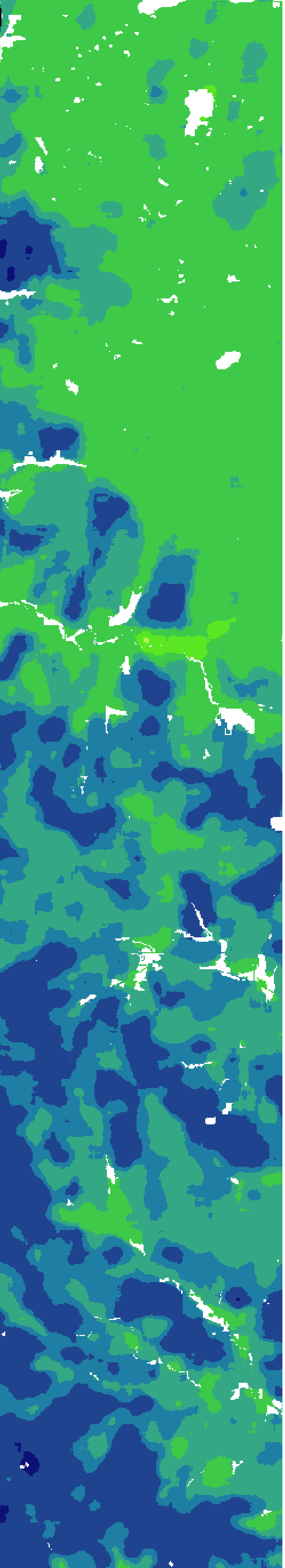
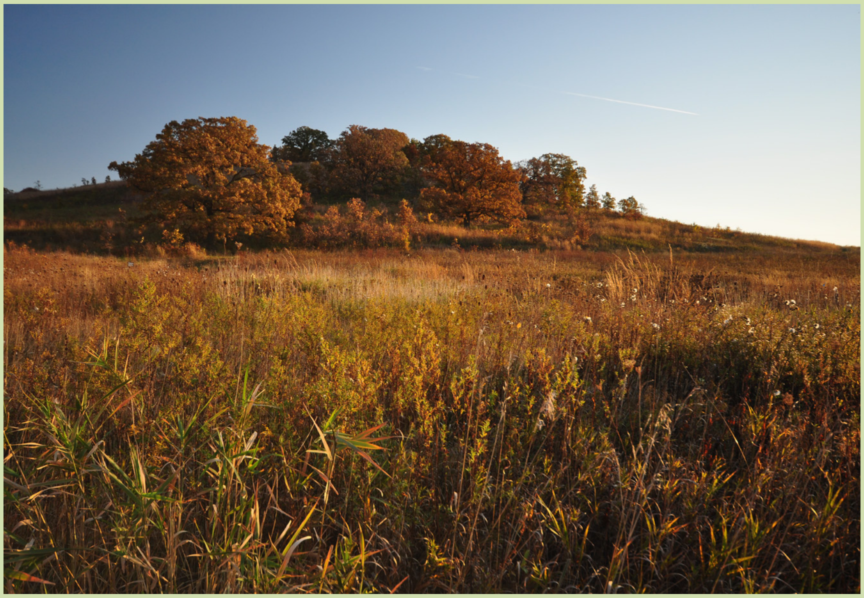


WISCONSIN GEOLOGICAL AND NATURAL HISTORY SURVEY

Groundwater recharge in Dane County, Wisconsin

Estimating recharge using a GIS-based water-balance model



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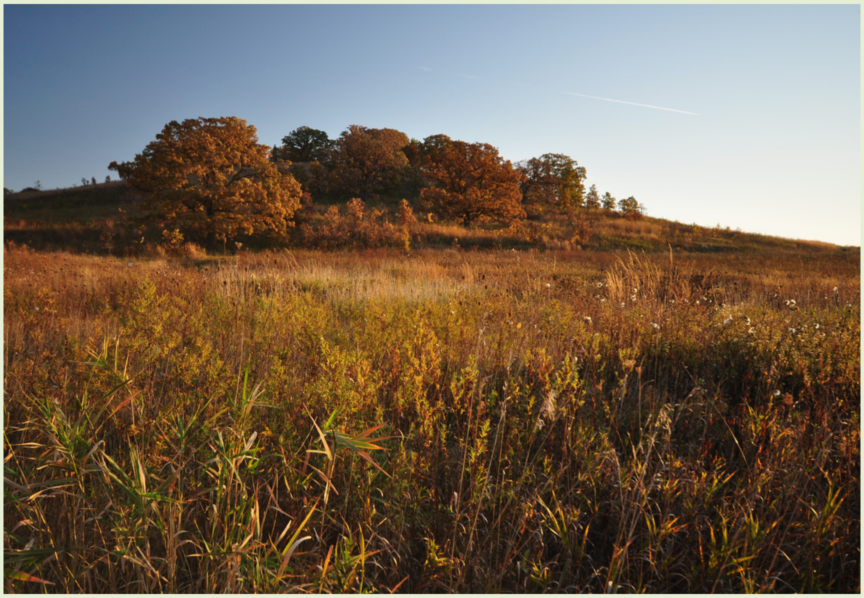
Groundwater recharge in Dane County, Wisconsin

