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GROUND-WATER RESOURCES PROGRAM

Ground-Water Recharge in Humid Areas of the United States—A Summary of Ground-Water Resources Program Studies, 2003-06

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Increased demands on water resources by a growing population and recent droughts have raised awareness about the adequacy of ground-water resources in humid areas of the United States. The spatial and temporal variability of ground-water recharge are key factors that need to be quantified to determine the sustainability of ground-water resources. Ground-water recharge is defined herein as the entry into the saturated zone of water made available at the water-table surface, together with the associated flow away from the water table within the saturated zone (Freeze and Cherry, 1979). In response to the need for better estimates of ground-water recharge, the Ground-Water Resources Program (GWRP) of the U.S. Geological Survey (USGS) began an initiative in 2003 to estimate ground-water recharge rates in the relatively humid areas of the United States.

This Fact Sheet summarizes the significant research contributions of recharge studies initiated by the GWRP in humid regions of the United States. As defined for these studies, the humid region refers to parts of the continental United States that receive greater than about 50 centimeters of average annual precipitation (fig. 1), not including some high-elevation areas of the Rocky Mountains.

Research priorities of this initiative included: (1) evaluating the temporal and spatial variability in ground-water recharge and identifying factors that influence that variability; (2) developing recharge estimates on a regional scale; and (3) developing innovative methods to estimate recharge and to quantify accuracy of estimates.

GWRP Recharge Studies

Six studies were conducted in this initiative (fig. 1) including four at basin- or statewide-scales:

- Minnesota (Delin and others, 2007),
- North Carolina (Coes and others, 2007),
- Pennsylvania (Risser and others, 2005),
- Wisconsin (Gebert and others, 2007).

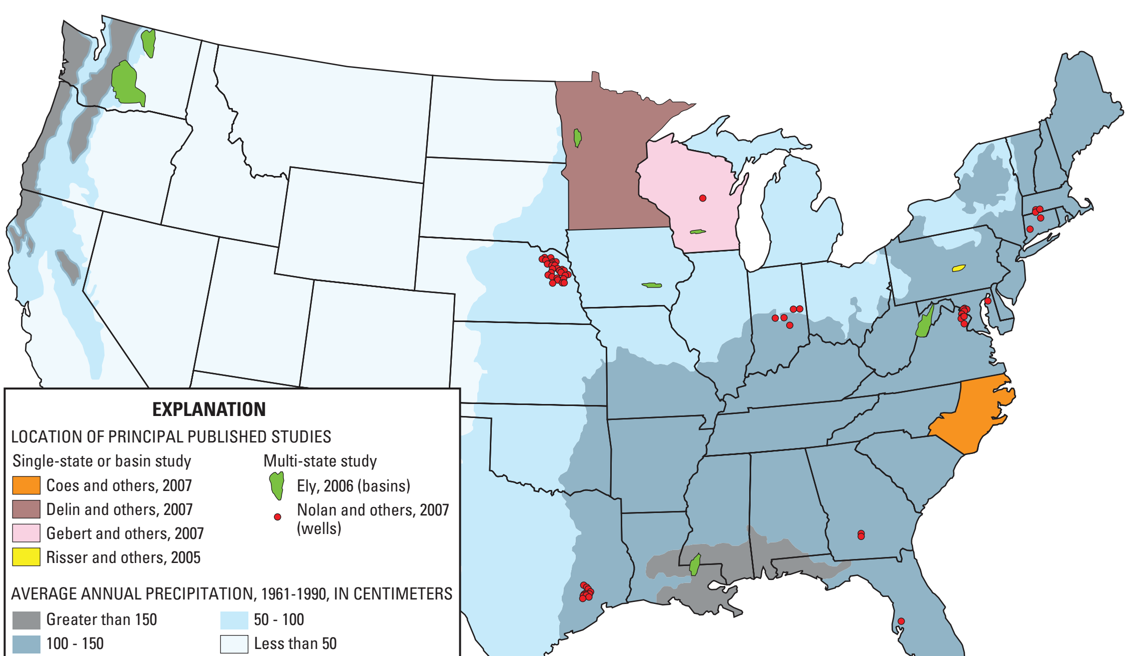
Two studies were conducted with sites in multiple states:

- Sensitivity analysis of seven watershed models (Ely, 2006),
- Statistical analysis of samples collected at multiple National Water Quality Assessment (NAWQA) sites (Nolan and others, 2007).

