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Factors influencing ground-water recharge in the eastern United States

Bernard T. Nolan, Richard W. Healy *, Patrick E. Taber, Kimberlie Perkins, Kerie J. Hitt, David M. Wolock

US Geological Survey, 413 National Center, Reston, VA 20192, United States

Summary Ground-water recharge estimates for selected locations in the eastern half of the United States were obtained by Darcian and chloride-tracer methods and compared using statistical analyses. Recharge estimates derived from unsaturated-zone (R_{UZC}) and saturated-zone (R_{SZC}) chloride mass balance methods are less variable (interquartile ranges or IQRs are 9.5 and 16.1 cm/yr, respectively) and more strongly correlated with climatic, hydrologic, land use, and sediment variables than Darcian estimates (IQR = 22.8 cm/yr). The unit-gradient Darcian estimates are a nonlinear function of moisture content and also reflect the uncertainty of pedo-transfer functions used to estimate hydraulic parameters. Significance level is <0.001 for nearly all explanatory variables having correlations with R_{UZC} of <-0.3 or >0.3. Estimates of R_{SZC} were evaluated using analysis of variance, multiple comparison tests, and an exploratory nonlinear regression (NLR) model. Recharge generally is greater in coastal plain surficial aquifers, fractured crystalline rocks, and carbonate rocks, or in areas with high sand content. Westernmost portions of the study area have low recharge, receive somewhat less precipitation, and contain fine-grained sediment. The NLR model simulates water input to the land surface followed by transport to ground water, depending on factors that either promote or inhibit water infiltration. The model explains a moderate amount of variation in the data set (coefficient of determination = 0.61). Model sensitivity analysis indicates that mean annual runoff, air temperature, and precipitation, and an index of ground-water exfiltration potential most influence estimates of recharge at sampled sites in the region. Soil characteristics and land use have less influence on the recharge estimates, but nonetheless are significant in the NLR model.
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* Corresponding author.
  E-mail address: rwhealy@usgs.gov (R.W. Healy).

Introduction

Recharge is a major component of the ground-water system and has important implications for shallow ground-water quality. Recharge commonly is estimated at the watershed scale using simple water-budget methods or numerical ground-water flow models. Whereas these methods provide an average recharge estimate for an area, recharge can vary substantially both within and between watersheds because of variations in topography, sediments, and climate. Recharge estimates with site-specific data, such as ground-water levels, ground-water ages, and unsaturated-zone data at points, can complement basin-scale methods. A large number of point estimates over a region, if estimated with reasonable certainty, would indicate the spatial distribution of recharge. The variability of recharge is key to understanding the susceptibility of aquifers to contamination from surface-derived sources.

Recharge may be categorized as diffuse or focused. Diffuse recharge refers to that which occurs over large areas as water from precipitation infiltrates and percolates through the unsaturated zone to the water table. Focused recharge refers to water moving downward to an aquifer from a surface-water body, such as a lake, stream, or canal. Arid regions commonly are characterized by deep water tables, losing streams, and focused recharge. Diffuse recharge usually dominates in humid portions of the United States, where shallow water tables and gaining streams are common. Focused recharge that does occur in humid areas is usually from surface runoff into land-surface depressions or macropores, followed by infiltration.

Diffuse recharge was estimated at 48 locations in southern New Jersey, using a Darcian method based on pedo-transfer functions (Baehr et al., 2003). These functions relate hydraulic parameters to easily measured sediment properties such as percent sand, silt, and clay, and are commonly used at regional scales owing to the difficulty and cost of directly measuring hydraulic conductivity (Görres and Gold, 1996; Petach et al., 1991; Soutter and Pannatier, 1996). A companion study (Nolan et al., 2003) evaluated the spatial variability of the recharge estimates and analyzed relations with sediment, landscape, and water-quality data. Multiple linear regression (MLR) was attempted to augment kriging predictions, but correlations between recharge and potential explanatory variables generally were poor. Topographic relief within the study area varied insufficiently to yield strong correlations between recharge estimates and landscape factors. We hypothesize that at a broad scale, such as a multi-state region, increased systematic variation in soil, landscape, and climate variables will facilitate improved correlations with recharge, assuming that recharge can be estimated with reasonable certainty. These correlations can be exploited with empirical models to identify factors that influence recharge and, ultimately, to predict recharge in unsampled areas. Accordingly, the objectives of the research described in this paper are to first obtain consistent estimates of recharge across a large multi-state region, and then to identify factors that significantly influence recharge at this scale.