Estimating recharge using a GIS-based water-balance model



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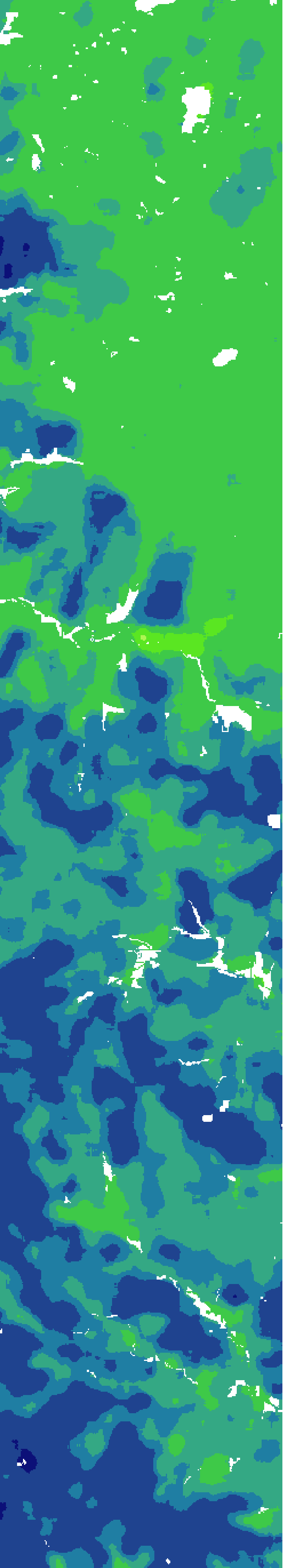


Contents

Introduction

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 for 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 Dane County, Wisconsin.

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

This recharge model provides a groundwater management tool to help guide land-use decisions and increase understanding of recharge in Dane County. The recharge distributions produced by this technique represent an essential input for groundwater flow models in the county.

Objectives

The objective of this project was to delineate and categorize recharge in Dane County. The resulting recharge map can be used to identify important groundwater recharge areas in Dane County and incorporate them into planning 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 inputs, the model uses readily available climate data and geographic information system (GIS) map data layers such as soil characteristics, land use, and topography.

Rain garden

Background and setting

Dane County is located in south-central Wisconsin and straddles the boundary between the unglaciated Driftless Area of southwestern Wisconsin and the area covered by glaciers during the Wisconsin Glaciation (Clayton and Attig, 1997). As a result, the unglaciated western part of the county has dissected uplands and a well-developed drainage system. Hills generally have flat tops and are commonly used for pastureland and row crops. Hillslopes are steep and commonly forested. In contrast, the glaciated eastern two-thirds of the county has rolling and moderately hilly topography. The drainage system is not as well developed and the region contains many lakes and marshes. The eastern part of the county contains numerous drumlins.

Bradbury and others (1999) note that Dane County's average annual precipitation is 30.88 inches (78.44 cm), with 60 percent of the precipitation occurring between May and September. The county's mean annual air temperature is 45.2°F (7.3°C), with an average maximum of 82.4°F (28.1°C) in July and an average minimum of 7.2°F (–13.8°C) in January.

In Dane County, groundwater use has increased as the population has grown. Total groundwater use increased from 53 million gallons per day to 69 million gallons per day between 1985 and 2005 (Ellefson and others, 1988; Buchwald, 2011).

A variety of recharge estimates have been made for Dane County in the past decade. Prior to countywide groundwater modeling in the 1990s, local estimates of average recharge rates ranged from 6 to 11 inches (15 to 28 cm) per year. Cline (1965) estimated a countywide average of 6 inches (15 cm) per year based on a water-budget analysis. Swanson (1996) used an early version of the SWB technique to estimate recharge rates of 0.3 to 6.8 inches (0.8 to 17.3 cm) per year. Krohelski and others (2000) developed a recharge array for a countywide groundwater flow model; they used a range of 0.2 to 6.7 inches (0.5 to 17.0 cm) per year, with an average of 2.6 inches (6.6 cm) per year. Bradbury and others (1999) presented a generalized map of recharge areas in the county. Gebert and others (2007) used base flow separation on streamflow-gaging stations to estimate recharge for selected river and stream basins. The range of recharge values for the gaged basins varied from 2.7 to 15.0 inches (6.9 to 38.1 cm) per year. Recharge estimates have also been conducted on smaller scales for the Pheasant Branch watershed and areas in northwestern Dane County (Steuer and Hunt, 2001; Krohelski and others, 2002).

The recharge estimates described in this report represent an improvement over previous estimates. In recent years, the Wisconsin Geological and Natural History Survey (WGNHS) and the U.S. Geological Survey (USGS) have continued to develop and refine the SWB model, improving its conceptual and theoretical aspects and its speed of operation. At the same time, computers and software have advanced, so it is now far easier and faster to manipulate the very large data arrays required for this model than it was in the past. Finally, the GIS-based environmental data sets now available are superior to those used in past efforts. This work grows out of similar recharge estimates conducted for southeastern Wisconsin (SEWRPC/WGNHS, 2008). The SWB model has the advantages of fine-scale resolution (less than 80 acres) and quantified estimates of recharge. The fine scale should be useful for land-use planning. For example, the impact of a new subdivision on recharge could be simulated by changing 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. A comparison of estimates from the SWB model with base flow separation estimates confirms that the SWB model recharge estimates are within reasonable measured ranges.

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 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

Calculating recharge

The model's governing equation is as follows, with the terms defined below. Each term has the same units as precipitation, in terms of amount per time period (for example, inches per year).

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

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 either 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 amount 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 represents the amount of water that must be added to the soil before recharge occurs.

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 a given cell is calculated and stored in an output file. Runoff for that cell is added to the precipitation term for the adjacent lowest-elevation 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 (2010).

