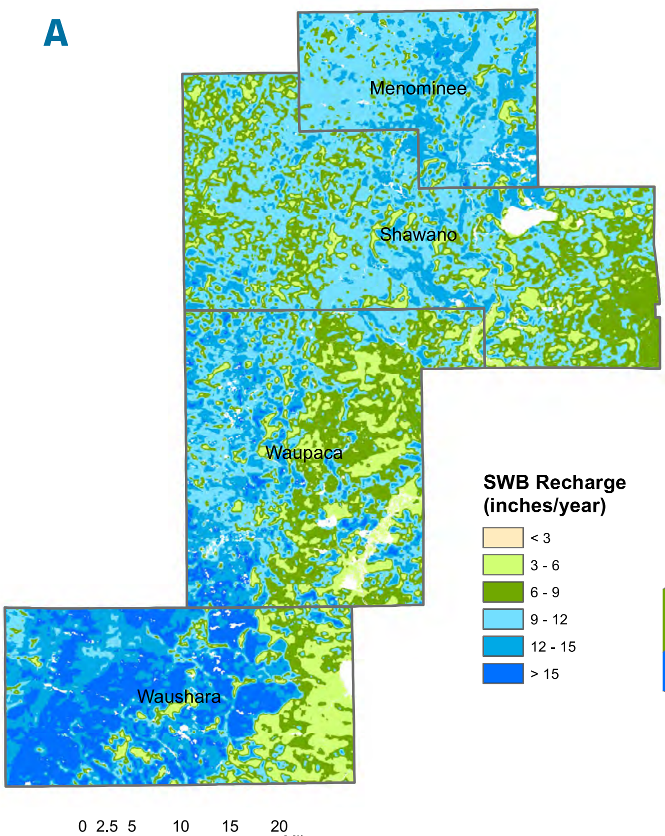
to the more direct USGS measurements of the baseflows provides a needed check of the SWB model. Figure 12 shows recharge estimated by the SWB model and the basins and the estimated recharge from baseflow in each basin.

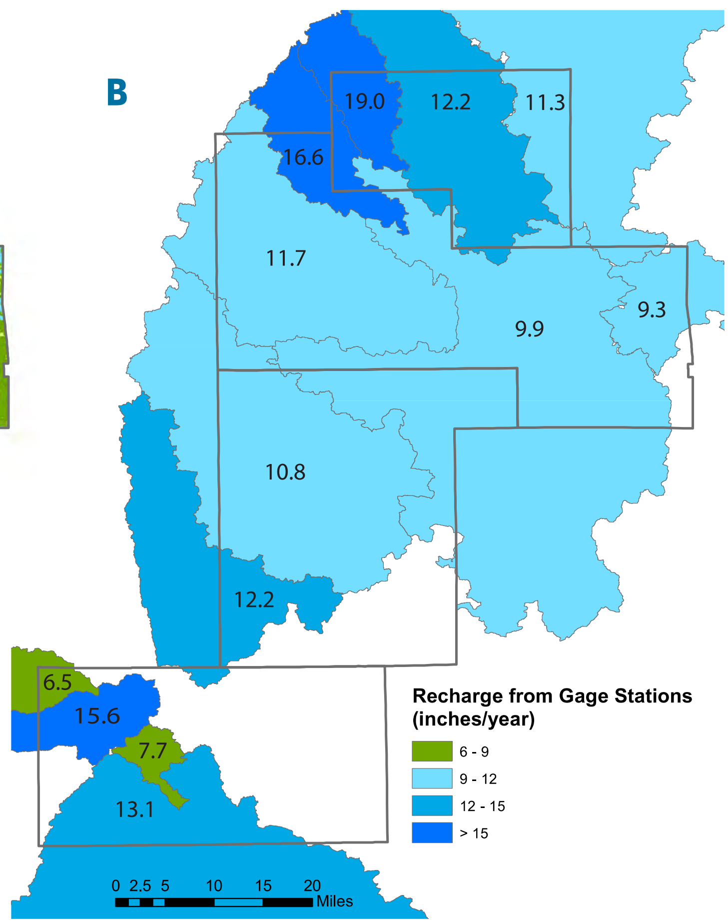
The two estimates of recharge agree in broad terms. Menominee and Waushara counties have the highest overall recharge in both estimates and Shawano and Waupaca have less recharge. However, there are some discrepancies. In northwestern Menominee and northern Shawano counties, recharge estimated by baseflow is at 19.0 and 16.6 inches/year. This is much higher than the values from the SWB model that are all less than 12 inches/year. Likewise, in western Waushara County the baseflow estimates are at 15.6, 13.1, 7.7, and 6.5 inches/year. While the higher values are in good agreement with the SWB model, the lower values, 6.5 and 7.7 are much lower than the SWB estimates. The intermediate values from the baseflow estimates in Shawano and Waupaca counties are in reasonable agreement with the SWB model. One of the complicating factors when comparing the two estimates is that parts of the basins are nearly always outside of the SWB model area. Another confounding factor is that the basin baseflow estimates are for the period from 1970 to 1999 while the SWB estimate is for the period from 1982 to 2011.