Recharge in the current study was estimated using ground-water and sediment core data collected by the US Geological Survey's (USGS's) National Water Quality Assessment (NAWQA) Program, in collaboration with the Ground Water Resources Program (GWRP). Data interpretation was limited to the eastern half of the US because the methods applied are designed to estimate diffuse recharge. Sites in eastern Nebraska and southeastern Texas were included in the analysis because associated aquifers are areally extensive in the east—west direction (Fig. 1). We anticipated that including these sites would enhance correlations between the recharge estimates and climate and landscape variables, for reasons discussed above. The climate of eastern Nebraska is typical of a humid continental region, with a mean annual precipitation of 720 mm (Fredrick et al., 2006). Mean annual precipitation near sampled sites in southeastern Texas is 1320 mm (Land et al., 1998).

The study area comprises the following principal aquifers: the glacial aquifer system in the northeast and midwest; the coastal lowlands aquifer system; Piedmont crystalline-rock aquifers; surficial aquifer system and the Floridan aquifer system; and the Northern Atlantic Coastal Plain aquifer system (Fig. 1). Also shown in the figure are boundaries of NAWQA study units for collection of sediment cores and ground-water samples used in the study.

To meet the second objective, we introduce a nonlinear regression (NLR) model, which differs from previous empirical approaches. Previous regression models used MLR to predict recharge based primarily on precipitation data (Delin et al., 2000; Nichols and Verry, 2001; Rangarajan and Athavale, 2000; Sophocleous, 1992) or soil and landscape variables (Nolan et al., 2003). An NLR model (the SPARROW model) was developed to predict nitrogen yield and phosphorus concentrations in streams based in part on stream-channel transport characteristics and spatially referenced watershed data (Smith et al., 1997). The SPARROW model includes linear input terms and multiplicative exponential terms describing either delivery or in-stream loss of contaminants. The nonlinear form seems appropriate to simulate water inputs and factors that proportionally increase or decrease water infiltration. We anticipated that applying NLR to a consistent set of ground-water recharge estimates would help identify factors that affect recharge in the region.

Methods

Sediment cores and ground-water samples were collected during installation of monitoring wells as part of NAWQA studies shown in Table 1 for principal aquifers of interest. Samples were analyzed by the USGS's National Water Quality Laboratory or in soil physics laboratories (for sediment bulk-physical properties and soil-water extracts) to provide estimates of ground-water recharge by the Darcian method and by chloride-tracer methods applied to the saturated zone and unsaturated-zone pore water. The recharge values were initially compared by examining correlations with spatial data, before developing an empirical model of recharge.

