

A Regression Model to Estimate Regional Ground Water Recharge

by David L. Lorenz¹ and Geoffrey N. Delin²

Abstract

A regional regression model was developed to estimate the spatial distribution of ground water recharge in subhumid regions. The regional regression recharge (RRR) model was based on a regression of basin-wide estimates of recharge from surface water drainage basins, precipitation, growing degree days (GDD), and average basin specific yield (SY). Decadal average recharge, precipitation, and GDD were used in the RRR model. The RRR estimates were derived from analysis of stream base flow using a computer program that was based on the Rorabaugh method. As expected, there was a strong correlation between recharge and precipitation. The model was applied to statewide data in Minnesota. Where precipitation was least in the western and northwestern parts of the state (50 to 65 cm/year), recharge computed by the RRR model also was lowest (0 to 5 cm/year). A strong correlation also exists between recharge and SY. SY was least in areas where glacial lake clay occurs, primarily in the northwest part of the state; recharge estimates in these areas were in the 0- to 5-cm/year range. In sand-plain areas where SY is greatest, recharge estimates were in the 15- to 29-cm/year range on the basis of the RRR model. Recharge estimates that were based on the RRR model compared favorably with estimates made on the basis of other methods. The RRR model can be applied in other subhumid regions where region wide data sets of precipitation, streamflow, GDD, and soils data are available.

Introduction

Many different methods are available for estimating recharge (Scanlon et al. 2002), and regional estimates of recharge also have been developed using a variety of approaches. For example, Arnold et al. (2000) developed regional estimates of recharge at the subbasin scale throughout the upper Mississippi River region using a water balance approach and two different methods that were based on streamflow. Dumouchelle and Schiefer (2002) estimated ground water recharge rates for 103 basins throughout Ohio using streamflow records and basin characteristics. Szilagyi et al. (2005) developed spatially

detailed regional estimates of recharge across Nebraska using geographic information system (GIS) layers of land cover, elevation of land and ground water surfaces, base flow recharge, recharge potential, and climatic data. Allison et al. (1990) scaled point estimates of recharge across a semiarid region using landscape units. Remote sensing methods have been employed by several researchers: Cook and Kilty (1992) scaled point estimates using electromagnetic methods, Jackson (2002) used microwave remote sensing to relate soil moisture to ground water recharge, and Gouweleeuw (2000) used satellite-based microwave data to estimate recharge. Other studies that have used multiple regression approaches on climatic/soil/topography parameters include Cherkauer (2004), Cherkauer and Ansari (2005), and Holtschlag (1996). Holtschlag (1996) developed a generalized recharge map for the Lower Peninsula of Michigan by analysis of streamflow, precipitation, and soil data. Generalized, regional estimates of recharge such as these examples provide consistent methods for approximating recharge rates over large areas.

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The purpose of this paper is to describe the development of a linear regression model to quantify regional recharge estimates at a regional scale. This effort was part of a larger study to estimate the spatial and temporal variability of recharge in Minnesota using multiple methods. The primary study objectives were to compare local scale recharge estimates to regional estimates and to evaluate whether the local scale measurements could be regionalized. Results presented in this paper can benefit future studies of ground water recharge and water management planning as well as construction and calibration of ground water flow models.

Regression Model

The form of the regional regression recharge (RRR) model was based on factors identified in previous studies (Bredenkamp 1988; Kennett-Smith et al. 1994; Scanlon et al. 2002) and to avoid bias in the regression coefficients, which can result from stepwise methods of variable selection (Harrel 2001). Scanlon et al. (2002) state that climate, geomorphology, and land cover are important characteristics to consider when developing a model for recharge. Bredenkamp (1988) describes a simple model for a homogenous region in South Africa. That model includes only net precipitation (precipitation minus a threshold amount). Kennett-Smith et al. (1994) found that clay content in the upper 2 m of soil was strongly related to recharge. Holschlag (1996) identified soil texture as one of the factors controlling recharge. For this model, precipitation and growing degree days (GDD) were included as climatic factors to estimate the net precipitation available for recharge. GDD was selected as a measure for estimating precipitation lost from the system and not available for recharge instead of evapotranspiration (ET) because (1) GDD is the primary factor in estimating ET; (2) annual estimates of ET are not universally available; and (3) there are several methods of estimating ET, which would complicate use across a larger study area. GDD is defined as the annual sum of the average temperature minus a base temperature, for example, 10°C, with negative values counting as zero for each day. The data are averaged over some period of time to provide an estimate of average recharge and to avoid the variability of recharge due to the variability of precipitation over short periods of time. For example, a 12-cm rainfall event could produce a different amount of recharge than six 2-cm storms. A single landscape characteristic that incorporates soil texture is selected that will satisfy the assumptions of the linear model and can be interpreted on the land surface. Scanlon et al. (2002) summarize several researchers who have identified land use and land cover as having an important effect on recharge. Land use and land cover were not considered in this RRR model because the dominant land use and land cover are highly correlated with precipitation and GDD in Minnesota (primarily forested in the northeastern part, becoming more agricultural toward the south and west), and within each general region, the land use and land cover are affected by soil texture. A post hoc analysis was performed to verify that

land use and land cover were not significant factors affecting recharge.

Based on the factors outlined in the previous paragraph, the proposed form of the RRR model is shown in Equation 1:

$$R_i = \beta_0 + \beta_1 P_i + \beta_2 \text{GDD}_i + \beta_3 \text{LC}_i + e_i \quad (1)$$

where R_i is the estimated recharge in centimeters per year (averaged over some period of time) for observation i ; P_i is the precipitation in centimeters per year for observation i ; GDD_i is the GDD in degrees Celsius above 10 d for observation i ; LC_i is some landscape characteristic for observation i ; e_i is the residual for observation i (assumed to be correlated but identically and normally distributed); and β_0 , β_1 , β_2 , and β_3 are regression coefficients. The linear model is assumed to be an approximate estimate of the true model, which is much more complicated and certainly nonlinear. S-PLUS[®] software was used to manage data and construct the linear regression model.