In addition to these principal publications, all or part of the research documented in several other publications was completed as part of this GWRP initiative and are noteworthy: Heppner and Nimmo (2005) presented a computer program for predicting recharge from water-table fluctuations; Dripps and others (2006) presented estimates of recharge with analytic element models and parameter estimation; Juckem and others (2005) evaluated scale effects of hydrostratigraphy and recharge zonation on base flow; Lorenz and Delin (2007) presented a regression model that was used to estimate recharge in Minnesota; Heppner and others (2007) compared multiple methods for estimating recharge; and Gebert and others (2005) discussed the importance of spatial and temporal variability of recharge.

Recharge Estimation Methods

Ground-water recharge in the six GWRP studies was estimated using many methods (table 1). The methods are grouped on the basis of the spatial scale: local, representing 1 to 1,000s of square meters; basin, representing 10 to 100s of square kilometers, and regional, representing 100s to 1,000s of square



Precipitation data modified from the Western Region Climatological Center, written commun., 2006, <http://www.wrcc.dri.edu/precip.htm>

Figure 1. Locations of U.S. Geological Survey Ground-Water Resources Program recharge studies in humid areas of the United States and 1961-1990 average annual precipitation.

Table 1. Summary of recharge methods used in the six principal studies and the range of estimated recharge as a percent of precipitation. Average values are in parentheses.

METHODS	GWRP STUDY SITES					
	Minnesota (Delin and others, 2007)	North Carolina (Coes and others, 2007)	Pennsylvania (Risser and others, 2005)	Wisconsin (Gebert and others, 2007)	NAWQA study (Nolan and others, 2007)	Model study (Ely, 2006)
Local Scale						
Water-table fluctuation (WTF)	6-56 (21)	25-94 (56)	19-48 (24)			
Age dating of ground water	7-49 (24)	2-36 (12)				
Unsaturated-zone water balance (UZWB)	25-60 (43)					
Gravity-drainage lysimeters			25-33 (29)			
Water-balance equation			25-32 (29)			
Darcian flux		62-69 (66)			0.00-1,064 (64)	
Chloride unsaturated-zone tracer					0.05-119 (10)	
Chloride saturated-zone tracer					0.1-327 (17)	
Basin Scale						
Rorabaugh equations	8-44 (19)	16-27 (24)	24-33 (29)			
Streamflow-hydrograph separation			21-28 (25)	3-54 (21)		
Model analyses						0.3-63 (24)
Regional Scale						
Regional or statewide regression equations	8-38 (21)			2-42 (20)		

kilometers. Methods based on unsaturated-zone and surface-water data provide estimates of potential or net recharge whereas those based on ground-water data generally provide estimates of actual recharge. The reader is referred to the individual reports for descriptions of these methods.

Contributions of the GWRP Recharge Research

This research initiative resulted in contributions to the science of recharge estimation as follows:

New Methods

Two new computer routines were developed to estimate recharge from water-table fluctuations. Both methods utilize a master recession curve for water levels in a well, which allows better recognition of recharge during periods when the water level in the well is not rising (Heppner and Nimmo, 2005; Delin and others, 2007).

Regional Estimates of Recharge

A new process was developed for regionalizing local- or basin-scale recharge estimates in Minnesota (Lorenz and Delin, 2007). Recharge based on this regional regression recharge (RRR) method (fig. 2) compared favorably with results from local- and basin-scale methods in Minnesota (table 1). The RRR rates were within 5 to 35 percent of the rates based on the unsaturated-zone water balance (UZWB) method, the water-table fluctuation (WTF) method, age dating of ground-water method, as well as those based on the computer code RORA (Rutledge, 1998).

A new process to estimate average annual base flow at ungaged sites in Wisconsin was developed by multiple-regression analysis using basin characteristics (Gebert and others, 2007). The equation with the lowest standard error of estimate had drainage area, basin storage, soil infiltration, and base-flow factor as independent variables.