Laboratory analysis of sediment properties

Sediment cores 0.6 m long and 5 cm in diameter were obtained about every 1.5 m from land surface to the water
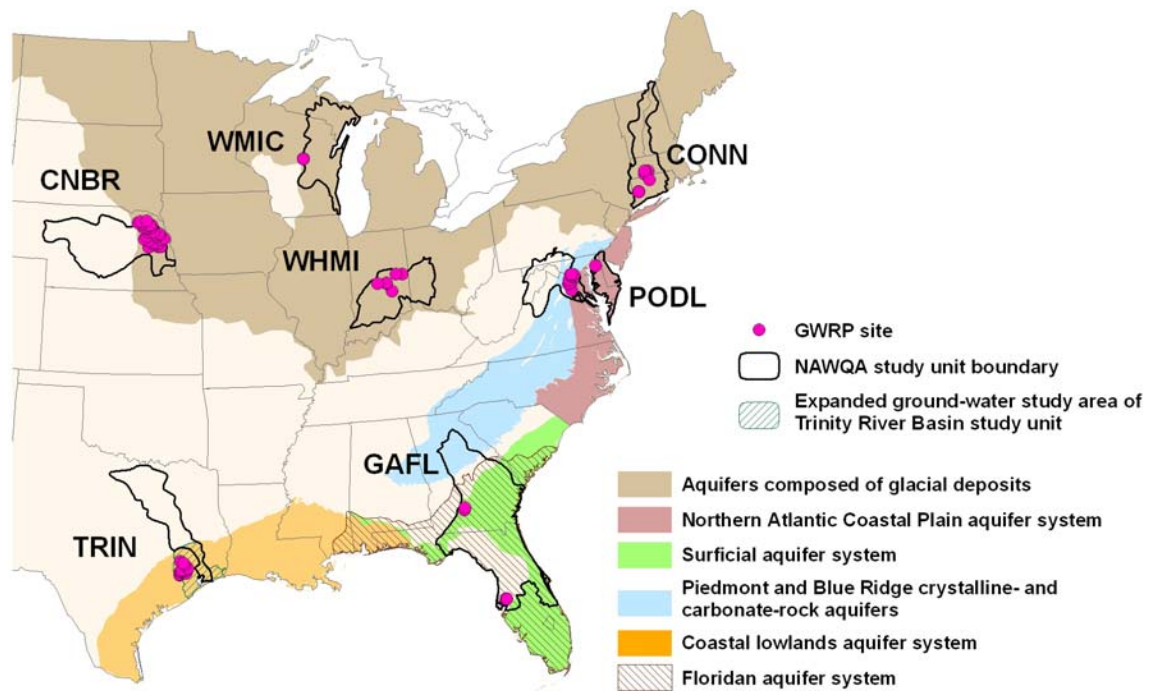
Figure 1 Sediment coring and ground-water sampling locations in the eastern half of the United States, with principal aquifers. Study unit definitions are: CNBR, Central Nebraska Basins; TRIN, Trinity River Basin; WMIC, Western Lake Michigan Drainages; WHMI, White—Miami River Basins; GAFL, Georgia—Florida Coastal Plain; PODL, Potomac—Delmarva River Basins; CONN, Connecticut, Housatonic, and Thames River Basins.

Table 1 Medians of water level and measured unsaturated-zone sediment properties by National Water-Quality Assessment Program study area (excludes irrigated sites)

Identifier	NAWQA study area	Number of sediment cores	Depth to water, m	Percent			Bulk density, g/cm^3	Volumetric moisture content, cm^3/cm^3
				Sand	Silt	Clay		
CNBR	Central Nebraska Basins	26	7.4	12.4	78.0	9.5	1.59	0.19
TRIN	Trinity River Basin	29	6.4	37.4	55.1	7.3	1.57	0.16
WMIC	Western Lake Michigan Drainages	4	4.9	87.6	9.9	2.5	1.85	0.09
WHMI	White-Miami River Basins	9	2.3	10.5	70.4	14.8	1.88	0.26
GAFL	Georgia—Florida Coastal Plain	6	8.1	89.1	8.5	2.3	1.50	0.15
PODL	Potomac—Delmarva River Basins	15	4.1	66.4	30.5	2.9	1.44	0.20
CONN	Connecticut, Housatonic, and Thames River Basins	31	6.1	86.9	11.0	1.8	1.49	0.16

table during installation of monitoring wells during the fall of 2002 through the winter of 2004. Nearly 500 cores were obtained (based on multiple sampling depths at each site) and analyzed to determine sand, silt, and clay percentages and bulk density for use with pedotransfer functions; moisture content (θ) for use in Darcian calculations of water flux; and pore-water chloride concentration for recharge estimation by unsaturated-zone tracer. During data analysis we obtained one recharge estimate by each method per site; for example, the deepest unsaturated-zone water flux from the pedotransfer method was used to infer Darcian recharge. Sand (>50 μm diameter), silt (2—50 μm), and clay

(<2 μm) fractions were determined by optical diffraction using a Coulter LS-230 particle-size analyzer (Gee and Or, 2002), which measures particles from 0.04 μm to 2 mm in size. Particles greater than 2 mm were separated with ASTM sieves ranging from 2 to 32.5 mm and later integrated into the particle-size distribution. Bulk density was determined by the core method (Grossman and Reinsch, 2002), and soil moisture content was determined gravimetrically (Topp and Ferre, 2002). To determine chloride concentration in pore water, the sediment cores were dried and mixed with water at a 1:10 weight ratio. Chloride in the extract solution was determined by ion chromatograph (McMahon et al., 2003).