Basin Selection and Recharge Estimation

All 340 continuous record gauging stations in Minnesota were accessed through NWISWeb (National Water Information System Web; <http://waterdata.usgs.gov/mn/nwis/sw>) and reviewed for possible inclusion in the study. The criteria for inclusion were that (1) gauging stations have at least a 10-year period of record; (2) gauging stations have no missing data within the 10-year periods; (3) the flow not be significantly affected by regulation and diversion structures, such as a dam; (4) the basins lie wholly within Minnesota or have soils that are not different from those found in Minnesota; (5) the basins have a drainage area of < 5000 km²; (6) if a basin is nested within a larger basin, then it must be restricted to < 15% of the larger basin; and (7) the basins have soils data that can be used to estimate landscape characteristics. The first criterion is needed to obtain good average recharge estimates; criteria 4 and 6 are included to simplify processing and analysis; criteria 2, 3, and 5 are required for estimating recharge; and criterion 7 is required for the regression model. The data sets were checked for missing values using the computer program SCREEN (Rutledge 2003). A total of 38 gauging stations were selected on the basis of the inclusive criteria (Table 1) and cover approximately 25% of the state.

Basin boundaries were delineated upstream from each gauge (Figure 1). All geographic data maintenance and analyses were done using the ARC/INFO[®] geographic information system (GIS).

Recharge was estimated using the program RORA (Rutledge 1998, 2000; Rutledge and Daniel 1994) and streamflow records for each of the 38 selected gauging stations. RORA is an automated method for estimating recharge in a basin from analysis of streamflow records using the recession curve displacement method of Rorabaugh (1960, 1964). In the Rorabaugh method, ground water flow is assumed to be perpendicular to the length of the stream and includes possible effects of a component that is parallel to the stream (the “downvalley” component). Rorabaugh (1964) and Glover (1964) show that

Table 1
USGS Gauging Stations Used in the Analysis

Map Number for Drainage Basin (Figure 1)	ID Number	Stream Name	Drainage Area (km ²)	Beginning Year	Ending Year	Recession Index (days per log cycle)
1	04014500	Baptism River	355	1950	1989	34.96
2	04015330	Knife River	216	1980	1999	22.75
3	04024098	Deer Creek	20	1980	1999	63.35
4	05061000	Buffalo River	841	1950	1999	55.07
5	05062500	Wild Rice River	2420	1940	1999	45.18
6	05069000	Sand Hill River	1090	1950	1999	35.08
7	05078000	Clearwater River	1440	1940	1999	55.24
8	05078230	Lost River	657	1970	1999	36.68
9	05087500	Middle River	661	1960	1999	23.42
10	05104500	Roseau River	1110	1950	1999	25.41
11	05124480	Kawishiwi River	658	1970	1999	63.75
12	05130500	Sturgeon River	467	1950	1999	40.53
13	05139500	Warroad River	440	1950	1979	21.83
14	05244000	Crow Wing River	2660	1940	1979	86.98
15	05245100	Long Prairie River	1120	1980	1999	67.56
16	05275000	Elk River	1450	1940	1979	64.59
17	05286000	Rum River	3580	1940	1999	76.66
18	05287890	Elm Creek	223	1980	1999	30.56
19	05294000	Pomme De Terre River	2240	1940	1999	53.22
20	05304500	Chippewa River	4860	1940	1999	62.23
21	05313500	Yellow Medicine River	1720	1940	1999	33.68
22	05315000	Redwood River	670	1950	1999	34.02
23	05317000	Cottonwood River	3380	1940	1999	39.46
24	05317200	Little Cottonwood River	434	1980	1989	37.07
25	05319500	Watowan River	2200	1980	1999	30.85
26	05320500	Le Sueur River	2870	1950	1999	31.84
27	05336700	Kettle River	2250	1970	1999	32.50
28	05337400	Knife River	279	1980	1999	21.33
29	05338500	Snake River	2250	1960	1979	35.91
30	05340000	Sunrise River	421	1950	1959	64.20
31	05353800	Straight River	1120	1970	1999	40.25
32	05376000	North Fork Whitewater River	261	1970	1989	136.16
33	05376500	South Fork Whitewater River	201	1940	1969	94.94
34	05379000	Gilmore Creek	23	1940	1959	212.75
35	05384000	Root River	1590	1950	1979	96.90
36	05384500	Rush Creek	343	1950	1979	174.94
37	05476000	Des Moines River	3230	1940	1999	38.24
38	06603000	Little Sioux River	44	1950	1959	15.91

the total potential ground water discharge to the stream at the critical time after the peak streamflow (Figure 2) is approximately one-half the total volume recharged. Rorabaugh (1964) showed that the critical time is proportional to the recession index. The recession index, which is the time required for ground water discharge to recede by one log cycle after recession, becomes linear or near-linear on the semilog hydrograph. The total recharge (R) is then proportional to the difference in the theoretical flows at the critical time (ΔQ) multiplied by the recession index (K).

$$R = 2\Delta QK/2.3026 \quad (2)$$

where 2 and 2.3026 are derived from the theoretical development of ground water discharge to the stream. Figure 2 shows an example of the recession curve displacement method in RORA.

Considerable uncertainty is inherent in the recession index. The results of applying the RORA program in this study generally indicated that it was not substantially sensitive to this variable, however. Selected stations were analyzed for sensitivity to differences in the recession index. The recession index was varied through one-half the total range of the observed values of recession rates. The mean difference in annual recharge estimates was <1%, and the maximum difference in any 1 year was approximately 5%.

The entire period of record for each basin was used to select recession periods to determine a recession index. The open water season (April through November) was used to provide those recession periods because many ice-covered periods have estimated streamflow. The median value of the selected periods was used as the recession index for the basin (Table 1). The selected