Model inputs and outputs

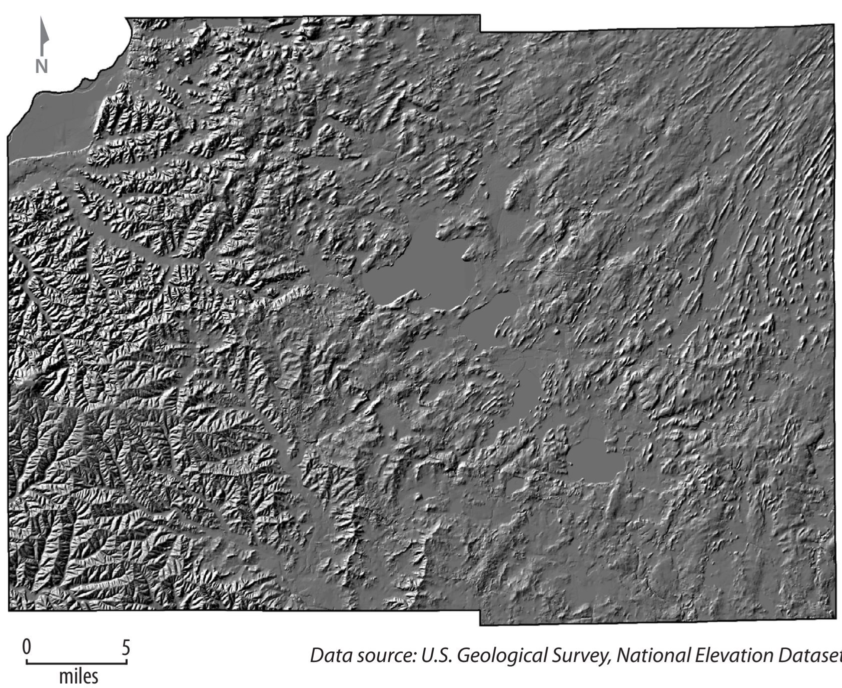
Input to the SWB recharge model consisted of daily climate records for the model period and four map data layers for the model extent: topography, soil hydrologic group, available soil water storage, and land use. The model was centered on Dane County and included portions of surrounding counties. The spatial resolution of the model grid was approximately 98 ft (30 m), which corresponds to the resolution of the elevation input data available from the USGS.

Daily temperature and precipitation observations recorded at the Dane County Regional Airport in Madison were tabulated for model input. Although these climate parameters vary across the county, this data set is representative of the county on average. Based on review of regional precipitation data (S.R. Corsi, written commun., 2008), the climate data for year 1981 were selected and incorporated into state code (Wisconsin Administrative Code NR 151) to represent a recent "typical" climate regime for runoff management for areas near Madison, Wisconsin. We used 1981 for the model climate data to remain consistent with the state code and runoff and infiltration models used for Dane County.

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 m digital elevation model (DEM) from the U.S. Geological Survey's National Elevation Dataset. 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 1.

Digital soil data from the Natural Resources Conservation Service (NRCS) Soil Survey Geographic (SSURGO) Database were used for two input data sets to the model: namely, hydrologic group and available water storage. The hydrologic group is a classification of the infiltration potential of a soil map unit; it is used to calculate runoff in the recharge model input. The primary categories range from A (low runoff potential) to D (high runoff potential). Several map units in the model domain were classified with dual designations, such as A/D. In these cases, the lower-runoff designation typically indicates artificially drained land. Since any

Figure 1. Digital elevation model input (showing relief shading) to the SWB model, Dane County, Wisconsin.



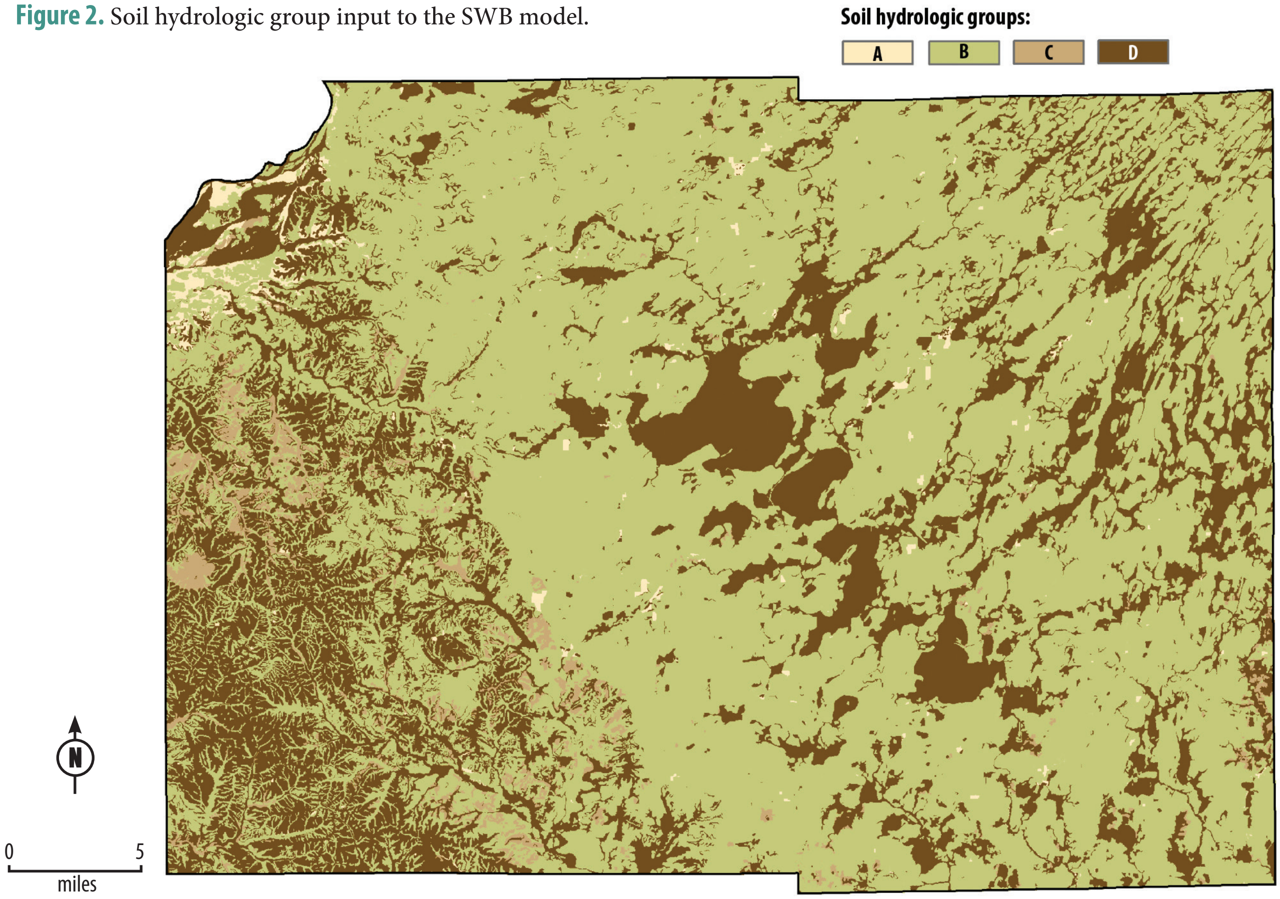
infiltration occurring in this situation would not contribute to groundwater recharge, all dual-designation soil map units were reassigned to the higher-runoff category for input to the recharge model. A map showing the soil hydrologic group data layer is provided in figure 2, in which lighter colors indicate more infiltration and less runoff and darker colors indicate less infiltration and more runoff.

