Groundwater recharge in Calumet, Outagamie, and Winnebago Counties, Wisconsin, estimated by a GIS-based water-balance model

David Hart
Peter Schoephoester

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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 Calumet, Outagamie, and Winnebago Counties, Wisconsin.

Groundwater recharge varies spatially and temporally. The spatial variation is due primarily to spatial differences in land use, soils, and topography. Recharge also varies temporally with climate and precipitation. Local planning decisions cannot alter the weather or geology, but can affect 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 Calumet, Outagamie, and Winnebago Counties. The recharge distributions produced by this technique represent an essential input for groundwater flow models in the three counties.

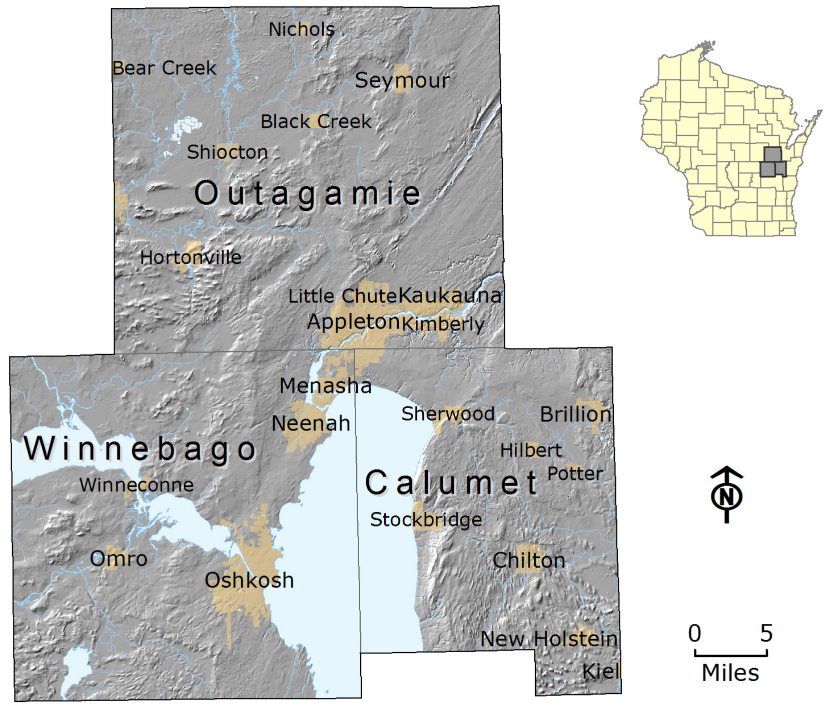


Figure 1. **Soil-water balance (SWB) model area: Calumet, Outagamie, and Winnebago Counties, Wisconsin.**

Objective

The objective of this project was to delineate and categorize recharge to the shallow aquifers of Calumet, Outagamie, and Winnebago Counties. The resulting recharge map can be used to identify important groundwater recharge areas in the three counties and incorporate the areas into planning and land development decisions. 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.

Background and setting

Calumet, Outagamie, and Winnebago Counties are located in east central Wisconsin. The three counties are shown in figure 1. The physical geography of the three counties is strongly controlled by the glacial history of the area and, in the case of Calumet County, the underlying bedrock. Outagamie and Winnebago Counties lie in the Fox River valley and are dominated by two landscapes that formed in front of the ice margins: rolling upland hills composed of glacial tills and flat lowlands formed on lake sediments. There are many small lakes and streams in these two counties (Anderson and others, 1927; Geib and others, 1921; Hooyer and Mode, 2008). Although Calumet County was also covered by glaciers, it has a different geography. Much of the county is underlain by Silurian-age dolomite. As the glaciers advanced and retreated, they scraped away the less resistive shale and sandstone to the west of the dolomite and left the steep cliffs of the Niagara escarpment on the western edge of Calumet County. The thickness of the glacial sediment in Calumet County is generally less than in Outagamie or Winnebago Counties, again because of the underlying dolomite bedrock. Here numerous drumlins or streamlined hills cover the landscape. Much of Calumet County is internally drained. Rather than flowing through streams and rivers, the water moves through the thin glacial sediment and fractured dolomite bedrock. Where the dolomite is absent, in the northern quarter of the county, the sediment thickness and geography is similar to that found in Outagamie and Winnebago Counties (Geib and others, 1925; Gotkowitz and Gaffield, 2006).

The average annual precipitation in the three-county area, as measured at the Appleton airport, is 30.1 in. The mean annual air temperature is 45.3°F, with an average maximum of 81°F in July and an average minimum of 8°F in January. Nearly 60 percent of annual precipitation falls in the five months of highest precipitation, May through September.

Groundwater use in Calumet, Outagamie, and Winnebago Counties was estimated to be 5.3, 13.6 and 10.1 million gallons per day (mgd), respectively, in 2005. These rates are less than the peak usage from years 1995 to 2000 in Calumet, Outagamie and Winnebago Counties when the maximum estimates were 7.56, 20.48, and 13.27 mgd, respectively. The decrease in pumping is likely due to municipalities going from groundwater to surface water for their supplies (Ellefson and others, 1997; Ellefson and others, 2002; Buchwald, 2005; Luczaj and Hart, 2009).

Recharge for the three-county area had been estimated previously to be around 0.7 inches/year (Conlon, 1998) and 16.8 inches/year (Feinstein, 1987) using groundwater flow models. The focus of the model developed by Conlon (1998) was the deep sandstone aquifer and so the recharge value used there is not indicative of the recharge to the shallow aquifers. More recently, Feinstein and others (2010) used an SWB model at a coarse scale to give similar estimates as the SWB model in this study. Gebert and others (2007) used baseflow separation on 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 three-county area varied from 1.6 inches/year for the Duck Creek basin to 7.7 inches/year for the Wolf River basin at New London. Krohelski (1986) estimated recharge in nearby Brown County by looking at water level rises in wells. Those values from six wells were found to range from 1 to 6 inches/year.

Compared to these methods, 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 suppported by the East Central Wisconsin Regional Planning Commission with financial assistance from the EPA's Lake Michigan Academy. 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. Westenbroek was particularly helpful in answering questions about code execution and output.

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 per time period (for example, inches/year).

Recharge: The volumetric rate 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).