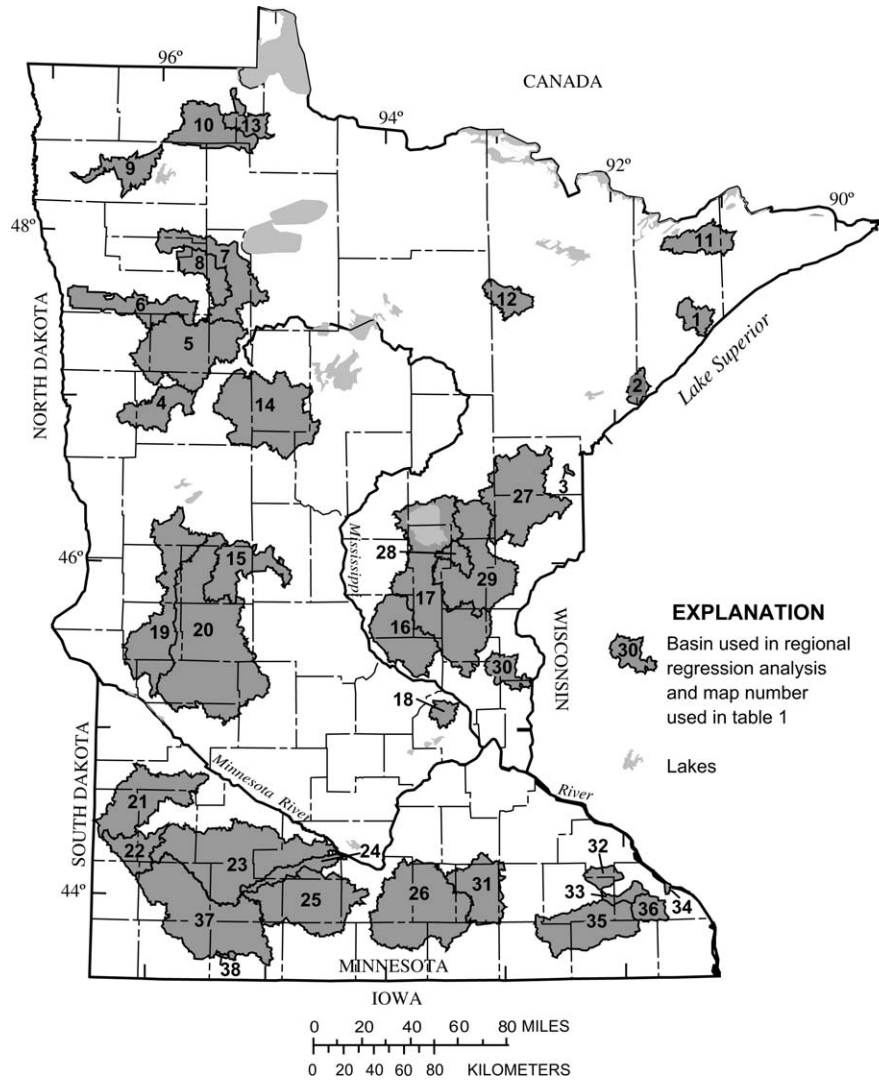


Figure 1. Basins in Minnesota used to estimate ground water recharge using the program RORA (Rutledge 1998, 2000).

recession periods were required to be at least 10 d in length and have a consistent recession rate.

Precipitation and GDD Data Processing

Data from the Minnesota State Climatology Office (Spoden 2003) represent interpolated annual precipitation values on a 10,000-m grid over the entire state. The gridded data were processed to represent the average precipitation within the decadal record for each basin. The decadal data then were converted to annual grids using topogrid in ARC/INFO. Drainage enforcement (an option that fills low spots in topography) was turned off so that locally small annual precipitation values were not artificially increased. The annual grids then were converted to polygon coverages and intersected with the basin boundaries using a GIS software. The annual precipitation for each basin was calculated as the mean weighted by area for the values that were in that basin. The average annual precipitation for 1971 to 2000 in Minnesota, based on the annual data provided by the Minnesota State Climatology Office, for the state is shown in Figure 3.

GDD summarized by month and year for weather stations in and near Minnesota were obtained from Shea (2006). Weather stations in neighboring states were included to reduce edge effects when interpolating data between stations. The weather station data were imported into a point coverage. The inverse distance weighting method of interpolation was used to construct grids for each year. The maximum interpolated distance was 150 km and no more than 12 stations were used for any point in the grid. The data from the GDD grids were extracted in the same manner as precipitation. The mean GDD data for 1971 to 2000 are shown in Figure 4.

Specific Yield as the Landscape Characteristic

Specific yield (SY) is defined as the ratio of the volume of water that drains from a soil due to gravity to the total soil volume (Meinzer 1923). SY is a storage term that can be estimated using a wide variety of laboratory and field methods (Prill et al. 1965; Johnson 1967; Healy and Cook 2002). There is a large degree of variation in the estimates of SY for a particular geologic material.

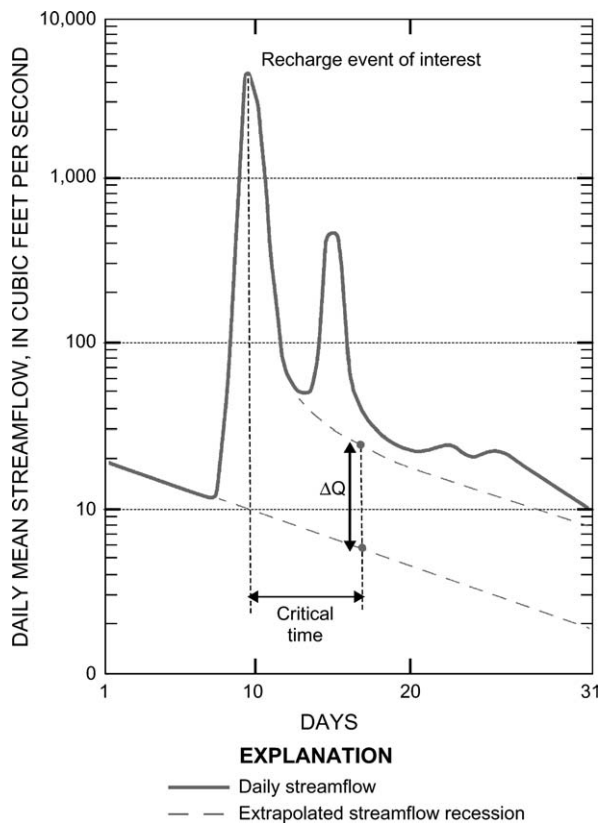


Figure 2. Example streamflow hydrograph showing recession curve displacement method to estimate ground water recharge in response to a recharge event (modified from Rutledge 1998).

This variability is due not only to the variety of estimation methods used but also to heterogeneity of the material itself and the amount of time allotted for laboratory estimation of SY. Many years may be required for some soils to fully drain to steady-state conditions, but full drainage almost never occurs in nature. Another complicating factor is that SY varies as a function of depth to the water table (Childs 1960). All of these factors result in considerable uncertainty in SY determination (Healy and Cook 2002).

For this study, SY was selected as a spatial explanatory variable in the regression model primarily because it is related to soil texture. Soil texture has been identified as a factor controlling recharge in several studies (Kennett-Smith et al. 1994; Holtschlag 1996; Keese et al. 2005). Scanlon et al. (2002) state that recharge models that use hydraulic conductivity as an explanatory variable are inherently inaccurate because hydraulic conductivity varies over several orders of magnitude. The high variability of hydraulic conductivity (permeability data in State Soil Geographic Database [STATSGO] are typically reported as order-of-magnitude ranges) makes it less desirable than SY for use as the landscape characteristic in the RRR model.