Available water storage, a measure of the amount of water held 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 3. Darker colors show lower soil water storage capacity; lighter colors show higher soil water storage capacity.

Land-use data are used in calculations of interception, runoff, and evapotranspiration and for the determination of root zone depth. Land-use data for 2005, developed by the Capital Area Regional Planning Commission (CARPC), were provided by the Dane County Land Information Office. The land-use categories were reclassified to match those used in the rainfall-runoff method in the SWB model. Runoff is calculated using the standard SCS/NRCS curve number method. A map showing the land-use data layer used in the model is provided in figure 4. As an enhancement to the land-use data, an additional data layer was developed to better represent the fate of runoff from transportation-related land-use categories, such as roadways and parking lots. Areas in the county where storm sewers provide direct connection between transportation-related areas and surface water eliminate opportunities for infiltration of runoff. These areas were delineated by CARPC using their records of storm sewer development. The areas were included in the model as a modifier of the land-use data for the runoff-routing calculations. Within these areas, any runoff generated by transportation land-use categories is removed from flow-routing calculations; outside these areas, runoff from transportation, like other land-use categories, is routed to the next downslope grid cell.

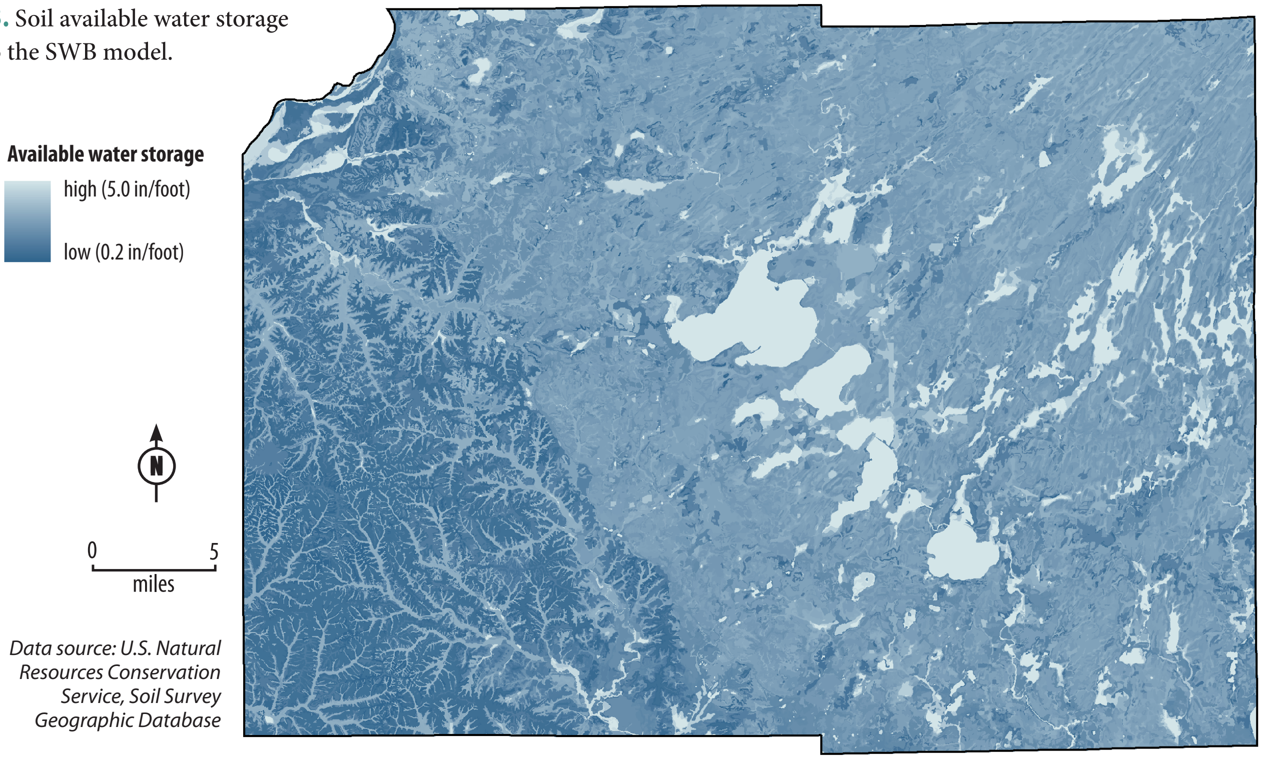
Data grids for the four map inputs were generated from these source data sets for input to the model. Climate data from 1981 was input

Figure 2. Soil hydrologic group input to the SWB model.