Methods of recharge estimation

Recharge was estimated by the Darcian method and two chloride-tracer methods. Darcian estimates based on pedotransfer functions are referred to in this paper as ''R_{PTF}''. Nonirrigated sites in the eastern half of the US resulted in 76 estimates of R_{PTF}, 108 estimates using chloride in soil pore water as an unsaturated-zone tracer (R_{UZC}), and 108 estimates using chloride in ground water as a saturated-zone tracer (R_{SZC}). R_{PTF} estimates could not be obtained at all sites because of missing textural, moisture content, or bulk density data at some locations.

Darcian-pedotransfer method
In the unsaturated zone, steady vertical flow is described by Darcy's Law:

$$q = -K(\theta)\left(\frac{d\psi}{dz} + 1\right), \tag{1}$$

where q is flux density in cm/yr, $d\psi/dz$ is the matric potential gradient (cm/cm), and $K(\theta)$ is hydraulic conductivity in cm/yr. If matric potential is constant with depth, then gravity is the only driving force and $d\psi/dz$ is equal to zero. In such cases the magnitude of q equals that of the hydraulic conductivity of the medium at the ambient water content. This approach is called the unit-gradient assumption and has been applied in a number of studies (Chong et al., 1981; Gardner, 1964; Sisson, 1987). Conditions conducive to unit-gradient water flux include location below the depth of the zero flux plane (i.e., the plane of zero hydraulic gradient in the unsaturated zone) and above the capillary fringe and steady flow over time. Under the unit-gradient assumption, a single $K(\theta)$ measurement can indicate long-term average recharge rate in zones of steady downward flow in deep unsaturated zones typical of arid regions (Nimmo et al., 2003). Temporal variability of recharge in such cases is dampened by physical averaging of flow paths (Nimmo et al., 2002). Although the current study sampled shallow unsaturated zones in a comparatively humid climate, dampening of variations in measured soil tension has been observed at shallow depths in central Indiana (Bayless, 2001). Whereas short-term variations in soil tension and moisture content were observed at depths of 0.6 m or less, measurements were stable at depths of 0.9–1.5 m. Sampling depth for sediment cores in the current study, which includes sites in central Indiana, ranges from about 1 to more than 30 m.

We calculated unit-gradient water fluxes based on data from the Rosetta program (Schaap et al., 1998, 2001). Recharge (downward flux) is the negative of q in Eq. (1), evaluated at the water table. Rosetta consists of hierarchical pedotransfer functions for estimating van Genuchten hydraulic parameters (van Genuchten, 1980) from bulk physical properties, such as bulk density and percentages of sand, silt, and clay. Several unit-gradient water fluxes were calculated for each well location. The deepest water flux that is above the capillary fringe is assumed to represent recharge (R_{PTF}).

Chloride tracer methods
Recharge was estimated by two chloride tracer methods, depending on the source of the chloride data: R_{UZC} refers to chloride concentration in the unsaturated zone (i.e., pore water from sediment cores used in R_{PTF} estimates), and R_{SZC} refers to chloride concentration in the saturated zone (i.e., in ground-water samples from the same wells where coring took place). Thus, there is one R_{UZC} estimate and one R_{SZC} estimate per well.