Climate and recharge

Climate affects recharge, with recharge typically increasing when precipitation increases and decreasing during time of drought. In addition to this fundamental relationship, the timing and intensity of precipitation and temperature also have important impacts on recharge. These variables are incorporated

Figure 12. Comparison of recharge estimated from the SWB model (A) and from baseflow measurements (B).



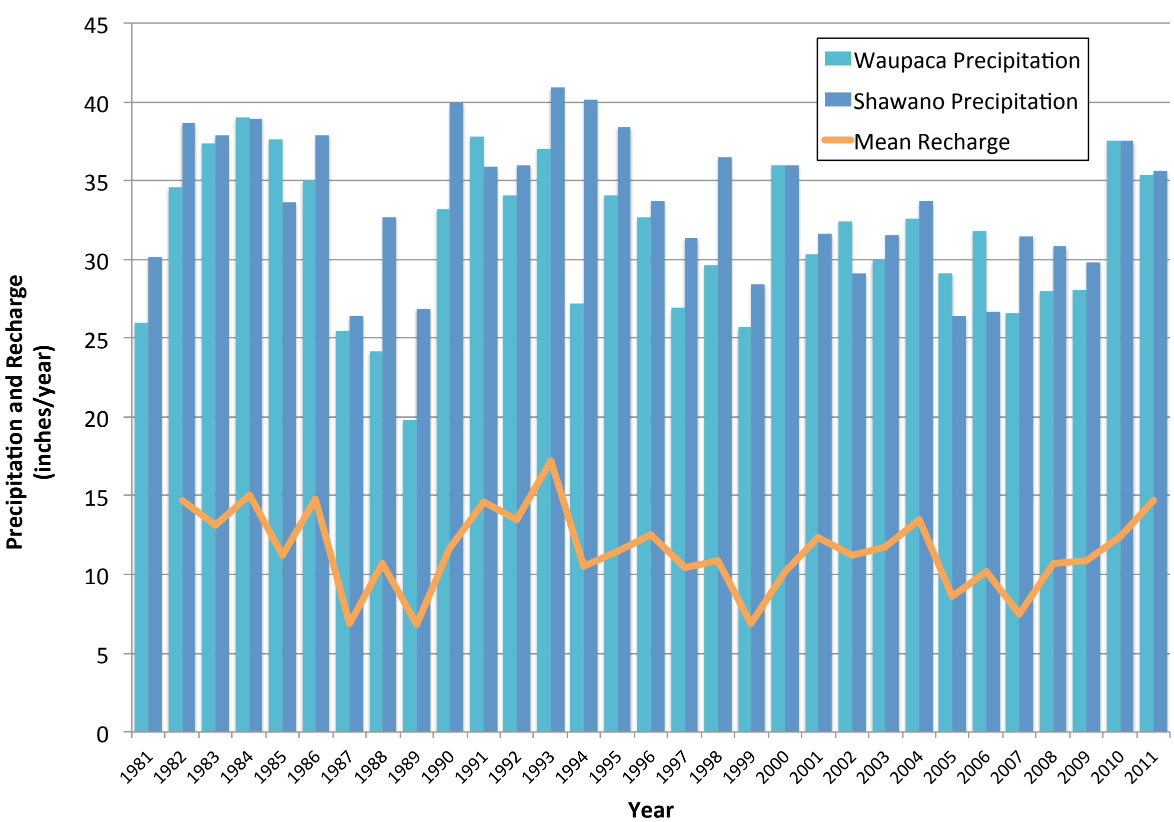


into the model via the processes of runoff, infiltration, and evapotranspiration.