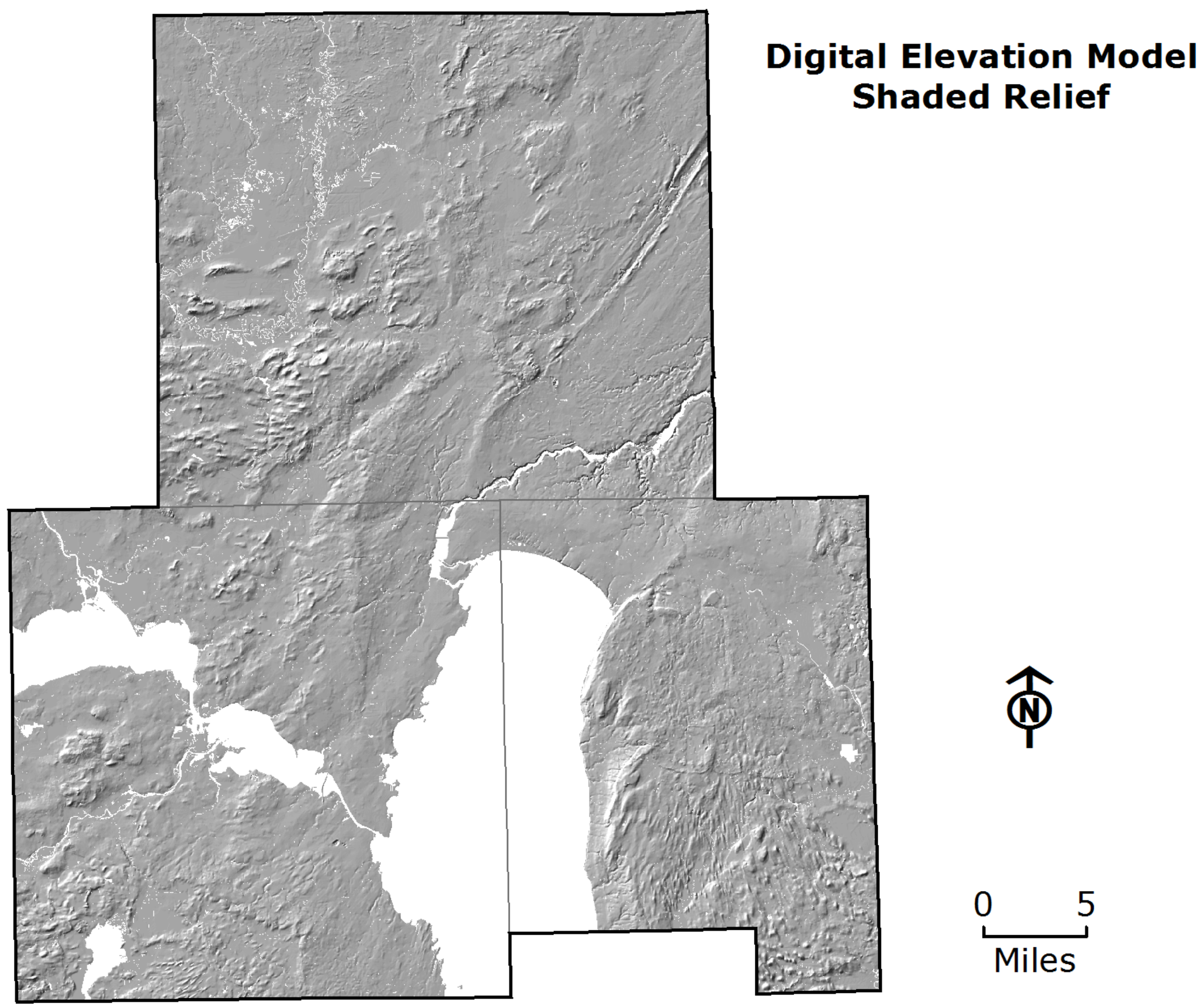
Model inputs and outputs

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 Calumet, Outagamie, and Winnebago Counties and included small portions of surrounding counties. The spatial resolution of the model grid was 30 meters (approximately 98 feet), corresponding to the resolution of the elevation input data available from the USGS.

Daily temperature and precipitation observations recorded at the Appleton weather observation station were tabulated for model input. Although these climate parameters vary across the region, this dataset is representative of the region on average. After review of the climate data, the period from 1982 through 2009 was chosen for input to the model. This recent period includes high-precipitation intervals, such as 1984-1985 and 2008, as well as low-precipitation intervals like 1988-1989 and 1996-1999, enabling analysis of the variability of groundwater recharge resulting from recent climate trends.

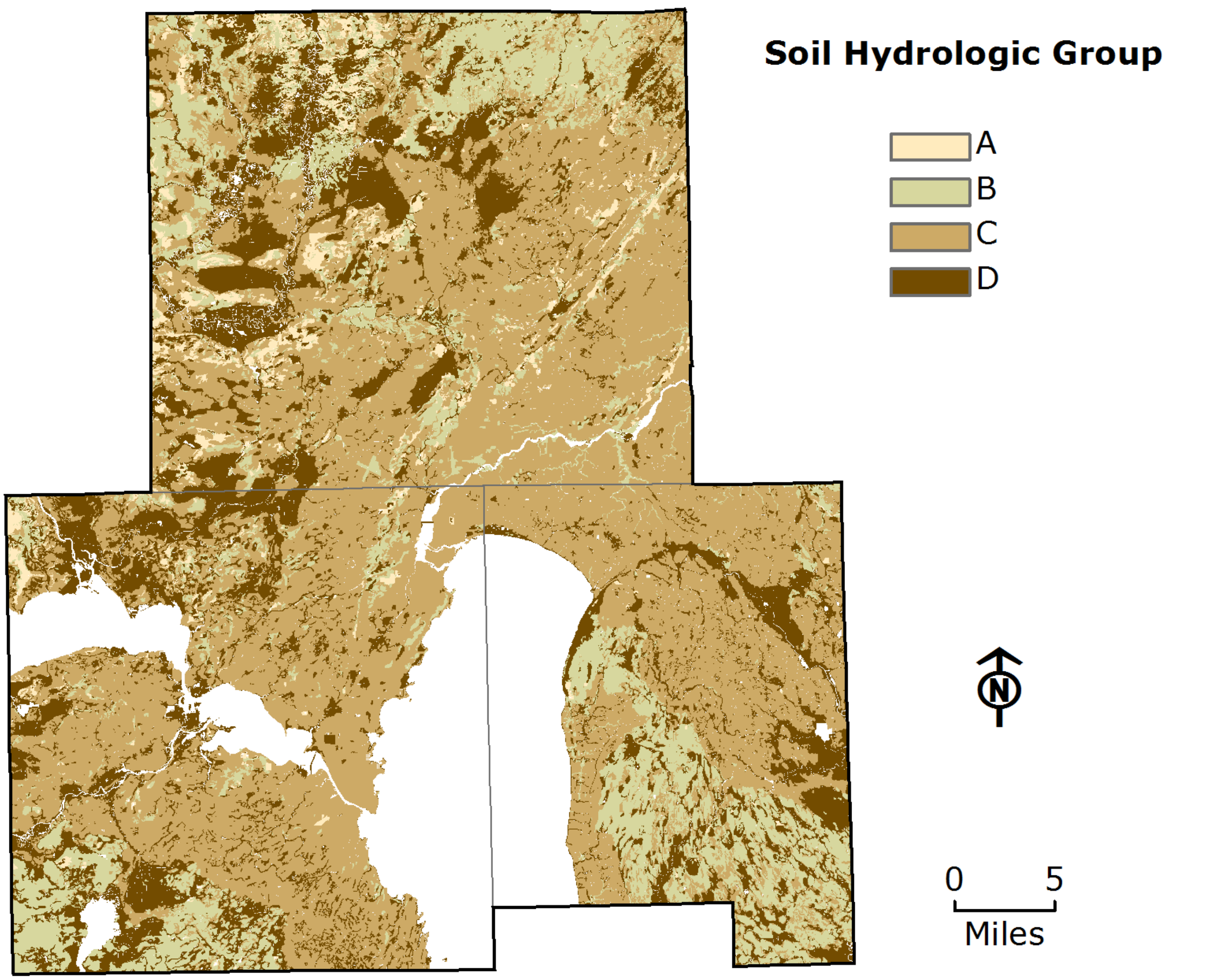
The recharge model uses topographic data to determine surface water flow direction and route runoff. A standard flow direction calculation was applied to a 30-meter digital elevation model (DEM) from the US Geological Survey's National Elevation Dataset (USGS, 2003). While more detailed elevation data are available for the area, the increased resolution produced inordinate model computation times. 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, Calumet, Outagamie, and Winnebago Counties, Wisconsin (USGS, 2003).**