The chloride tracer method compares the rate of chloride deposition on land surface with chloride concentration in the unsaturated zone or saturated zone (Nimmo et al., 2003; Scanlon et al., 2002). Chloride is conservative and its mass inflow to the system must be balanced by mass outflow from the system or by a change in storage of chloride in the unsaturated zone or saturated zone. Under natural conditions, chloride is deposited on the land surface in precipitation and dry deposition. Other natural sources, such as marine-derived sediments and saline water in deep aquifers, were determined to contribute insignificant quantities of chloride to the study areas. Chloride may also be applied through the activities of humans, predominantly agricultural practices. Outflow (i.e., recharge) is from the unsaturated zone to the water table. Recharge by this method is described as

$$R = 1000 \cdot (Cl_{wetdep} + Cl_{drydep} + Cl_{applied})/Cl_{water}, \tag{2}$$

where R is recharge (cm/yr) based on chloride data from the unsaturated zone (R_{UZC}) or saturated zone (R_{SZC}); Cl_{wetdep} and Cl_{drydep} are chloride wet and dry atmospheric deposition rates, respectively (mg/cm^2/yr); $Cl_{applied}$ is the rate at which chloride is applied by humans (mg/cm^2/yr); and Cl_{water} is chloride concentration in the unsaturated zone or saturated zone (mg/l). This equation assumes that all precipitation infiltrates locally. In areas where total infiltration is less than total precipitation because of surface runoff, the chloride tracer recharge value will overestimate true recharge. Infiltration-excess runoff, however, is negligible in the study area (about 7% of streamflow on average), based on output from a watershed hydrology model (Beven and Kirkby, 1979; Wolock, 1993) at sampled locations. Also, some of the runoff flows onto nearby low-lying areas (i.e., surface water ''runon''), where it is a source of recharge.

Values for Cl_{wetdep} were obtained through the National Atmospheric Deposition Program (NADP) (National Atmospheric Deposition Program, 2006). Dry deposition of chloride is not measured at NADP sites, but dry and wet deposition data are available for sulfate, nitrate, and ammonia. Wet deposition accounted for 92%, on average, of total depositions of these constituents (coefficient of variation 3%) in 2002 (US Environmental Protection Agency, 2006). Therefore, it was assumed for purposes of this study that wet deposition also accounted for 92% of the total chloride deposition (i.e., dry chloride deposition rate, Cl_{drydep}, was set equal to 8.7% of the wet rate). The primary source of chloride applied to land surface by humans is agricultural chemicals, in particular muriate potash (KCl), which is applied as a potassium fertilizer for crops. County-level estimates of potassium inputs to land surface have been compiled (Ruddy et al., 2006). For each sampled well, chloride input was estimated by assuming that muriate potash accounted for 90% of applied potassium (US Department of Agriculture, 2006) and by weighting the county-level fertilizer data on the basis of agricultural land use within 500-m radius circular areas (buffers) around sampled wells; i.e., chloride input was multiplied by the ratio of agricultural land in the well buffer to the total

agricultural land in the county. For weighting purposes, agricultural lands comprise row crops, small grains, and orchards and/or vineyards. The 500-m radius buffer may not correspond to the actual recharge area of sampled wells, but is a reasonable approximation. NAWQA monitoring wells have shallow screened interval depths (typically from 7 to 9 m) and sample recently recharged ground water (typically <10 years). Also, land cover is comparatively homogeneous within ground-water land-use studies conducted by NAWQA, such that land use near a well is similar to that elsewhere in the monitoring network.

Estimates of R_{SZC} used chloride data from wells sampled by NAWQA personnel during 2002–2004. All wells were sampled according to procedures described by Koterba et al. (1995), and dissolved Cl was analyzed according to procedures in Fishman (1993).

Spatial data for empirical modeling of recharge estimates

Soil, climate, topographic, and land-use data were compiled for sampled wells using a geographic information system (GIS) to generate explanatory variables for empirical modeling of recharge. Land-use data categories were compiled as percentages of well buffers, and the remaining variables (excluding presence-or-absence type variables) were compiled as weighted averages within buffers. Selected variables described here are significantly correlated with recharge estimates. A complete list (including evapotranspiration, for example) is provided in Appendix 1.

Soil data came from the US Department of Agriculture's State Soil Geographic (STATSGO) maps, which are produced at 1:250,000 scale by generalizing soil survey data (US Department of Agriculture, 1994). Initially compiled at 1-km resolution (Wolock, 1997) by converting soil mapping units to grid cells in a GIS, the STATSGO data were recompiled at 100-m resolution in the current study to simulate local-scale variation in soil properties.