A strict definition of recharge states that it is water that crosses the water table. The SWB model does not estimate the amount of water that crosses the water table. It does estimate the water that infiltrates below the rooting zone and enters the unsaturated zone. That water will eventually become recharge as it moves downward through the unsaturated zone to the water table. The timing of that flow and movement is not simulated by the SWB approach. If it is important to know when the deep infiltration estimated by SWB crosses the water table then a more sophisticated code such as the UZF package in MODFLOW (Niswonger and others, 2006) must be used. For this reason, the actual timing of recharge will lag behind the deep infiltration predicted by the SWB model as the water moves through the saturated zone and will be buffered by the unsaturated zone above the water table. Even with these caveats about the difference between recharge and deep infiltration, the SWB model can illustrate how the shallow groundwater flow system can be affected by several dry years or inundated in several wet years.

The SWB model was used to illustrate the relationship between climate and deep infiltration that will ultimately be recharge. Figure 13 shows the annual variation of precipitation at Shawano and Waupaca, WI. These two weather stations were chosen to represent the climate of the four-county area. Annual estimates of deep infiltration or potential recharge are also shown in figure 13 with land use held constant at the 2000 pattern. During this

Figure 13. Annual precipitation and potential recharge, 1982–2011.
Recharge was estimated using year 2000 land-use conditions for the entire period.



period, annual precipitation varied from a low of 19.8 inches/year in 1989 in Shawano to a high of 40.9 inches/year in Waupaca in 1993. The lowest yearly recharge rate of 6.8 inches/year occurred in 1989. A consecutive period of dry years, such as those prior to 1989, can cause recharge rates to decrease dramatically, because the soils have high available storage available that prevents deep infiltration and the plants have higher transpirations needs that also prevents deep infiltration. The average precipitation for the two weather stations remained below 29 inches/year for the period from 1987 to 1989. Recharge decreased over this period by half. Alternatively, the period of wet years from 1990 to 1993 with precipitation of more than 35 inches/year created conditions for the highest yearly recharge rate of 17.2 inches/year because the soils are unable to store the water and the plants have more soil moisture than they need for transpiration allowing water to infiltrate more quickly.

Irrigation and recharge

The impact of irrigation to groundwater is often difficult to assess. We used the SWB model to determine whether it might be a useful tool to determine impacts to groundwater from irrigation. We ran the model for a quarter-section (160 acre) field using soil properties from northwestern Waushara County under climate year 2004 for both irrigated and non-irrigated conditions. The land use and cover was for a generic agricultural category. Potential evapotranspiration and rooting depths specific to a crop type, for example, corn or potatoes, were not applied. The irrigation amount was applied daily with the rate calculated from the monthly total pumping divided by the number of days in the months of May, June, July, and August. These rates were an average of 2011 and 2012 rates from the WDNR high capacity water use database for a field in northwest Waushara County. Table 4 gives the irrigation rates for the four months.

We determined an upper and lower limit of the impact of irrigation to recharge estimated by the SWB model. The limits were found by applying different assumptions about how the precipitation and irrigation are routed after application to the field. Figure 14 shows the outputs of the SWB model for irrigated and non-irrigated conditions and give the upper and lower limits for the impact to groundwater. The net gain to groundwater is measured as the difference between recharge and irrigation pumping. Under non-irrigated conditions (fig. 14A), recharge is 6.3 inches and pumping is 0.0 inches for a net gain to groundwater of 6.3 inches under the field during the growing season. Under irrigated conditions with assumptions producing greatest impact to groundwater (fig. 14B), recharge is 9.0 inches and pumping is 8.6 inches for a net gain to groundwater of 0.4 inches under the field during growing season. The difference between the upper limit for irrigation (fig. 14B) and non-irrigation (fig. 14A) is 5.9 inches of recharge lost. This difference is made up of increased evapotranspiration, runoff, and soil moisture storage in the irrigated model.

The estimate above provides an upper limit of the impact of irrigation on the groundwater system. Assumptions are made with this

Table 4. Irrigation rates by month, May–August.