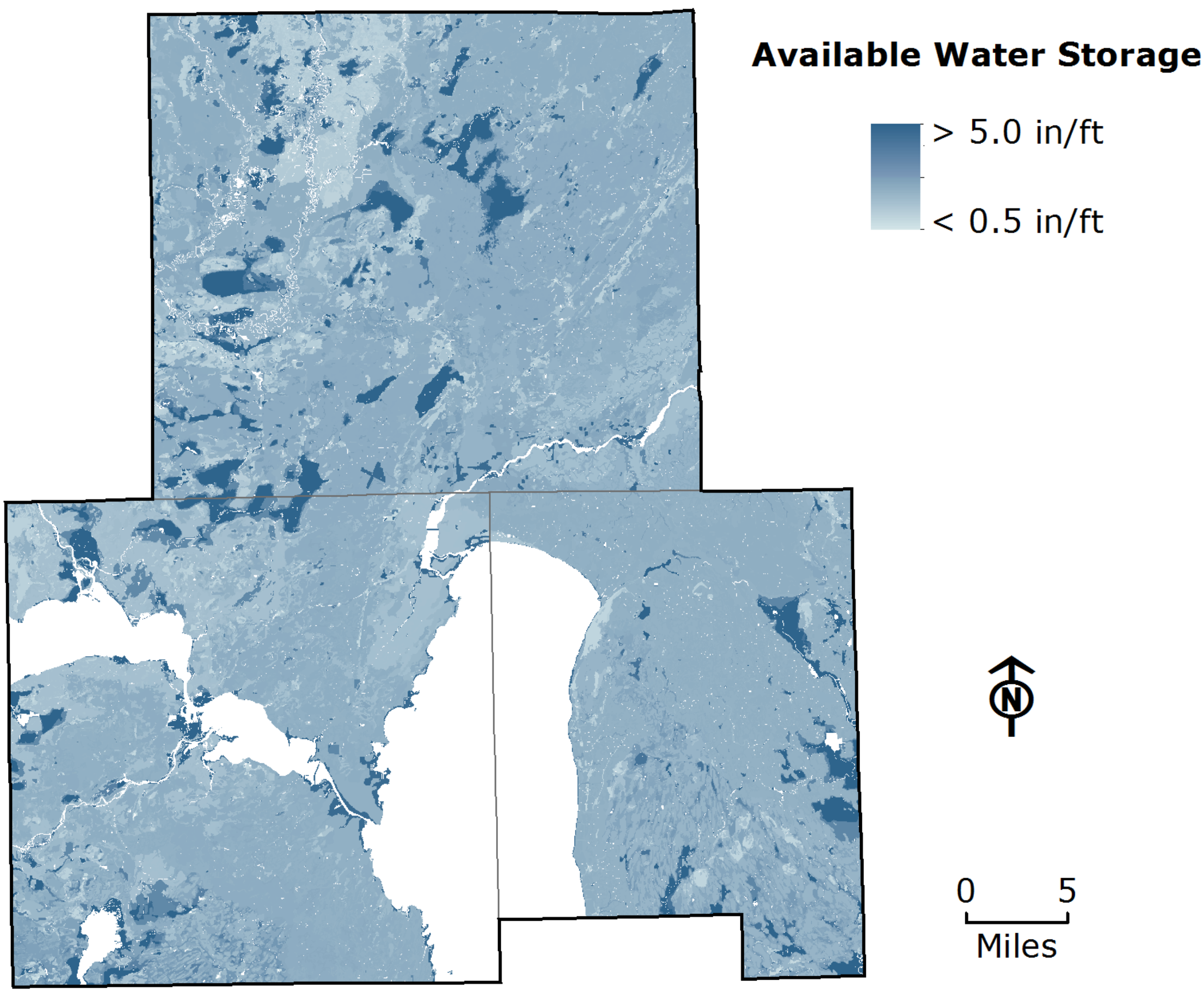
Digital soil data from the Natural Resources Conservation Service (NRCS) Soil Survey Geographic (SSURGO) Database were used for two input datasets to the model, hydrologic group and available water storage (NRCS, 2010). The hydrologic group is a classification of the infiltration potential of a soil 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, Calumet, Outagamie, and Winnebago Counties, 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.

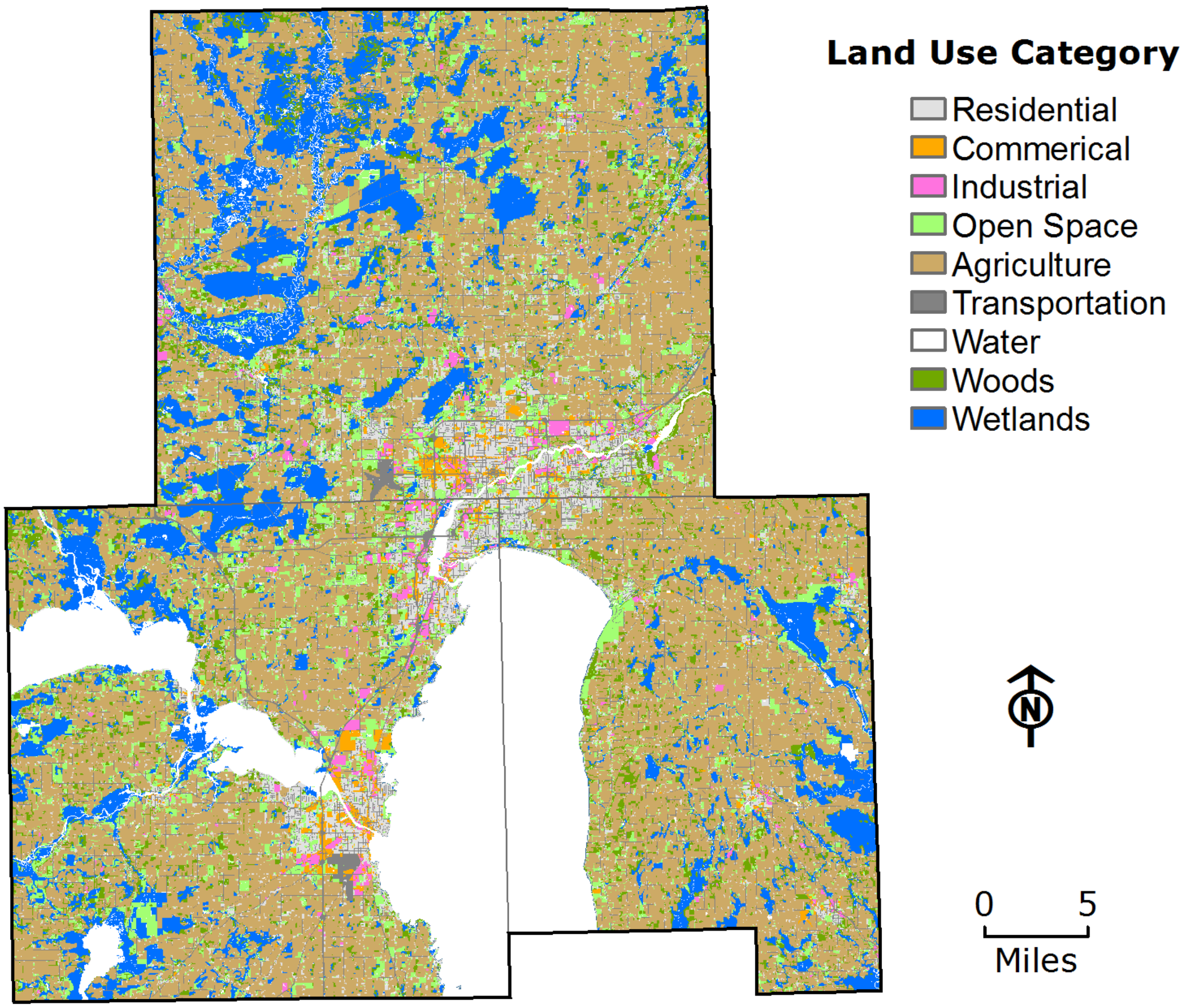
Figure 4. **Soil available water storage input to the SWB model for Calumet, Outagamie, and Winnebago Counties, Wisconsin (NRCS, 2010).**