Another attractive feature of including SY as the spatial explanatory variable is that it can easily be estimated from STATSGO (1994) data, which are available for the entire United States. STATSGO data refer to soil associations, or groups of soils, commonly found together and

called map units. There are detailed data about soils organized by layer that can be used to estimate SY. The STATSGO soil data generally extend 150 or 200 cm below land surface. For this analysis, only layers beneath 76 cm were used. It was assumed that the texture characteristics of those deeper layers were similar to the materials at or near the water table. It also was assumed that the bottom layer of soil represents the top of the saturated zone (water table) over most of the region.

Estimation of SY

As previously described, SY can be estimated on the basis of a variety of laboratory and field methods (Healy and Cook 2002). A reasonable approach to estimating SY is as the difference between the water content of saturated soil (θ_s) and the water content of soil at field capacity (θ_{fc}) (assumed to be the water content at -330 cm of pressure head). The value for θ_{fc} is assumed to be analogous to the water that is retained in the soil after it is drained by gravity. These values were computed using soil texture, bulk density, amount of organic matter, and other characteristics in the STATSGO database using three methods: (1) Rosetta software (Schaap 1999); (2) the Water Erosion Prediction Project (WEPP; Alberts et al. 1995) model; and (3) a method described by Rawls et al. (1982). Of the three methods considered, the “best” estimate for SY was obtained from the Rawls method on the basis of the p value of the coefficient for SY in the regression model. SYs computed by the Rosetta and WEPP methods had p values > 0.1 , whereas the p value for Rawls method (SY_{Rawls}) was 0.0003. Consequently, the Rawls method was used to estimate SY.

The first step toward estimating SY was to compute mean values of organic matter, clay, and sand content for each layer of soil in the state deeper than 76 cm. *Percent clay* is provided in the STATSGO layer data, but *% sand* and *silt* must be computed from percentages passing certain sieve sizes. Using STATSGO terminology, the *% sand* was computed as $100 - (100 \times NO200/NO10)$, where *NO200* is the mean percentage of material smaller than 7.6 cm diameter passing a no. 200 sieve (75 μ m) and *NO10* is the mean percentage of material smaller than 7.6 cm diameter passing a no. 10 sieve (2 mm). The *% silt* was computed as $100 - \% \text{ clay} - \% \text{ sand}$.

Saxton et al. (1986) reviewed methods for estimating soil-water characteristics and cited Rawls et al. (1982) for their work in developing equations for water content at various pressures. Saxton et al. (1986) cited an equation for the saturated water content, which can be used with the water content at field capacity to compute SY. Computation of SY_{Rawls} is based on the difference between saturated water content and water content at field capacity. All values of SY were corrected for the effects of coarse particles. Alberts et al. (1995) describe this correction factor as a function of the fraction of coarse material by weight.

The mean SY computed for each soil layer was computed for each STATSGO soil component, weighted by thickness of the layer. Those mean values then were used to compute the mean, weighted by area, for each map unit using GIS software. The soil association data were

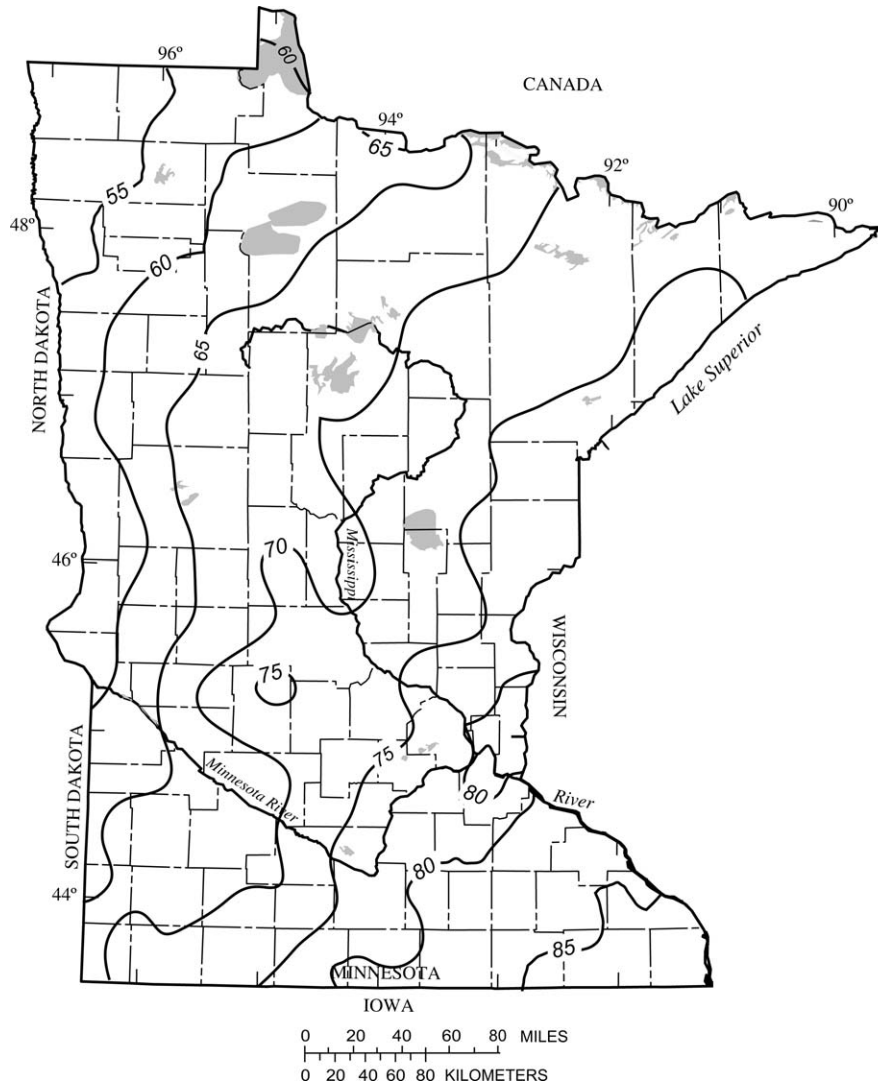


Figure 3. Mean annual precipitation in Minnesota, in centimeters per year, 1971 to 2000 (data from Spoden 2003).

intersected with the basins, and the mean SY, weighted by area of each map unit, was computed for each basin. Because of the limitations inherent to the STATSGO data, SY determinations should only be viewed as “regional” values. In other words, they should not be considered accurate at the local scale but may be useful for map unit scale or larger analyses. Spatial distribution in SY for the soil associations in Minnesota on the basis of the Rawls method is shown in Figure 5.