Comparison of Methods and Factors Affecting Recharge Estimates

- Estimates of long-term average recharge in the GWRP studies ranged from 10 to 66 percent of precipitation (table 1). Recharge estimates from the UZWB, Darcian, and chloride methods were extremely variable because they represent local recharge. Estimates of average recharge from the Darcian-

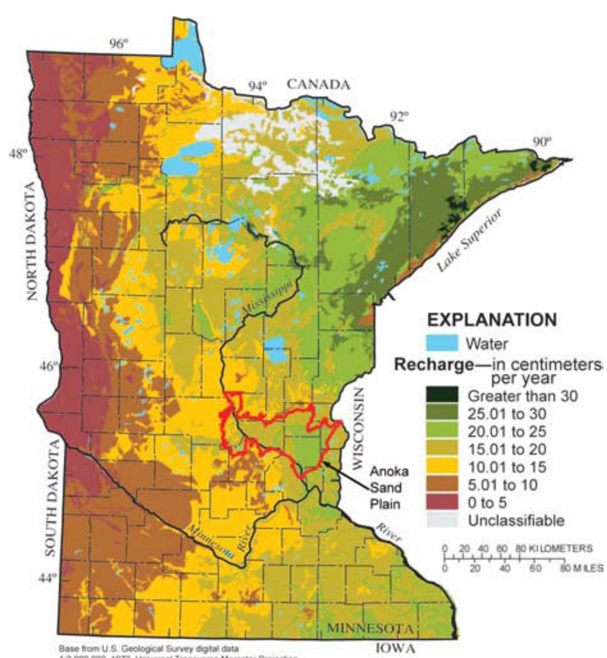


Figure 2. Average annual recharge rate to surficial materials in Minnesota (1971-2000) estimated on the basis of the regional regression recharge method (Lorenz and Delin, 2007)

flux method was large compared to the other methods; estimates based on the chloride methods were small, on average, compared to the other methods.

- Watershed size affected base-flow estimates for some hydrograph-separation methods (Risser and others, 2005). If watersheds of various sizes are being compared, it may be advantageous to use the computer code PART (Rutledge, 1998) or the local-minimum version of the computer code HYSEP (Sloto and Crouse, 1996) because these programs did not seem to be artificially affected by watershed scale.
- The spatial distribution of mean annual recharge from unsaturated-zone and ground-water data collected in the Coastal Plain of North Carolina was examined against seven environmental indicators, only two of which—the sand content and silt content of the surficial sediments—significantly correlated with estimated recharge (Coes and others, 2007).
- In the multi-state study by Nolan and others (2007), recharge estimates using chloride-tracer methods were less variable and more strongly correlated with variables representing climate, hydrology, land use and management, and soil properties compared with Darcian-flux recharge estimates. The Darcian estimates had considerable uncertainty because of the nonlinear function of hydraulic conductivity with moisture content, and because of uncertainties in the pedotransfer functions used to estimate water-retention parameters. A nonlinear regression model explained 61 percent of the regional variation in ground-water chloride-tracer estimates of recharge (Nolan and others, 2007).
- Model-sensitivity analysis indicated that large-scale climate and flow processes (mean annual runoff, air temperature, precipitation, and topographic wetness index) most influenced the recharge estimates derived from the precipitation-runoff modeling system (Ely 2006).

Conclusions of the GWRP Recharge Research

The following conclusions were gleaned from this research initiative:

Comparison of multiple methods is recommended. The GWRP recharge research demonstrated that no single recharge method can be assumed to be most appropriate in humid areas over all scales and time periods. This research confirms the results of previous studies that, because of the limitations and uncertainties of each method, the use of multiple recharge-estimation methods is beneficial.

For example, in the Coastal-Plain sediments of North Carolina, Coes and others (2007) found that mean annual potential and total recharge determined using ground-water age dating, Darcian flux, and WTF methods were as much as 250 percent greater than mean annual net recharge determined by the computer code RORA. The large disparity was primarily attributed to ground-water losses between recharge and discharge areas, leading to the conclusion that RORA probably underestimates recharge in this setting. In contrast, for Minnesota watersheds mantled with glacial sediments, Delin and others (2007) found that recharge rates using the computer code RORA were within the range of recharge estimated from the ground-water age dating, WTF, and UZWB methods.