Land-use data are used in calculations of interception, runoff, evapotranspiration, and for determination of root zone depth. Land-use data for 2007-2008 were provided by the East-Central Wisconsin Regional Planning Commission (ECWRPC, 2010a). The data also specified curve numbers for each land-use category. These values are used in the standard NRCS TR-55 rainfall-runoff method (NRCS, 1986) 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 1982 through 2009 was input as daily minimum, maximum, and average temperatures and total daily precipitation observations. The model was used to simulate 28 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 per year. Land-use categories of wetland and water were removed from further processing and labeled as undefined. These land-use types are hydrologically complex and cannot be accurately represented in the SWB recharge model. 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 for Calumet, Outagamie, and Winnebago Counties, Wisconsin (ECWRPC, 2010a).

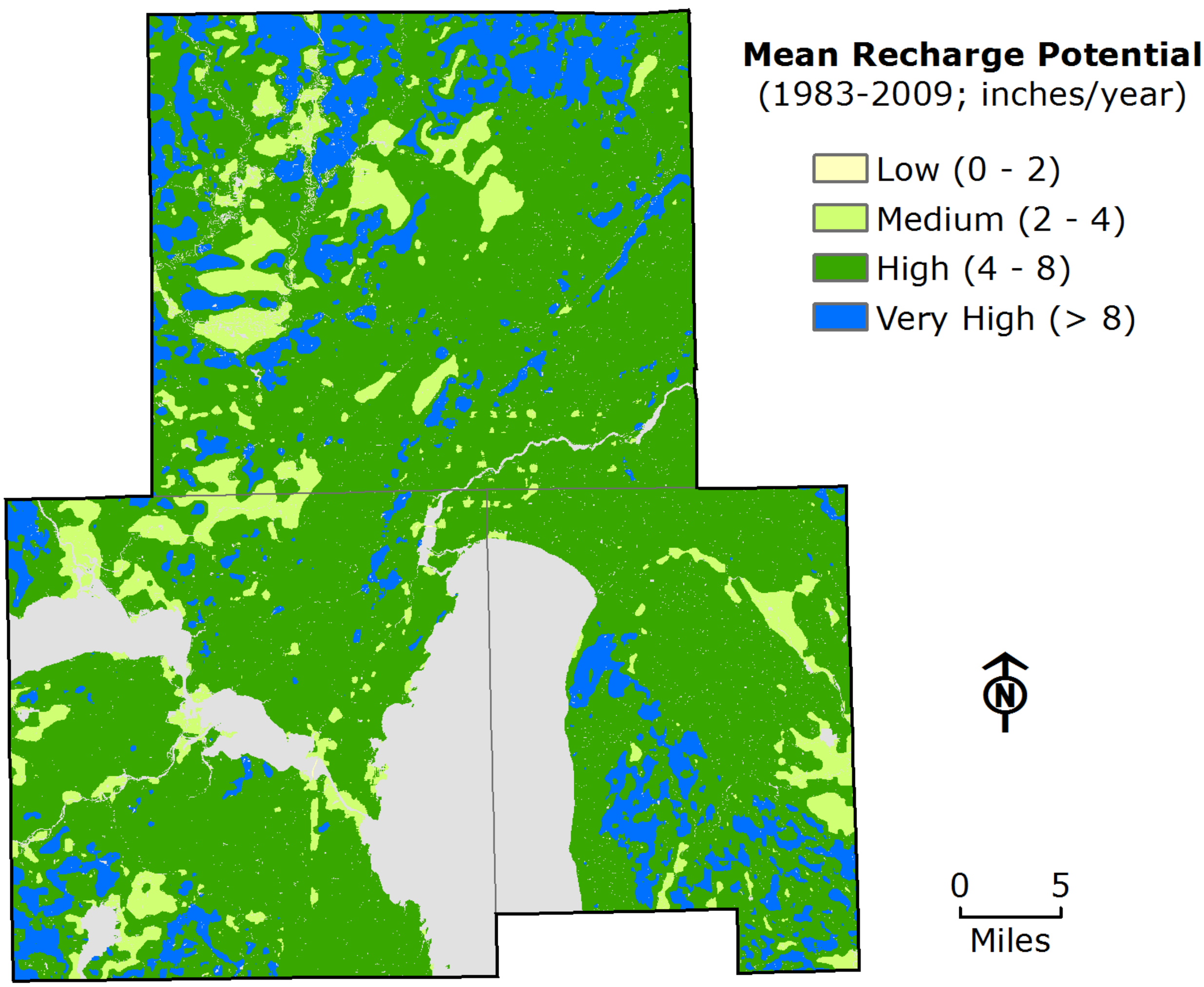


Results and applications

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 1983-2009 using 2007-2008 land use patterns. The mean recharge for the three counties is 6.0 inches/year. Calumet, Outagamie, and Winnebago Counties have mean estimated recharge values of 6.0, 6.2, and 5.6 inches/year, respectively. The mean recharge varies from place to place across the three-county area by more than 10 inches/year. 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.

Figure 6. **Recharge in Calumet, Outagamie, and Winnebago Counties.**



Some general trends, correlating with surficial geology and land-use patterns, are evident in the recharge map. The greatest spatial control on recharge in the three-county area is surficial geology. The entire area was glaciated. When the glaciers retreated they left a variety of sediments ranging from lower conductivity lake sediments to sandy tills. Subsequently, these glacial sediments were formed into soils. Heavier, more clay-rich soils tend to promote runoff and hold water for a longer period. Sandier soils tend to allow greater infiltration and hold less water. In Calumet County the very high recharge areas correspond to the Kewaunee silt loam in the southwest, medium and high recharge areas correspond to the Kewaunee silt clay loam and the Superior clay loam in the center and north, and the low recharge areas correspond to soils formed in low-lying peat areas in the east (Geib and others, 1925). Outagamie County has more varied soils but similar trends are present. The southeast region of the county has medium and high recharge except for two northeast-southwest linear trends that correspond to sandy loams with very high recharge. Sandy loams are also responsible for the very high recharge areas seen in northwest Outagamie County. The areas of low recharge correspond to the peat soils (Geib and others, 1921). In Winnebago County the very high recharge zones on the southwest and northwest portion correspond to the silt and sandy loam, the medium and high areas in the center and the east correspond to clay and silt loams, and the low recharge areas are in the Houghton mucks and other peat soils (Anderson and others, 1927).