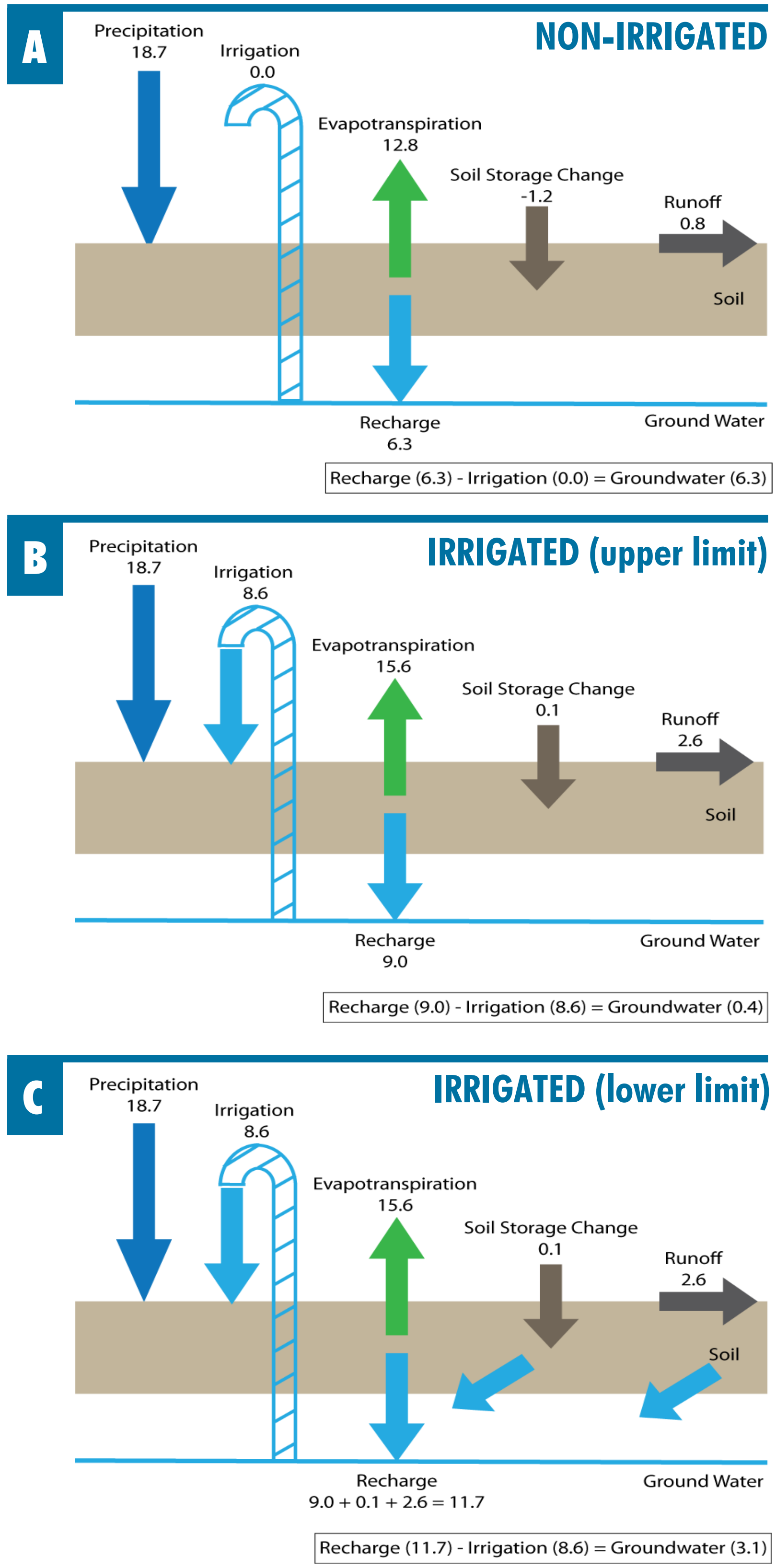
	Month			
	May	**June**	**July**	**August**
Monthly pumpage (gallons)	18,000	10,797,000	15,093,000	12,051,000
Daily pumping rate (gpm)	0.4	250	338	270
Daily application rate (inches/day)	0.0001	0.081	0.11	0.088

SWB model that, in general, will cause it to overestimate impacts to groundwater from irrigation. These assumptions include the potential evapotranspiration rate, runoff routing, and irrigation rate. In the model, potential evapotranspiration for a crop did not vary over the growing season. Instead, it was set to a constant level more consistent with a crop in the middle of the growing season. Runoff was removed beyond the field boundaries and was not allowed infiltrate. It seems likely that if the runoff encountered the ditches surrounding most fields, it would infiltrate and become recharge. Finally, irrigation rates were averaged over the entire month, regardless of recent precipitation. Such averaging might create excess runoff and evapotranspiration if the soil is near water-holding capacity.