Results and Discussion

Recharge estimates were made for every year in the period of record for each of the 38 basins (Figure 1) that satisfied the inclusion criteria in Minnesota. Preliminary analysis of these period-of-record estimates indicated that the proposed form of the regression model (Equation 1) was acceptable on the basis of overall significance of the regression. The analysis also indicated that recharge could be modeled linearly using precipitation and SY. The effects of precipitation were not modeled accurately, however, because of the aggregation to a long period of

time (generally greater than decadal). The period-of-record model showed increasing scatter of the residuals as the predicted value increased and indicated a need for shorter time periods to model the effects of precipitation. Consequently, the annual recharge estimates were aggregated into consistent 10-year periods (decades) and the mean precipitation for each decade was calculated. Consistent decades were used to facilitate data processing. The resulting decadal regional regression model showed a linear fit with no residual diagnostic concerns.

Further evaluation of available data using the initial regression model indicated that the relation between GDD and recharge appears to be linear at GDD rates of less than approximately 1350 degree days and flat at >1350 cm/year for the selected basins. Therefore, a modified GDD was computed as the minimum of GDD and 1350 degree days.

The final regression equation estimates average recharge for basins on the basis of precipitation (Figure 3), SY computed by the Rawls method (Figure 5), and GDD (Figure 4), modified for values > 1350 degree days, as follows:

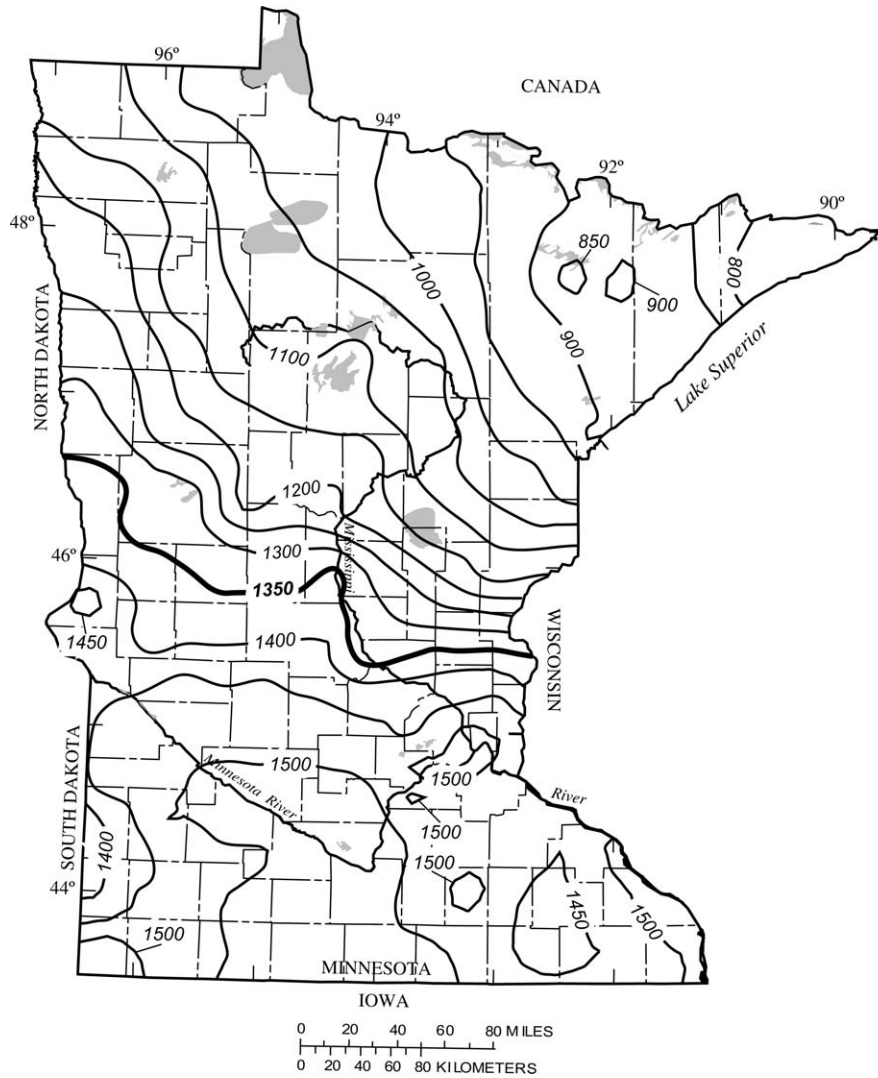


Figure 4. Mean annual GDD in Minnesota, in degrees above 10°C d, 1971 to 2000.

$$R = 14.25 + 0.6459P - 0.02231\text{GDD} + 67.63\text{SY}_{\text{Rawls}} \quad (3)$$

R is recharge, in centimeters per year; P is the precipitation, in centimeters per year; GDD is the modified GDD, in degrees Celsius above 10°C d; and SY_{Rawls} is the SY computed by the Rawls method. Because the decadal averages are correlated with one another for a single basin, generalized least squares was used to correct for that correlation. The correlation model is block diagonal, with 1 on the diagonal, ρ for correlations within a station for different decades, and 0 for different stations. The computed residuals are adjusted for correlation by the method described in Draper and Smith (1998). The residual standard error for average recharge was 2.79 cm/year with 129 degrees of freedom and ρ was 0.5422 as determined by the maximum likelihood method. The analysis of variance table (Table 2) shows summary statistics for each of the explanatory variables in the final model. Table 2 reports the statistics based on all observations but correctly accounts for the correlation of observations within each of the 38 basins. The overall p value of the

model is < 0.0001 based on the likelihood ratio test between the regression model and the null model, which includes only the intercept term and the correlation structure.

Residual plots showed good, linear fits for SY_{Rawls} , P , and GDD in the final regression model (Figure 6). A loess smooth through the residuals for each of the explanatory variables shows no nonlinearities. Some deviation is noted at the low end for SY but likely that is caused by edge effects. There is some increase in the spread of residuals for increasing precipitation. The residuals show no obvious spatial pattern across Minnesota (Figure 7). In most decades, there was no bias of residuals, but the 1940s were biased low and the 1980s were biased high. The biases in those two decades cannot be explained by departures in precipitation or GDD.