The impact of land use can be seen in Winnebago and Calumet Counties as the medium recharge areas around Oshkosh and Menasha, and the north-south Highway 41 corridor to the south of Oshkosh. More impervious surfaces associated with transportation, industrial, and commercial uses create more runoff and less chance of infiltration. Changing how the runoff is handled can offset these impacts but the model assumes that when runoff is routed to roads in urban areas, it is shunted to surface waters and so it is removed from the model.

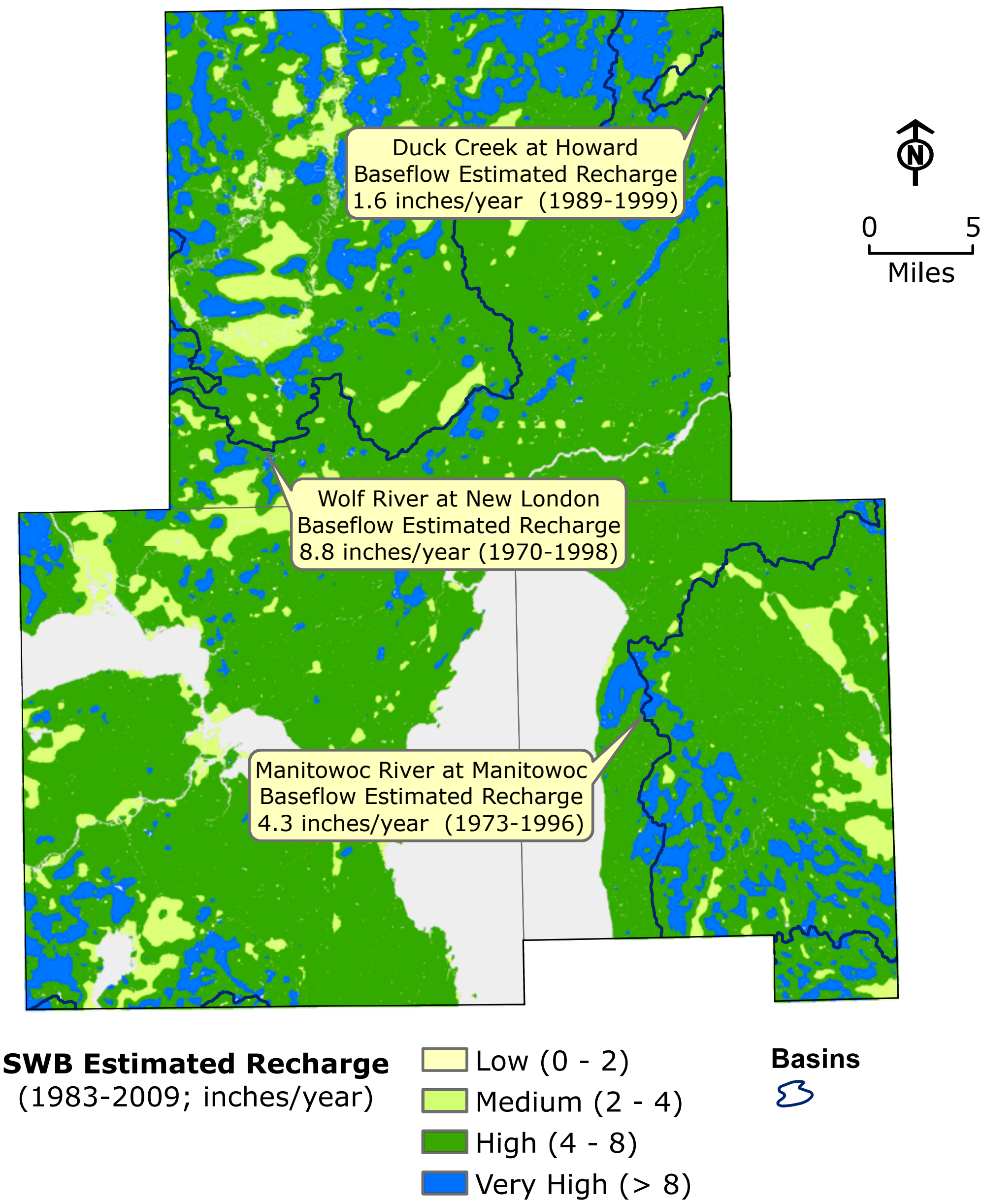
The SWB recharge model was compared to USGS baseflow measurements (Gebert and others, 2007). Unlike the USGS baseflow measurements, the SWB model does not include any direct measurements of flow in the hydrologic system and so a comparison to the more direct USGS measurements of the baseflows provides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

The comparison was made with three different basins that lie, in part, in the three-county area. Figure 7 shows the basins and the estimated recharge from baseflow in each basin along with the recharge estimated from the SWB model. The basins and their recharge as estimated by baseflow are the Wolf River at New London in the northwest with an estimated recharge of 8.8 inches/year, the Manitowoc River in the southeast with an estimated recharge of 4.3 inches/year and Duck Creek in the northeast with an estimated recharge of 1.6 inches/year. Not all parts of the basins were inside of the modeled area. The percentages of the basins inside the modeled area are 60% of the Manitowoc River basin, 80% of the Duck Creek basin, and 50% of the Wolf River basin. The differences between the baseflow and the SWB estimates were calculated for the region of the SWB models inside each basin. The Wolf River basin baseflow estimate was 2.5 inches greater than the SWB estimate, the Manitowoc River baseflow estimate was 1.7 inches less than the SWB estimate, and the Duck Creek baseflow estimate was 4.3 inches less than the SWB estimate. The differences between the estimates at Wolf River and the Manitowoc River are not large and can be explained in part by the basin extending beyond the SWB estimated area. Another possible explanation of the difference is that the basin baseflow estimates are for the period from 1970-1999 while the SWB estimate is for the period between 1983-2009.

The reason for the large difference seen at Duck Creek is unclear. It may be that the conductivity used for clay soils in the SWB model was set too high and so the SWB model overestimated the recharge. It might also be that the Duck Creek baseflow does not represent the recharge. Duck Creek is a small basin and is located in the area that would have been providing water to the deep sandstone aquifer in the central Brown County during a period of relatively high pumping. Krohelski (1986) measured flows in Duck Creek and saw that it was losing flow along certain reaches. He concluded that flow was going to the deep aquifer. The regional flow model by Feinstein and others (2010) simulated significant downward flow in this region in agreement with this possibility.

Although some differences arise among the models (possibly due to groundwater flow to a regional system rather than discharging locally or due to differences between the climate data used), in general, are within a couple inches/year of recharge. This agreement provides some confidence when applying the smaller-scale recharge results to the entire county.

Figure 7. Comparison of recharge estimated from the SWB model to recharge estimated from baseflow measurements.



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 discuss 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 a daily total value, 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 accounted as recharge, resulting in unreasonably large recharge. To account 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 between and within the groups would be significant and so infiltration might easily be overestimated or underestimated by an order of magnitude under unit gradient or saturated conditions. An upper bound on this error was set by limiting the recharge in any cell to 50 inches/year; effectively converting the excess recharge to runoff and removing it from the model.

Uncertainty in land-use categories and evapotranspiration (ET) represents another potential model error. The amount of ET for the different land-use categories is dependent on values of rooting depths for the different soil types for assumed vegetation in the specified land-use category. The model output is very sensitive to these rooting depths 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, the SWB model only applies ET following precipitation or snowmelt, assuming that water is not available for ET after infiltration to recharge. For this reason, wetlands are not included in the model output. Surface waters are also not within the calibrated ranges of inputs for the SWB model and were excluded.