We can also estimate a lower limit of impact to groundwater (fig. 14C). If we assume that only evapotranspiration removes water from the model and that all runoff and soil moisture eventually becomes recharge, then the model provides a lower estimate of the impacts to groundwater from irrigation. As argued above, the runoff could infiltrate and become recharge and the soil moisture at the end of the growing season could end up as recharge since little transpiration would occur after harvest. In this case, recharge (9.0 inches) is increased by runoff (2.6 inches) and soil moisture (0.1 inches) to 11.7 inches over the growing season. Using these assumptions, recharge is 11.7 inches and pumping is 8.6 inches for a net gain to groundwater of 3.1 inches during the growing season. The difference between the lower limit for irrigation (fig. 14C) and non-irrigation (fig. 14A) is 3.2 inches of recharge lost.

The model appears to give reasonable estimates of the impacts to groundwater from irrigation. Both assumptions predicted that while recharge was significantly decreased, some recharge would still enter the groundwater system under irrigated conditions. Water is still added to the groundwater system under irrigation, just not as much as under non-irrigated conditions.

Figure 14. Comparisons of non-irrigated (A) and irrigated (B, C) water budgets over the growing season. Units are in inches/growing season.



This simulation was conducted for the growing season. For the remainder of the year, when crops are not being irrigated, recharge amounts for both scenarios would be similar because no pumping is occurring. However, there may be a small difference due to differences in soil moisture storage at the end of the growing season.

Decreased recharge due to irrigation will eventually result in decreased discharge to surface waters.

Before the model is widely applied to estimations of reduced recharge due to irrigation, the question of appropriate evapotranspiration parameters should be answered and a field validation of the model should be conducted.

Summary

A new estimate of the distribution of groundwater recharge for Menominee, Shawano, Waupaca, and Waushara counties, Wisconsin, is based on a soil-water balance (SWB) recharge model constructed for the counties. Results from the application of that model are in reasonably good agreement with other recharge estimates with respect to relative amounts of recharge. The strength of the SWB model is its high resolution, wide coverage, and relatively low effort. Its weakness is the lack of direct measurements and the reliance on imperfectly modeled hydrologic processes. The recharge map was prepared on a scale of approximately 80 acres, much smaller than the subwatershed or watershed scale of previous estimates. This project has produced both a detailed recharge GIS data layer for the counties, and a tool (the SWB model itself) for generating other recharge estimates for different scenarios (such as changing climate or variations in land-use practices).

Recharge is variable over time and location. The annual SWB recharge or deep infiltration for Menominee, Shawano, Waupaca, and Waushara counties varied from 6.8 inches/year to more than 17 inches/year for the period from 1982 to 2011. This temporal variation is caused by annual climatic variability.

The variation of recharge in space depends on the land use, the soil type, and the land surface topography. Society most alters recharge by altering land use, the other inputs being less easily changed by human interaction. This gives land-use planning a critical role in recharge management.

The following list summarizes key points from the model and suggests ways the information might be put to use:

- **Consider soil types and geology when making land use decisions that will reduce infiltration.** Due to the presence of sandy soils, these four counties all have high recharge compared to other areas of the state. Springs are more common and have higher flows in the higher recharge areas of the four counties.

  Recommendation: The model can identify areas that contribute most to the groundwater flow system. Maintaining recharge may be important for human groundwater supply or to maintain a natural feature such as a spring, stream, or lake. Note, too, that infiltration basins constructed in heavy soils will not be as effective as those built in sandy soils.

- **The amount of water entering the groundwater flow system is highly variable.** The amount of water entering the groundwater flow system as deep infiltration was estimated to vary from 17.2 inches after several wet years to 6.8 inches after several consecutive dry years.

  Recommendation: Educate the public and policy makers so that they can take this variability into account. For example, after several wet years, some areas may flood that were thought to always be dry, and after several dry years, water levels in wells, lakes, rivers, and streams may drop. Recharge is very sensitive to climate variability. Decision-makers should always keep long-term trends and potential future climate variability in mind when considering changes on the landscape.

- **Land-use changes can alter recharge availability.** Although this area does not have large urban areas that inhibit recharge, there has been an increase in irrigation. The model predicted that net inflows to groundwater is reduced from 6.3 inches/growing season to a range of 3.5 to 0.4 inches/growing season beneath the field going from non-irrigated to irrigated conditions. That range depends on model assumptions that should be tested. Additionally pumping is a significant portion of recharge in some areas, 14.2% in Waushara County.

  Recommendation: The SWB model might be a useful tool for understanding the impacts to groundwater from irrigation but needs to be validated before it is put into use at field scales studies of recharge in the Central Sands. The work by Radatz and others (2012) and Kraft and others (2012) would be part of that validation. The impacts of pumping in areas where it is a significant part of recharge should be better evaluated. This evaluation can include groundwater flow models, analysis of pumping rates with time and location, and collection of groundwater and lake levels and flow rates in streams. A discussion of water use and the value of water could also take place.