The residuals were also examined for any relation to the dominant land use and land cover characteristics. The dominant land use and land cover characteristics for the basins used were row crops, deciduous forest land, and woody wetlands. Row crops and deciduous forest are dominant crops for all of Minnesota; woody wetlands are dominant in northern Minnesota. The residuals showed no relation to

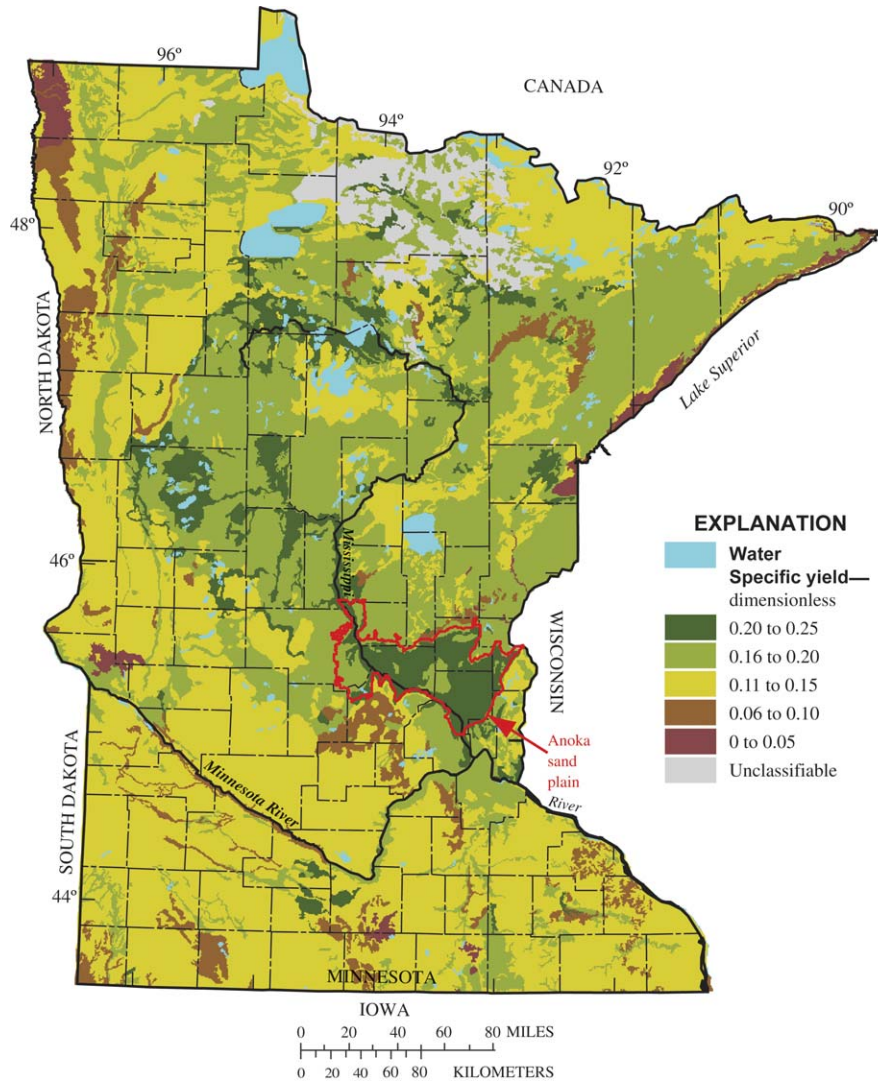


Figure 5. Spatial distribution of SY in Minnesota computed from STATSGO soils data using the Rawls method (Rawls et al. 1982).

any of the dominant land use and land covers, thus justifying omitting land use and land cover from the model.

The map illustrating spatial distribution in the RRR rates in Minnesota (Figure 8) was generated by applying the coefficients of the regression model (Equation 3) to the statewide data sets of P , SY, and GDD. In some areas where P and SY values were small, the computed recharge was negative; in these situations, the recharge rate was set to 0. The RRR rates illustrated in Figure 8 generally are representative of the average soil conditions

in an area. Local conditions such as confining units at or near the land surface could greatly reduce the estimated recharge rates to aquifers. These data should not be used for point estimates of recharge because local hydraulic properties and topography affect the estimation of recharge but were not considered in this analysis. The recharge estimates can be used at a scale appropriate for STATSGO mapping units.

As expected, there is a strong correlation (Table 2) between the RRR rates (Figure 8) and precipitation (Figure 3). Where precipitation is least in the western and northwestern parts of the state (50 to 65 cm/year), recharge also is smallest (0 to 5 cm/year). Similarly, recharge is greatest in the eastern part of the state, greater than approximately 15 cm/year, where precipitation is greater than approximately 75 cm/year.

A strong correlation (Table 2) also exists between RRR rates and SY; SY is least in areas where glacial lake clay occurs (0 to 0.1), shown as the brown-shaded areas in Figure 5 primarily in the northwestern part of the state. Recharge in these areas is in the 0- to 5-cm/year range (Figure 8). Similarly, sand-plain areas in the central part of the state, with SYs primarily in the 0.2- to 0.25-cm/

	Degrees of Freedom	Sum of Squares	Mean Sum of Squares	F	p
P	1	374.5	374.5	309.5	<0.0001
GDD	1	101.7	101.7	84.0	<0.0001
SY	1	16.8	16.8	13.9	0.0003
Residual	129	156.1	1.21		