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 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 modeled by the SWB model. 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 Unsaturated Zone Flow (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 8a shows the variation of precipitation at Appleton, WI. This data was chosen to represent the climate of the three-county area because it was centrally located. Figure 8b shows deep infiltration or potential recharge over time for the three counties between 1983 and 2009 with the land use held constant to the 2007–08 pattern. During this period, annual precipitation varied from a low of 21.6 inches/year in 1989 to a high of 40.6 inches/year in 1984 while recharge varied from a low estimate of 1.1 inches/year in 2000 in Winnebago County to 9.9 inches/year in Outagamie County in 1984.

A string of dry years can cause recharge rates to decrease dramatically because dryer soils have more room to hold more precipitation, and plants capture a higher percentage of the total soil moisture. Between 1996 and 2001, Appleton's precipitation remained below 28 inches/year (fig. 8a). In response, recharge decreased from 6.6 inches/year to 1.7 inches/year (fig. 8b). Alternatively, recharge rates increase during wet periods because soils are unable to store the excess water and plants capture a lower percentage of the total soil moisture, allowing deep infiltration of more water. This occurred between 1982 and 1986 when Appleton received precipitation of more than 30 inches/year (fig. 8a). During this period the area experienced higher recharge rates of between 6 and 10 inches/year (fig. 8b).

If the SWB model estimates deep infiltration or that water that will eventually become recharge entering the flow system, then flow discharge measurements in rivers and streams can be used to estimate the discharge or the water exiting the system. Figure 8b also shows the annual SWB estimates for Winnebago County and the annual discharge of the Fox River at Oshkosh. The Fox River basin includes most of Winnebago County as well as much of the surrounding counties to the west and north. Both the SWB model and the Fox River flows show a gradual decrease in flow during the dry period from 1996 to 2001. During that time the precipitation remained relatively constant. There is also reasonable correlation from 1992 to 1995 during a previous wetter period. The correlation between the two sequences becomes less strong after 2001 during times of more intermediate and variable precipitation. Although this particular analysis is a first look at the issue here, it illustrates that at climate peaks and troughs, the inflows and outflows of the groundwater flow system are correlated. A more in-depth analysis would utilize the UZF package and track the entire flow path from infiltration to discharge.

Figure 8a. **Annual precipitation at Appleton, Wisconsin (1982–2009).**

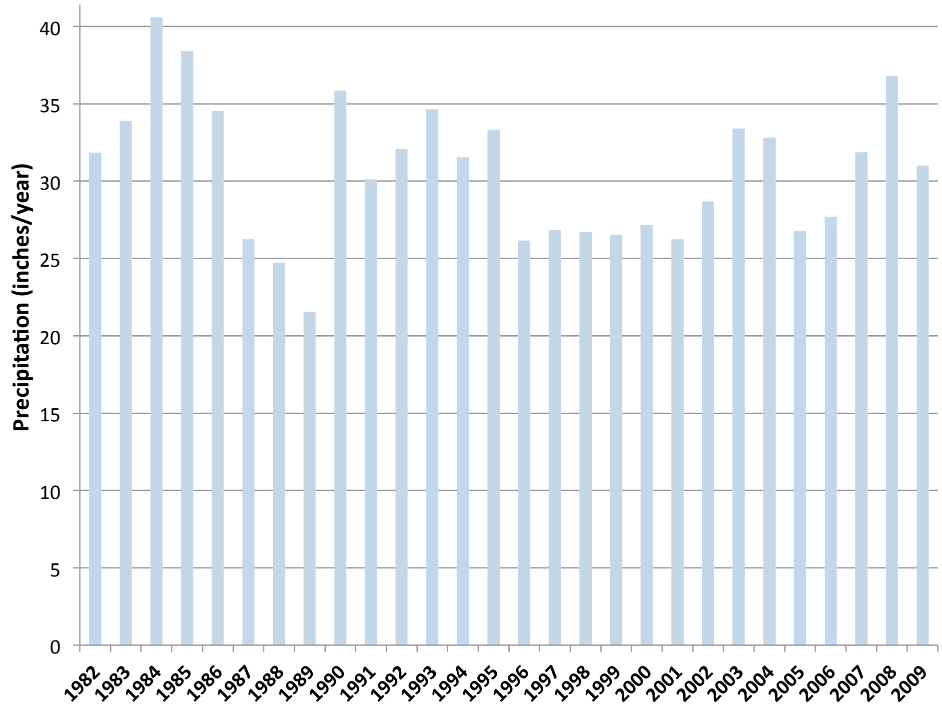
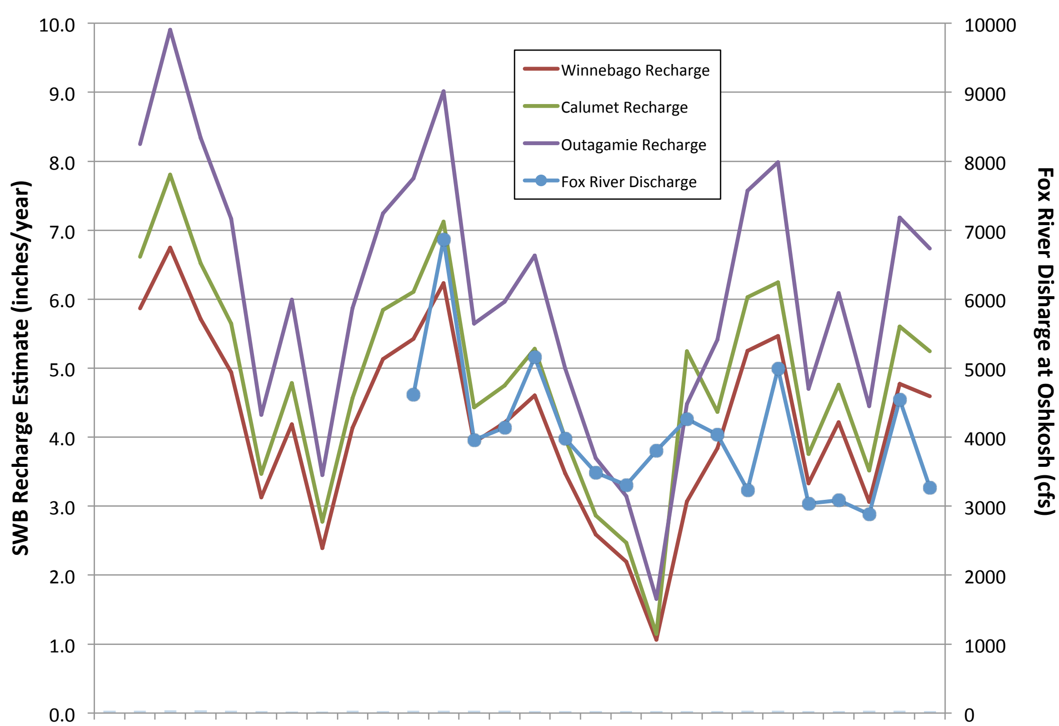


Figure 8b. **SWB recharge in Calumet, Outagamie, and Winnebago Counties (1983–2009) and average annual discharge of the Fox River at Oshkosh (1992–2009).** For the recharge estimates, land use was held constant to the 2007–08 pattern.