Comparison of multiple methods at a small basin in Pennsylvania showed that the simple determination of long-term base flow can provide a useful estimate of recharge. In this study, base flow was within the range of variability of recharge estimates from the water-balance equation, WTF method, and gravity-drainage lysimeters that were considerably more difficult to apply (Risser and others, 2005).

High-quality, long-term continuous hydrologic and climatic records are important. Because recharge can vary significantly year to year (Risser and others, 2005; Dripps and others, 2006; Delin and others, 2007), long-term continuous records of hydrologic (fig. 3) and climatic data are required to truly characterize recharge. Long-term continuous records are required for use of some computer programs that compute recharge from streamflow, ground-water levels, or hydrologic water-balance data. If missing values need to be estimated, an additional degree of uncertainty is added to the results. Ely (2006) showed that recharge estimated by five watershed models across the United States was sensitive to air temperature, emphasizing the importance of temperature data.

Delin and others (2007) showed that frequency of water-level measurements is important in applying the WTF method. Measurements made less frequently than about once per week resulted in as much as a 48 percent underestimation of recharge based on an hourly measurement frequency.

Local-scale estimates of recharge are highly variable and may be difficult to regionalize or transfer from one location to another. Numerous factors influence the spatial variability of recharge locally including physical characteristics of the soil, vegetation cover, land use, topography, water content of surface materials (fig. 4), depth of the confining layers and aquifers, and the present climate conditions. These localized, small-scale variations cannot be included in regionalized recharge estimates, such as the RRR method (fig. 2). Low-permeability units at or near land surface and evapotranspiration effects in areas of shallow ground water could greatly reduce estimated local-scale recharge rates, for example. In contrast, focused recharge of water in depressional areas due to surface-water runoff from surrounding upland areas would result in higher estimates at those sites. Because of this spatial variability, local estimates of recharge are of limited use in estimating basin- or regional-scale recharge.

Temporal variability must be considered. Results clearly demonstrate recharge rates vary seasonally and annually at any given location (Risser and others, 2005; Dripps and others, 2006; Delin and others, 2007). Temporal variations of recharge stem from factors such as the amount, intensity, and duration of precipitation; ET rates; and temperature. Changes in land use, such as agricultural practices, also can appreciably affect recharge.

Figure 3. Streamflow-gaging station in north-central Pennsylvania used to estimate ground-water recharge from streamflow records.

Figure 4. Instrumentation installed in the unsaturated zone at a site near Bemidji, Minnesota, to estimate recharge using the UZWB method.

Regionalized recharge estimates should be used with caution. Recharge based on the regionalization of local- or basin-scale data should be used with caution for annual estimates of recharge because average values of precipitation, recharge, and other variables were used to construct the maps and regression equations. Actual recharge will vary from year to year depending on climate. Data collected at local and basin scales are necessarily averaged to make regionalized estimates of recharge.

Differences in the positions of the surface-water and ground-water divide can make a large difference in average annual base-flow values averaged over the entire basin. Estimation of average recharge rates from stream base flow requires knowledge of the ground-water area contributing to base flow. Where the perimeter of the contributing ground-water area is defined by ground-water divides, the traces of the divides must be defined to compute a contributing area. Assuming that ground-water divides are coincident with overlying surface-water divides can result in erroneous estimates of recharge (Gebert and others, 2007).

The WTF method requires extra caution in materials with low specific yield. Small absolute errors in estimating specific yield in low-storage fractured-rock aquifers can cause large errors in recharge estimates by the WTF method (Risser and others, 2005). Where possible, estimates from multiple observation wells should be used.

Acknowledgments

The authors would like to acknowledge the contributions of all USGS personnel who worked on this GWRP research initiative, most notably Alissa Coes, D. Matthew Ely, Richard Healy, Christopher Heppner, Randall Hunt, David Lorenz, John Nimmo, Thomas Nolan, and Thomas Winter.

GWRP Information Products

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