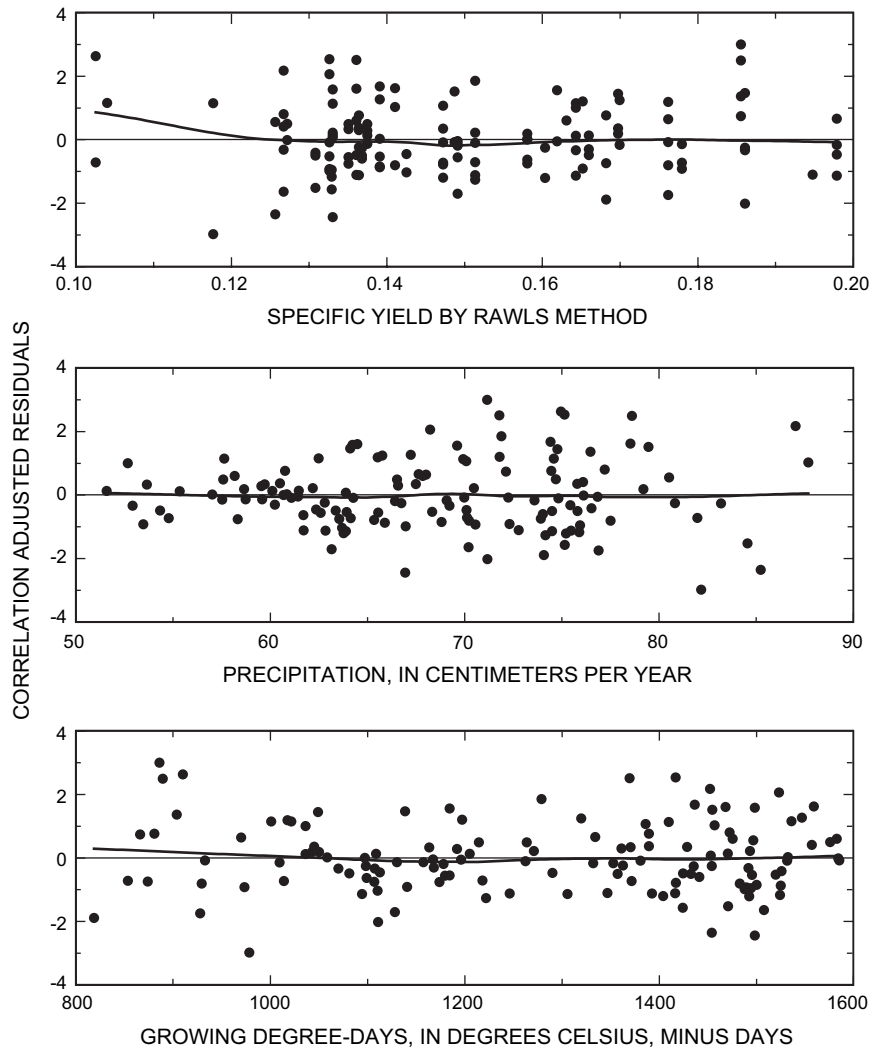


Figure 6. Distribution of correlation-adjusted residuals for each of the explanatory variables in the final regression model.

year range, correspond to RRR rates in the 15- to 25-cm/year range. The Anoka sand plain, the largest sand plain in the state, is prominently visible on the SY map (Figure 5) but is less visible on Figure 8.

The average recharge rate to a surficial aquifer in Minnesota can be estimated on the basis of the RRR model by applying Equation 3 to average or typical values for the input variables. For example, the average recharge to an aquifer in central Minnesota where the precipitation is 74 cm/year, the SY is 0.177, and the GDD is 1400 degree days would be $-14.25 + 0.6459 \times 74 + 67.63 \times 0.177 - 0.02231 \times 1350 = 15.4$ cm/year.

Recharge rates estimated with the RRR model compare favorably with rates estimated from previous studies in Minnesota. Table 3 lists several recent studies distributed throughout the state where recharge was estimated by water table fluctuation methods and ground water flow models. The mean difference between recharge estimated by the RRR model and water table fluctuation methods in those studies was -1.6 cm/year. The mean absolute difference between the RRR model and water table fluctuation methods was 31%. Ground water flow models also were constructed in all but one of those studies. The

mean absolute difference between the calibrated recharge and water table fluctuation methods was 39%. That larger difference suggests the difficulty in estimating recharge.

The RRR model results should be helpful to water managers as they develop water management plans at regional and local scales. The RRR model can provide ground water modelers with independently obtained mean recharge estimates required as regional-scale model input. Because the RRR model was based on decadal recharge and climate data, the model should not be used for annual estimates of recharge. Actual annual recharge will vary from year to year depending on local weather patterns. The RRR model can be relatively easy to apply in other humid areas where state- or regional-scale databases for soils (such as STATSGO), precipitation, and GDD estimates are available, plus high-quality continuous record streamflow data that fit the inclusion criteria described herein. The RRR model is not applicable in arid or semiarid areas where perennial streams do not occur. Other factors related to estimating recharge from streamflow hydrographs outlined by Rutledge (2000) as well as Halford and Mayer (2000) also need to be considered before applying this method in a study area. The

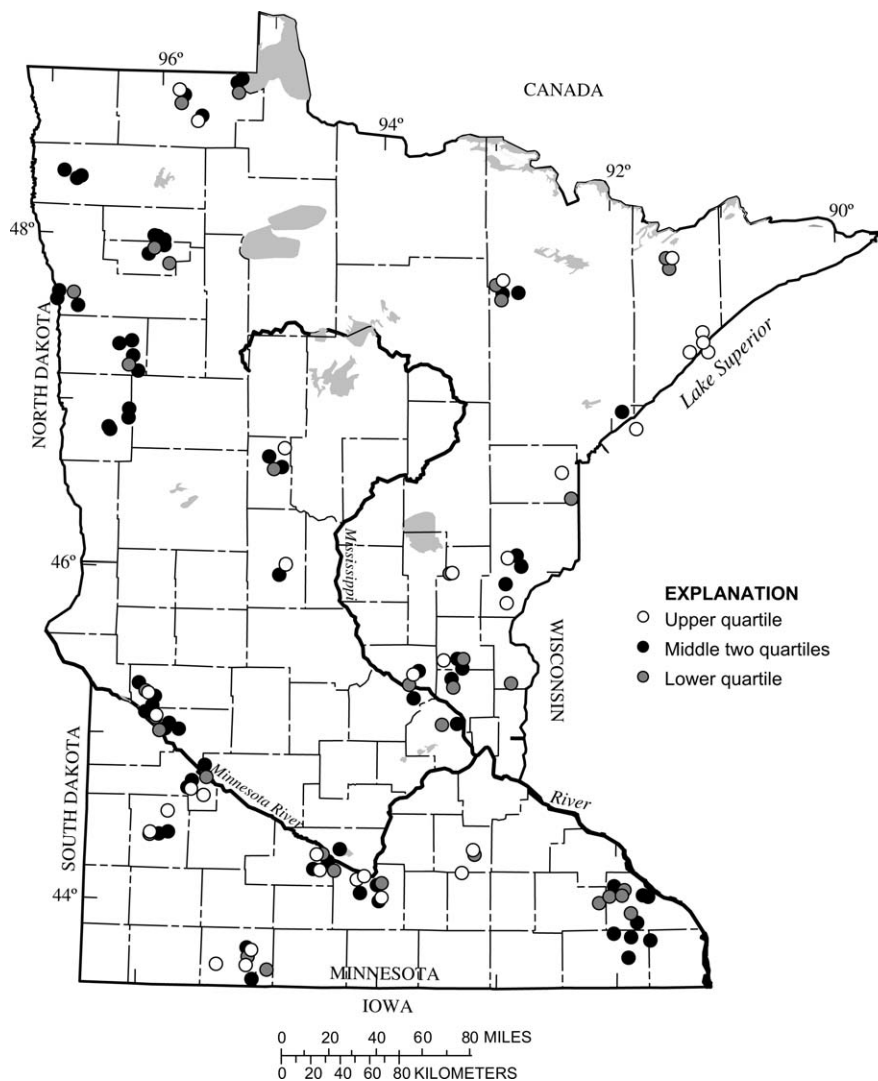


Figure 7. Spatial distribution of correlation-adjusted residuals in the final regression model.

method for estimating SY described in this paper would be helpful, where a detailed soils database is available, to water managers and the research community as an initial estimate of regional SY.