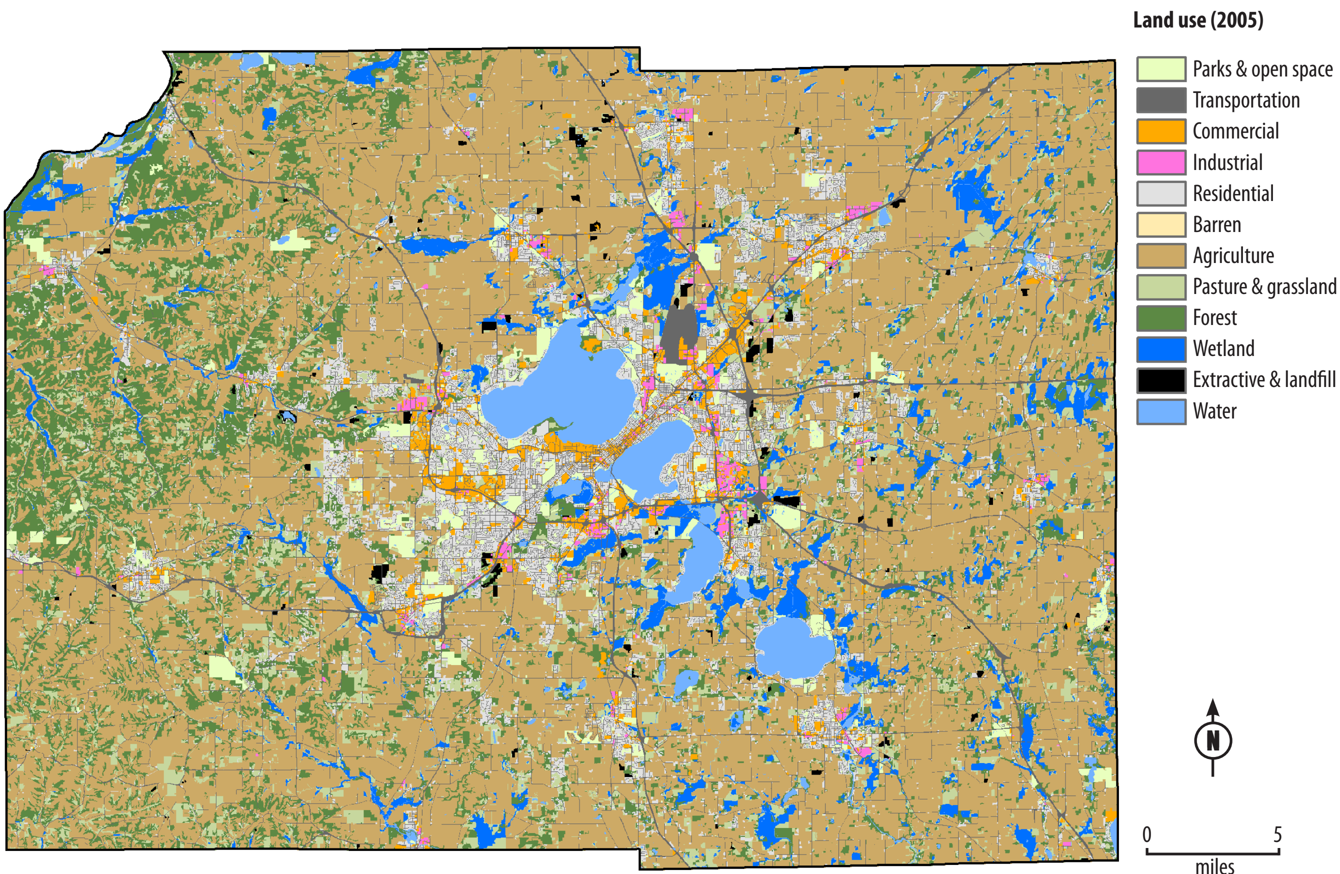
Data source: U.S. Natural Resources Conservation Service, Soil Survey Geographic Database

Figure 3. Soil available water storage input to the SWB model.



Data source: U.S. Natural Resources Conservation Service, Soil Survey Geographic Database

Figure 4. Land-use data input to the SWB model.



Data source: Dane County Land Information Office and Capital Area Regional Planning Commission as daily minimum, maximum, and average temperatures and daily precipitation observations. The model was used to simulate two years of recharge, with the first year used to develop antecedent conditions for the second year. Output was reported as total annual recharge in inches per year. Unrealistic high values (specifically, recharge greater than 50 inches, or 127 cm, per year) were converted to 50 inches, with the remainder likely representing additional runoff to surface water features. Extractive (such as quarries), wetland, and water land-use categories 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 area (approximately 80 acres).