Mean annual precipitation and temperature for 1980–97 were derived from DAYMET, a climate model that predicts daily temperature, precipitation, humidity, and radiation based on digital elevation data and observed values of precipitation and minimum and maximum temperature from weather stations (Thornton and Running, 1999). Several hydrologic factors were compiled to see if local recharge estimates were correlated with flow characteristics estimated by watershed models. Estimated percentage of Hortonian overland flow in total streamflow was calculated for the entire country using 5-km-grid cells with TOPMODEL, a rainfall-runoff watershed model that integrates climate and landscape characteristics (Wolock, 2003d). TOPMODEL simulates water flow in a watershed beginning from when water enters the watershed as precipitation until it exits as streamflow. Hortonian overland flow is generated when precipitation exceeds the infiltration capacity of the soil.

Base flow is the component of streamflow attributable to ground-water discharge to streams. The base-flow index (BFI) is the ratio of base flow to total streamflow, expressed in percent. These percentages were determined on a 1-km grid by interpolating from point BFI values at USGS stream gages (Wolock, 2003a). The point values were computed from time series of historical daily streamflow values using an automated hydrograph separation computer program (Wolock, 2003c). Mean annual base flow was estimated by multiplying the grid of BFI values by a grid of mean annual runoff values (Gebert et al., 1987). Computation of the subsurface-flow contact time index is based on a simple conceptualization of the lateral movement of both shallow and deep saturated subsurface flow toward a stream (Vitvar et al., 2002). The index was calculated using 1:250,000-scale digital elevation maps (US Geological Survey, 1987) and the STATSGO data describing subsurface hydraulic characteristics. Subsurface-flow contact time increases as the soil porosity and ridge-to-valley flow length increase, and decreases as topographic slope and saturated hydraulic conductivity increase. The index is intended to describe relative differences in subsurface contact time among watersheds, and agreed well with estimates of mean baseflow residence time derived from isotopic data (Vitvar et al., 2002).

Topographic wetness index (TWI) quantifies the effect of topography on the redistribution of moisture within a watershed. High values of TWI can indicate locations within a watershed where the water table intersects the land surface. Hence, TWI values indicate the potential caused by the effects of topography for ground-water exfiltration. The TWI index is given by $\ln(a/\tan\beta)$, where a is the upslope area per unit contour length and $\tan\beta$ is the slope gradient along which drainage occurs. TWI values were computed at 1-km resolution from digital elevation data (Wolock and McCabe, 1995).

Land-use percentages are based on a combination of 30-m resolution National Land Cover Data (NLCD 92) derived from 1992 Landsat imagery (Vogelmann et al., 2001) and USGS Land Use and Land Cover (LULC) data derived from 1970s to 1980s aerial photography (US Geological Survey, 1990). Residential, orchards/vineyards/other, and tundra categories of NLCD 92 data were reclassified using LULC data because some land covers are difficult to distinguish with satellite imagery (Nakagaki and Wolock, 2005).

Statistical methods

Statistical analyses of recharge estimates consisted of summary statistics, Spearman correlations, and analysis of variance (ANOVA) and multiple comparison tests (MCTs) on ranked data to assess relations with potential explanatory variables. Nonlinear regression (NLR) was used to identify factors – in a multi-variate context – that most influence recharge for the sites studied. Recharge depends not on a single factor but on the simultaneous influence of several factors representing climate, soil, and landscape processes. These interactions cause some variables, such as TWI, to emerge as significant in NLR even though they are insignificant in univariate correlations. For this reason, additional variables not shown in Table 2 were screened with the NLR model, including all available STATSGO, NLCDe 92, National Resources Inventory (US Department of Agriculture, 1995), and water-use variables (Solley et al., 1998) (Appendix 1). Over 100 variables were tested in the NLR model.