Runoff and infiltration to a sinkhole

Nutrient management plans help protect Wisconsin's waters by reducing farm runoff. An area that poses extra difficulties is Calumet County with its shallow depths to fractured dolomitic bedrock (Gotkowitz and Gaffield, 2006). Groundwater studies have shown this area to be especially vulnerable (Masarik, 2010). Calumet County has issued performance standards to minimize runoff issues (Calumet County, 2007). One of the standards is to berm areas around sinkholes. We used the SWB model to provide support showing how that standard is protective of groundwater.

We applied the SWB model to a sinkhole in Calumet County. In this simulation, the sinkhole drains runoff from a closed depression. Using the typical climate year, 1984, we used the SWB model to predict the necessary rainfall that would produce runoff flow to the sinkhole.

Figure 9. Runoff into a sinkhole, plotted against precipitation.

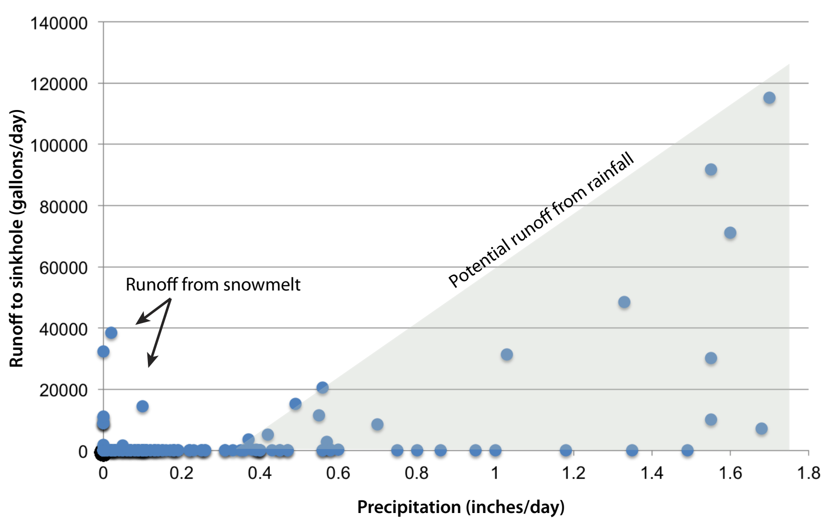


Figure 9 shows the daily amount of water that enters the sinkhole for a given amount of precipitation. Runoff is likely when precipitation exceeds 0.4 inches/day (the area shown within the gray triangle). No runoff occurs when the ground is thawed and precipitation is less than 0.4 inches/day—all of the water is infiltrated, evaporated, or transpired. These lower-intensity rainfall events are less likely to cause issues with groundwater and land spreading. However, as shown in the figure, there may still be runoff when there is little or no precipitation if snowmelt occurs while the ground is frozen.

The model supports recommendations to conduct land spreading only on thawed ground and not before high rainfall is predicted. To further protect groundwater, sinkholes should be surrounded by a shallow berm and not farmed, as recommended in the *Local Performance Standards for Agriculture* (Calumet County, 2007). The berm allows the runoff to be filtered by several feet of soil rather than having a direct path into the fractured dolomite bedrock found in this part of Calumet County even during high rainfall events.

Stormwater management in an urban setting

Impervious surfaces such as parking lots, roads, and buildings can alter how and where recharge occurs, especially in an urban setting. In recent years, various practices have been used to reduce runoff by increasing infiltration. These practices include rain gardens, infiltration basins, grassed swales, and stormwater wetlands.

The SWB model was used to demonstrate how urbanization without applying storm water best management practices leads to lower recharge. The area around the City of Menasha was used for this demonstration. The model assumes, as a worst case, that any roadway within the newly urbanized area has a storm sewer installed that routes the water directly to surface waters rather than using storm water infiltration and holding practices. The actual land use changes will likely have less impact than this, depending on how the storm water is managed.

When the water is not allowed to infiltrate, the recharge decrease. Storm sewers move the water directly to surface waters. Commercial, transportation, and industrial land uses have the greatest impact on infiltration patterns because they have higher percentages of impervious surfaces with storm sewer drainage. Figure 10a shows the existing land use for the Menasha area. Figure 10b shows the generalized proposed land use for the year 2030 for the Menasha area with commercial shown in orange, industrial in pink, and transportation in gray and black.

Figure 10a. **Existing land use around Menasha, Wisconsin (ECWRPC, 2010a).**

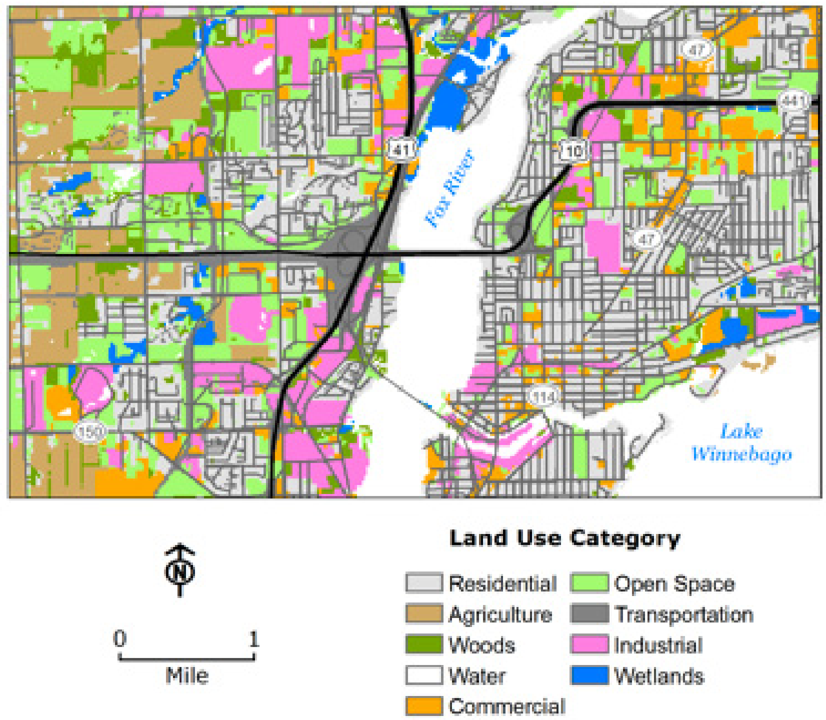


Figure 10b. **Proposed 2030 land use around Menasha, Wisconsin (ECWRPC, 2010b).** Dominant changes from existing land use are from agriculture and open space to residential, commercial, and industrial.