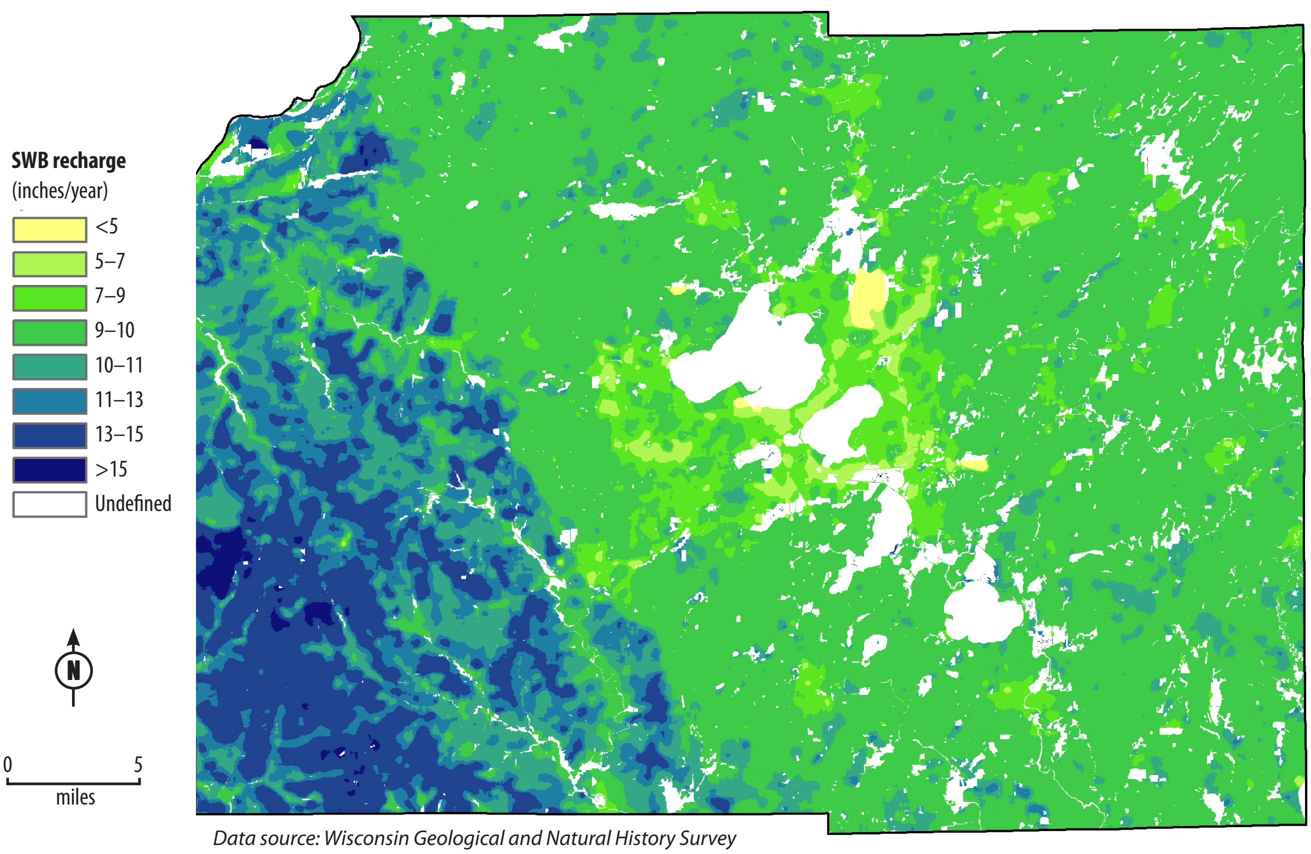
Results and applications

Regional recharge

The recharge map (shown categorized at a reduced scale in figure 5) was prepared as a raster data set in Environmental Systems Research Institute grid format, suitable for overlay and analysis with other GIS data layers. The map was prepared using existing land use as of 2005 and a typical climate year, 1981. For this model year, recharge varies by more than 10 inches (25 cm) per year across the county. Using other years with different precipitation patterns and antecedent moisture conditions will result in different recharge estimates. In general, the pattern of recharge will remain constant, but the overall average will vary with the precipitation and antecedent soil moisture.

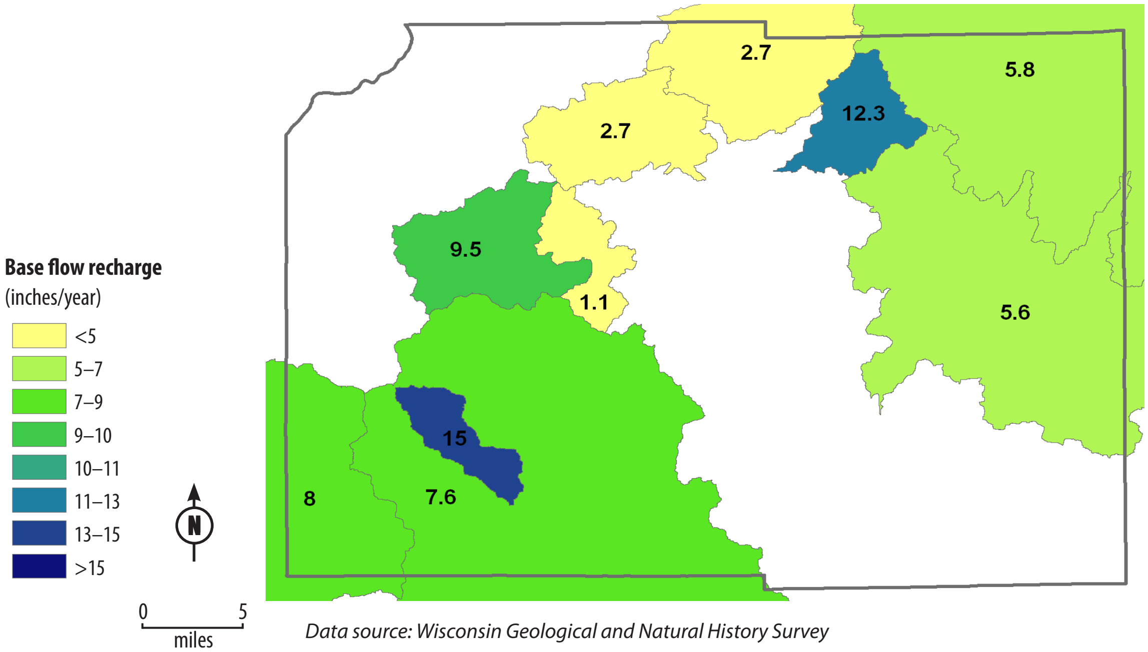
Some general trends, correlating with surficial geology and land-use patterns, are evident in the recharge map. The greatest spatial control on recharge in Dane County is surficial geology. The unglaciated western and southwestern part of the county (Clayton and Attig, 1997) has the highest recharge, shown in dark green and blue. Recharge is high here because thin soils with low storage capacity occur over carbonate and sandstone bedrock. In contrast, the eastern two-thirds of the county, the glaciated area, has moderate recharge with little variation. In this area, the moderate hydraulic conductivity and higher storage capacity of the glacial tills reduce recharge rates. The lower recharge values in the central part of the county are due primarily to urban development in the Madison

Figure 5. Recharge map for Dane County.