References

Attig, J.W, Bricknell, M., Carson, E.C., Clayton, L., Johnson, M.D., Mickelson, D.M., and Syverson, K.M., 2011, Glaciation of Wisconsin (fourth edition): Wisconsin Geological and Natural History Survey Educational Series 36, 4 p.

Buchwald, C.A., 2009, Water use in Wisconsin, 2005: U.S. Geological Survey Open-File Report 2009–1076, 76 p.

Dean, T.J., Barks, J.H., and Williams, J.H., 1976, A guide for the geologic and hydrologic evaluation of small lake sites in Missouri: Missouri Department of Natural Resources Water Resources Report 31, 56 p.

Dripps, W.R., and Bradbury, K.R., 2007, A simple daily soil-water balance model for estimating the spatial and temporal distribution of groundwater recharge in temperate humid areas: *Hydrogeology Journal*, v. 15, no. 3, p. 433–444.

East Central Wisconsin Regional Planning Commission (ECWRPC), 2010, Existing land use data for 2007–2008 for Menominee, Shawano, Waupaca, and Waushara Counties, Wisconsin: ECWRPC, GIS data files, received November 2010.

Ellefson, B.R., Mueller, G.D., and Buchwald, C.A., 2002, Water use in Wisconsin, 2000: U.S. Geological Survey Open-File Report 02-356, 1 plate.

Farrand, W.R., Mickelson, D.M., Cowan, W.R., and Goebel, J.E., 1984, Quaternary geologic map of the Lake Superior 4 x 6 Quadrangle, United States and Canada, in Richmond, G.M., and Fullerton, D.S., eds., Quaternary geologic atlas of the United States: U.S. Geological Survey Map I-1420 (NL-16), scale 1:1,000,000.

Gebert, W.A., Radloff, M.J., Considine, E.J., and Kennedy, J.L., 2007, Use of streamflow data to estimate baseflow/groundwater recharge for Wisconsin: *Journal of the American Water Resources Association*, v. 43, no. 1, p. 220–236.

Hooyer, T.S., and Mode, W.M., 2008, Quaternary geology of Winnebago County, Wisconsin: Wisconsin Geological and Natural History Survey Bulletin 105, 2 plates, 41 p.

Kraft, G.J., Clancy, C., Mechenich, D., and Haucke, J., 2012, Irrigation effects in the northern lake states: Wisconsin central sands revisited: *Ground Water*, v. 50, no. 2, p. 308–318.

Lineback, J.A., Bleuer, N.K., Mickelson, D.M., Farrand, W.R, and Goldthwait, R.P., 1983, Quaternary geologic map of the Chicago 4 x 6 Quadrangle, United States in Richmond, G.M., and Fullerton, D.S., eds., Quaternary geologic atlas of the United States: U.S. Geological Survey Map I-1420 (NK-16), scale 1:1,000,000.

Macholl, J.A., 2007. Inventory of Wisconsin's Springs: Wisconsin Geological and Natural History Survey Open-File Report 2007-03, 1 CD-ROM.

Natural Resources Conservation Service (NRCS), 2010, Soil survey geographic (SSURGO) database for Calumet, Outagamie, and Winnebago Counties, Wisconsin: http://soildatamart.nrcs.usda.gov, accessed September 2010.

Niswonger, R.G., Prudic, D.E., and Regan, R.S., 2006, Documentation of the unsaturated-zone flow (UZF1) package for modeling unsaturated flow between the land surface and the water table with MODFLOW-2005: U.S. Geological Techniques and Methods Book 6, Chapter A19, 62 p.

Radatz, A.M., Lowery, B., Bland, W.L., and Hartemink, A.E., 2012, Groundwater recharge under compacted crop areas compared with prairie vegetation in central Wisconsin, USA: ISTRO Conference, Uruguay.

U.S. Department of Agriculture (USDA), 2007, National engineering handbook, part 630 hydrology: U.S. Department of Agriculture, chapter 7, p. 5.

U.S. Geological Survey (USGS), 2003, National elevation dataset digital elevation data for Wisconsin: http://ned.usgs.gov, data received in 2003.

Westenbroek, S.M., Kelson, V.A., Dripps, W.R., Hunt, R.J., and Bradbury,K.R., 2009, SWB—A modified Thornthwaite-Mather soil-water-balance code for estimating groundwater recharge: U.S. Geological Survey Techniques and Methods 6–A31, 61 p.

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