Several factors beyond the scope of this paper need to be considered for future applications of the RRR model. The presence of open water was ignored in the computation of mean SY for the basins selected for inclusion in the paper. Some value needs to be included that relates the precipitation to the open water to the amount delivered to base flow. Consideration given to land surface slope and its relation to runoff and recharge for any given soil characteristic might also improve regional estimates of recharge. The effect of impervious surfaces was not considered in this study. Recharge estimated in this paper should not be used in urban areas where there are substantial impervious surfaces. Finally, for basins in high-relief areas, the location of large value SY soils within the terrain may be an important factor affecting recharge. There was some indication of effects from the previous factors in the data used for this analysis, but the few basins affected by each factor limited their analysis.

Summary

A regional regression model was developed to estimate the spatial distribution of ground water recharge for Minnesota. The RRR model was based on basin-wide estimates of recharge for 38 surface water drainage basins, precipitation, average basin SY, and GDD in each basin. The RRR estimates were derived from analysis of stream base flow using a computer program that was based on the Rorabaugh method.

The RRR model computed recharge estimates ranging from near 0 to a maximum of approximately 32 cm/year across Minnesota. Ground water recharge generally increased from west to east across the state in correlation with precipitation variability and from south to north in correlation with ET (as reflected by GDD). Where precipitation was least, in the northwestern part of the state (50 to 65 cm/year), recharge computed by the RRR model also was lowest (0 to 5 cm/year). A strong correlation also exists between the recharge and SY. SY is least in areas where glacial lake clay occurs, primarily in the northwestern and north-central parts of the state. Recharge estimates made on the basis of the RRR model were in

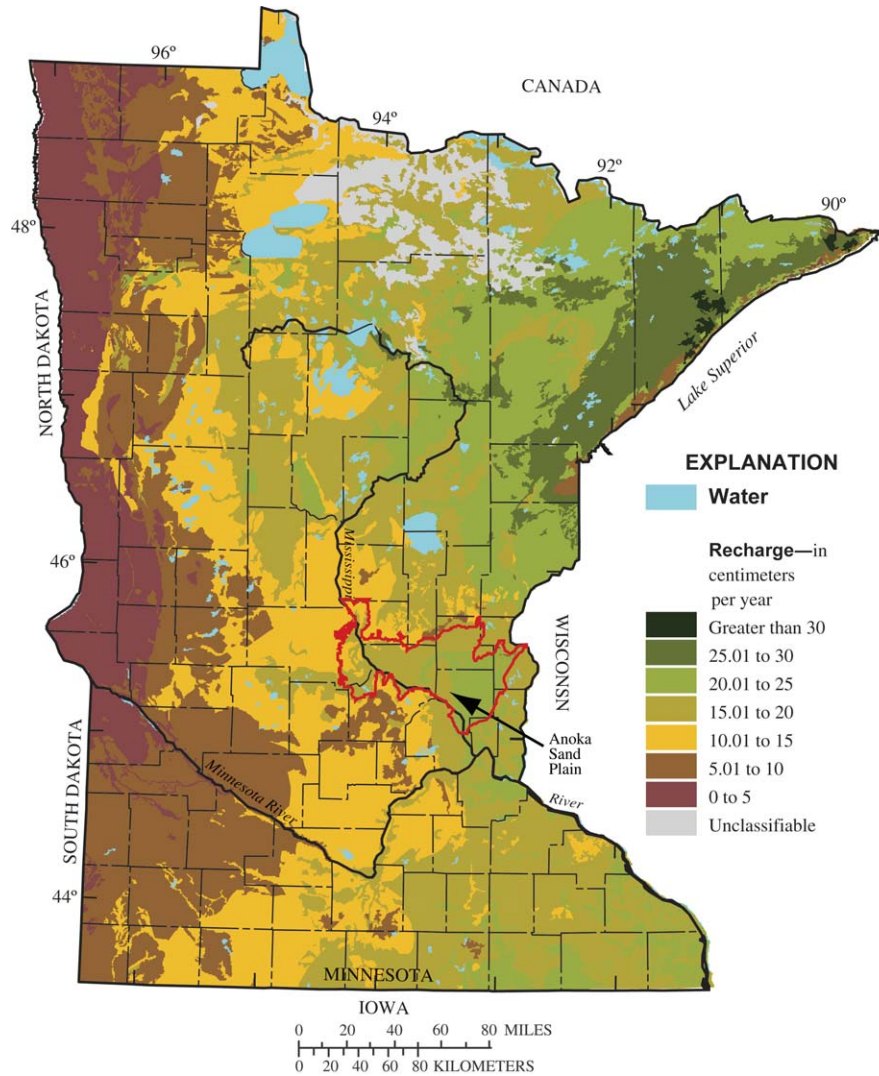


Figure 8. Average annual recharge to surficial materials in Minnesota (1971 to 2000) estimated on the basis of the RRR model.

the 0- to 5-cm/year range in these areas. In sand-plain areas where SY is greatest, recharge estimates made on the basis of the RRR model are in the 15- to 32-cm/year range. Recharge estimates made on the basis of the RRR model compared favorably with estimates based on other

methods; the RRR model yields reasonable estimates of regional recharge.

The RRR model can be relatively easy to apply in other humid areas where state- or regional-scale data-bases for soils, precipitation, and GDD estimates are

**Table 3
Comparison of Recharge Estimates**

Authors	Nearby Town	Water Table Fluctuation Recharge (cm/year)	Ground Water Model Recharge (cm/year)	RRR (cm/year)
Ruhl et al. (2002)	St. Paul, MN	24	—	21
Lindgren (2002)	Cold Spring, MN	18	20	15
Delin (1991)	Rochester, MN	22	13	23
Lindgren and Landon (2000)	Luverne, MN	15	18	12
Lindgren (1996)	Crookston, MN	19	20	10
Stark et al. (1991)	Bemidji, MN	10	18	18
Myette (1986)	Willow River, MN	20	13	26
Average		19	17	18

Note: —, not estimated.

available, plus high-quality continuous record streamflow data that fit the inclusion criteria described herein. The RRR model is not applicable in arid or semiarid areas where perennial streams do not occur. RRR model results should be helpful to water managers as they develop water management plans at regional and local scales. The RRR model can help ground water modelers by providing them with independently obtained mean recharge estimates required as regional-scale model input. The method for estimating SY described herein is applicable in humid and subhumid areas with gauged perennial streams where a detailed soils database is available.

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Editor's Note: The use of brand names in peer-reviewed papers is for identification purposes only and does not constitute endorsement by the authors, their employers, or the National Ground Water Association.

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