Data source: Wisconsin Geological and Natural History Survey

Figure 6. Estimates of recharge from base flow measurements.



Data source: Wisconsin Geological and Natural History Survey

area and its suburbs. In many of those areas, storm water is routed directly to surface waters through storm sewers, making it unavailable for recharge. To account for that routing, runoff was removed from the model when it encountered streets or highways in areas where storm sewers discharge to surface waters.

Not all runoff from transportation land-use categories was removed from the model. In the mid-1980s, discharge from storm sewers to surface waters was recognized as having an impact on lakes and streams in urban Dane County. Consequently, storm sewers are now built so that they route runoff to infiltration basins, retention ponds, and environmental corridors, thus improving infiltration and reducing runoff to the county's lakes and streams. The model was adjusted to account for this policy change. Runoff from transportation land-use was not removed from the model in areas where updated storm sewer routing practices have been implemented. This zoning change is evident in some of the newer outlying residential areas, where there is little to no simulated reduction in recharge between areas identified as agricultural and residential. Runoff from transportation land-use categories in these areas is not removed from the model as it might ultimately infiltrate and become recharge.

Comparison with other methods

The SWB recharge model has been compared to USGS base flow measurements (Gebert and others, 2007) and to a precipitation runoff modeling system (PRMS) estimate for the Pheasant Branch watershed basin in central Dane County (Steuer and Hunt, 2001). Unlike the USGS base flow measurements and the PRMS estimate, the SWB model does not include any direct measurements of flow in the hydrologic system. The comparisons between the SWB recharge model and the other two methods provide a needed check of the SWB model.

In general, the spatial trends seen in the SWB model (figure 5) are also seen in the USGS base flow measurements, which are shown in figure 6. The highest values of base flow are in the west and southwest portion of the county, while moderate values of recharge are found in the eastern portion. The two estimates of recharge differ in the north-central part of the county. There, the SWB recharge estimates are from 7 to 9 inches (17.8 to 22.9 cm) per year, while the USGS base flow estimates are less than 3 inches (7.6 cm) per year for three of the measured basins and greater than 12 inches (30.5 cm) per year for a fourth basin. The difference between the two estimates is possibly due to the assumption that base flow represents all recharge in a basin. In the case of Pheasant Branch, located in the glaciated area of Dane County, the base flow estimate of recharge is 1.1 inches (2.8 cm) per year. The difference between the two recharge estimates might reflect the fact that much of the recharge does not ultimately discharge into Pheasant Branch Creek, but instead flows downward and enters the regional groundwater flow system (Steuer and Hunt, 2001). Similar effects are probably also present for the other two basins in north-central Dane county, with recharge estimates below 3 inches (7.6 cm) per year.

The PRMS recharge estimates generally agree with those generated by the SWB model for the basin where the PRMS analysis was conducted. The PRMS analysis estimated a recharge range from 2.3 to 9.7 inches (5.8 to 24.6 cm) per year, with an average of 8.1 inches (20.6 cm) per year; the range of recharge based on the SWB for the typical year, 1981, is 2.5 to 11.3 inches (6.4 to 28.7 cm) per year, with an average of 9.1 inches (23.1 cm) per year. The difference between these two analyses is small and might be reduced further by using the same climate data. An earlier version of the SWB model (Dripps, 2003) used the same climate data for the Pheasant Branch basin with the result that the SWB and PRMS analyses were in excellent agreement.

Although some differences arise among the models (possibly due to groundwater flow to a regional system versus local discharge or due to differences in the climate data used), the SWB model is generally in agreement with the other methods. This agreement provides increased confidence when applying the smaller-scale recharge results to the entire county.

Model limitations

The accuracy of the recharge predicted by this model is limited by the uncertainty and 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 determines 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 temporal resolution also affects the accuracy of the model. In this model, the precipitation data were input as a total daily value, so the model cannot differentiate between a steady rainfall and a 30-minute storm event.


Swale in housing development

Finer-scale inputs would lead to finer-scale outputs. The precision and accuracy of the input data are 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 thus would not be included in the model as a closed basin.

This SWB model had to be altered to avoid introducing error into recharge calculations through the 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 included as recharge, resulting in unreasonably large recharge values greater than 1,000 inches (2,540 cm) per year. 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.

The model further 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, 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 (127 cm) per 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 depends 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 there is probably significant variation within land-use categories. For example, residential vegetation can vary from deep-rooted trees to shallow-rooted grass, but the model assigns the same rooting depths for all vegetation in the residential land-use category.

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. Pits and quarries were excluded because their status as a recharge area is dependent on whether the pit or quarry is being dewatered, a detail the model cannot incorporate. Surface waters are also not within the calibrated ranges of inputs for the SWB model and were therefore excluded.