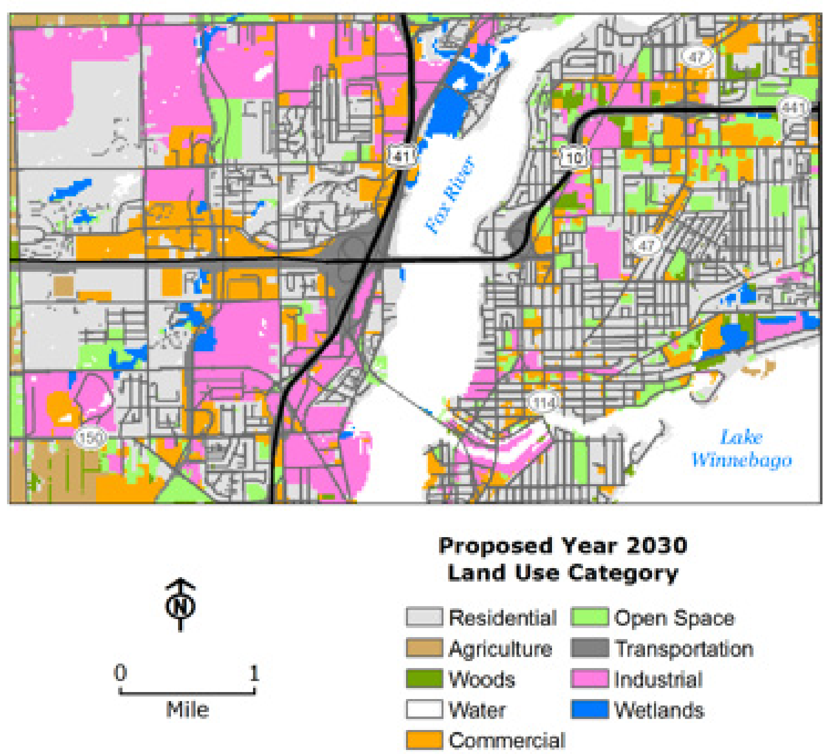


Figure 11. SWB recharge in 2030 with proposed land use.

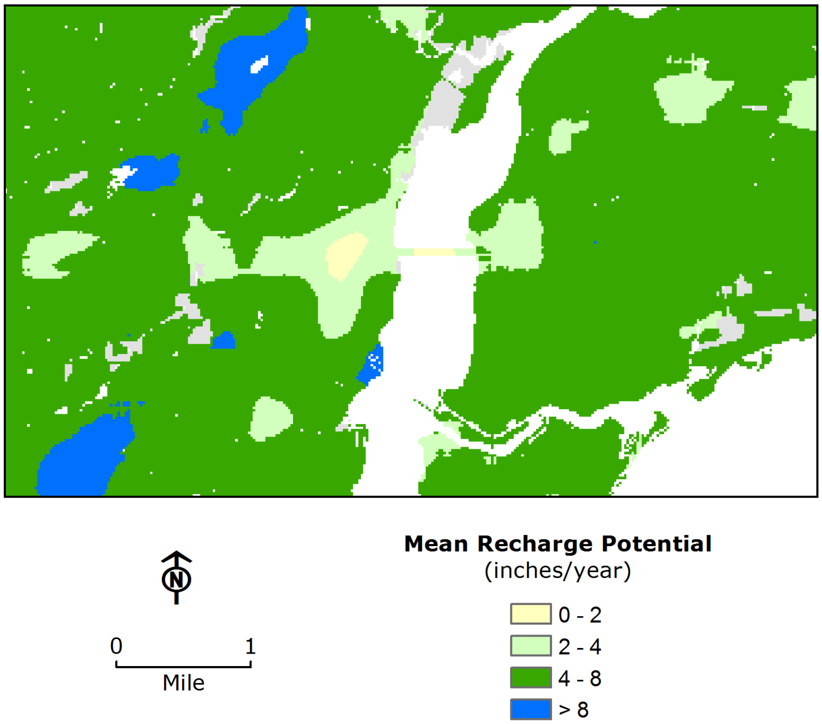
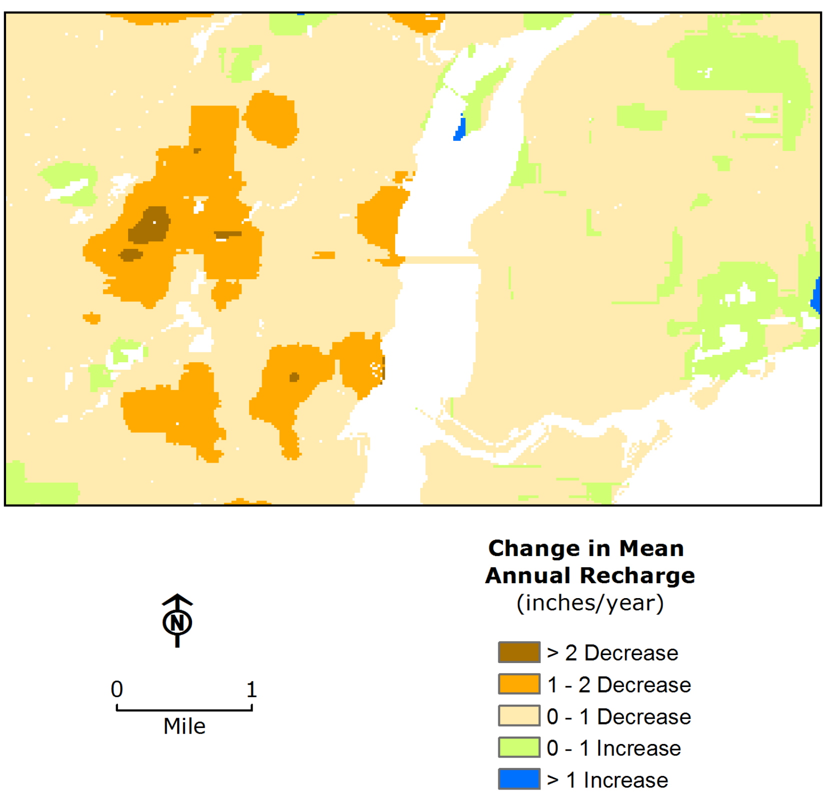


Figure 11 shows the worst-case recharge pattern for that potential future land use. The recharge is still largely governed by the soil properties but is significantly lower where storm sewers along roads and highways are present to remove the water from the model rather than allow it to infiltrate. The reduction in recharge due to impervious surfaces that are drained by storm sewers is shown in figure 12. As estimated by the SWB model over the Menasha area, development with impervious surfaces that allow no infiltration could reduce overall recharge by 0.4 inches/year over the area shown and by more than 2 inches/year in several locations.

Figure 12. Estimated decrease in recharge between current and proposed land use. This is a worst-case scenario that assumes no infiltration of stormwater runoff.



Using the model

This recharge model provides a groundwater management tool that can be used to guide land-use decisions. The following list summarizes key points from the model and suggests ways the information might be put to use:

- **Consider soil types when making land-use decisions that will reduce infiltration.** Soil types strongly control the amount of recharge, with sandy soils allowing significantly higher levels of infiltration than clayey soils.

  Recommendations: The model can be used to identify areas that contribute most to the groundwater flow system. Maintaining recharge may be important for managing groundwater supply or for preserving natural features such as a stream or a 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.** Amounts of water entering the flow system were estimated to range from nearly 10 inches following several consecutive wet years to less than 2 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. Conversely, during an extended drought, water levels in wells, lakes, rivers, and streams may drop.

- **Land-use changes can alter recharge availability.** Buildings, roads, parking lots, and other impervious surfaces reduce recharge when runoff water is directly routed to surface waters.

  Recommendation: Consider alternative means of handling stormwater runoff, including infiltration swales, basins, and rain gardens. This is especially important if springs, small streams, or wetlands are farther down the flow system from the recharge area. These smaller surface waters are very sensitive to changes in recharge.

- **High rainfall events can contribute to runoff in agricultural areas.** When sinkholes are present, this nutrient-laden runoff can be funneled directly into the groundwater.

  Recommendations: Continue education efforts that point out the issues involved with land spreading when the ground is frozen and before high rainfall is predicted. Determining crop nutrient requirements and timing applications to meet those needs will ensure maximum availability to the plants and minimize runoff potential. Encourage use of berms around sinkholes to protect the groundwater.

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James M. Robertson, Director and State Geologist