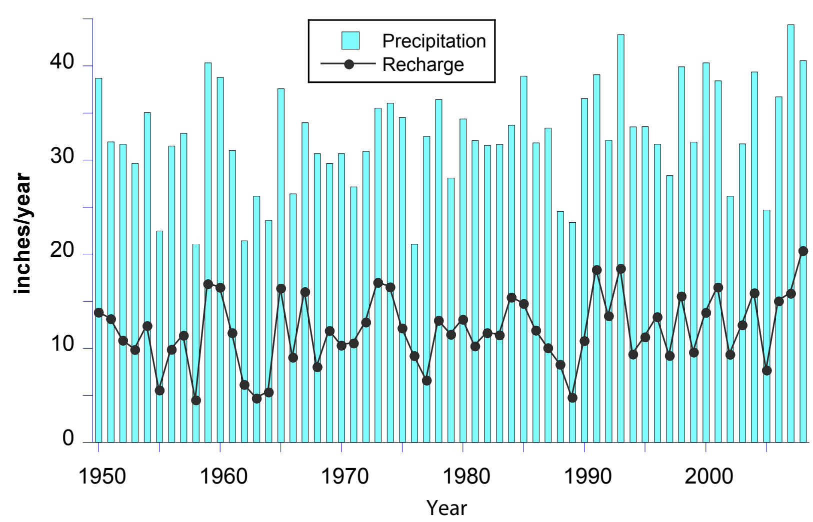
Finally, the model assumes that the soil types in the NRCS SSURGO database are representative of the subsurface from the ground surface to the water table. This assumption may be violated if, for example, an outwash sand overlies a lake clay.

Climate and recharge

Climate affects recharge, with recharge typically increasing when precipitation increases and decreasing during times 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.

The SWB model was used to illustrate the relationship between climate and recharge. Figure 7 shows the variation of precipitation and recharge over time for Dane County between 1950 and 2008, with land use held constant to the 2005 distribution. At the time of modeling, the December 2008 climate data were not available and thus were not included in the analysis. Although the 2008 results only include the first 11 months, the overall recharge estimate for 2008 is not expected to change significantly since little recharge typically occurs in December. During this period, annual precipitation varied from a low of 21.1 inches (23.6 cm) per year in 1958 to a high of 44.4 inches (112.8 cm) per year in 2007, while recharge averaged over Dane County varied from 4.5 inches (11.4 cm) per year in 1958 to 20.4 inches (51.8 cm) per year in 2008. A period of consecutive dry years can cause recharge levels to drop dramatically. From 1985 to 1989, precipitation decreased from 38.9 inches (98.8 cm) per year to 23.4 inches (59.4 cm) per year, while recharge decreased from 14.8 inches (37.6 cm) per year to 4.8 inches (12.2 cm) per year. Conversely, a period of wet years causes recharge to increase. Between 2006 and 2008, precipitation was well above average, with the result that recharge was also well above average. A similar period of wet years preceded 1993. Spring flooding occurred in Dane County in 1993 and in 2008 after heavy rainfalls. The increased recharge helps explain both why the flooding occurred and why flood waters persisted in some areas. The saturated soils would not have been able to store any additional

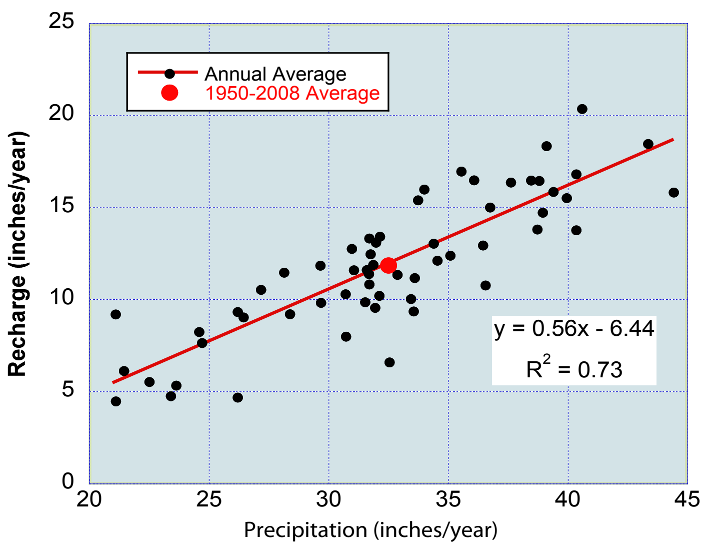
Figure 7. Precipitation and SWB model recharge for Dane County from 1950 to 2008.



water, leading to increased runoff flooding immediately following heavy rainfalls; the increased recharge would have caused the water table to rise to the ground surface at some locations, resulting in long-term flooding that only subsides after the groundwater system drains sufficiently to allow the water table to drop beneath the land surface.

The relationship between recharge and precipitation is also illustrated in figure 8. This plot indicates that, as expected, higher precipitation is correlated with higher recharge. It also indicates the variation of recharge with similar precipitation. For instance, the average recharge across Dane County varies from less than 7 inches (17.8 cm) per year to nearly 14 inches (35.6 cm) per year at the average annual precipitation of 32.5 inches (82.6 cm) per year. That variation is due to the other climatic factors: the antecedent soil moisture, unmelted snow from the previous year's precipitation, the strength and duration of rainfall, and the amount of evapotranspiration as controlled by temperature.

Figure 8. A cross-plot of precipitation versus SWB model recharge for Dane County.



Summary

A new estimate of the distribution of groundwater recharge for Dane County, Wisconsin, is based on a soil-water-balance (SWB) recharge model constructed for the county. 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 and relatively low effort. Its weaknesses are 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, which is much smaller than the subwatershed or watershed scale of previous estimates. This project has produced both a detailed GIS-based recharge coverage for the county and a tool (the SWB model itself) for generating other recharge estimates for different scenarios such as changing climate and variations in land use.

Recharge is variable over time and location. The annual SWB recharge for Dane County varied from less than 5 inches (12.7 cm) per year to more than 20 inches (50.8 cm) per year in the period from 1950 to 2008. 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, with the other inputs being less easily changed by human interaction. This gives land-use planning a critical role in recharge management.

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