The NLR model has a multiplicative structure with explanatory variables representing water input (precipitation) and factors that either enhance or inhibit

Table 2 Univariate correlations between estimated recharge and potential explanatory variables screened in the nonlinear regression model (L, length; T, time; %, percent)

Variable	Spearman correlation coefficient (p-value)		
	Chloride tracer in saturated zone (R_{SZC})[a]	Chloride tracer in unsaturated zone (R_{UZC})[b]	Darcian-pedotransfer method (R_{PTF})
Climate and hydrology			
Mean annual base flow, L/T	0.426	0.437	0.228 (0.050)
Hortonian overland flow, %	−0.554	−0.443	−0.136 (0.250)
Mean annual runoff (1951−80), L	0.329	0.362	0.207 (0.074)
Subsurface flow contact time, T	−0.305	−0.357	−0.046 (0.697)
Land cover and management			
Orchards/vineyards/other, %	0.111 (0.256)	0.357	0.086 (0.461)
Woody wetlands, %	0.256	0.304 (0.001)	0.041 (0.727)
Irrigated acres, micro-irrigation systems, L^2	0.175 (0.073)	0.443	0.050 (0.670)
Irrigated acres, surface-irrigation systems, L^2	−0.338	−0.346	−0.208 (0.074)
Measured sediment properties			
Sand above water table, %	0.256	0.307 (0.001)	0.146 (0.207)
Silt above water table, %	−0.258	−0.320	−0.159 (0.171)
STATSGO soil properties or groups			
Soil hydrologic group A, %	0.369	0.420	0.187 (0.107)
Soil hydrologic group A/D, %	0.294	0.406	0.099 (0.399)
Soil loss tolerance factor	−0.392	−0.376	−0.205 (0.078)
Soil shrink−swell potential	−0.374	−0.322	−0.224 (0.054)
Vertical permeability, L/T	0.319	0.382	0.142 (0.225)
Permeability of least permeable layer, L/T	0.353	0.366	0.083 (0.480)
Available water capacity, fraction	−0.124 (0.207)	−0.336	−0.187 (0.109)
Organic matter, % by weight	0.237 (0.014)	0.329	−0.040 (0.732)
Sand, %	0.201 (0.038)	0.362	0.173 (0.139)
Silt, %	−0.148 (0.131)	−0.322	−0.153 (0.190)
Clay, %	−0.247 (0.011)	−0.337	−0.195 (0.098)
Soil <8 cm in size and passing a 0.074 mm sieve	−0.230 (0.018)	−0.351	−0.200 (0.086)
Entisols, %	0.217 (0.026)	0.320	−0.079 (0.500)
Histosols, %	0.407	0.407	0.101 (0.389)

[a] p-value < 0.01 for all variables, except as noted.
[b] p-value < 0.001 for all variables, except as noted.

water transport to ground water. After the exhaustive screening of variables in Appendix 1, those that remain in the model either are significant at the 0.05 level or are considered conceptually important. The explanatory variables are organized into water-input and transport components described by

$$R_i = b + I_i \cdot T_i + \varepsilon_i, \qquad (3)$$

where

$$I_i = \sum_{n=1}^{N} \beta_n X_{n,i} \qquad (4)$$

$$T_i = \exp\left(\sum_{j=1}^{J} \alpha_j Z_{j,i}\right) \qquad (5)$$

and

b = intercept
R_i = natural log of ''measured'' recharge at sampling point i, from estimation by measured chloride tracer in the saturated zone (R_{SZC}), ln(cm/yr)

I_i = total water input at i
T_i = proportional increase or decrease in water input at i due to transport factors
$X_{n,i}$ = normalized water input n at i, such as precipitation or irrigation
$Z_{j,i}$ = normalized transport factor j at i
β_n = coefficient for water input variable n
α_j = coefficient for transport factor j
ε_i = model error at sampling point i

Recharge estimates were natural log transformed for use in the NLR model, because this resulted in more constant variance of model errors across the range of predictions, as well as normally distributed errors. Predicted values of recharge then were back transformed into real space for plotting purposes using a ''smearing'' estimate (Helsel and Hirsch, 1992). The smearing estimator converts log-transformed values to original units (cm/yr in this case) using a bias-correction factor, and is robust because it makes no assumption regarding the distribution of regression residuals.

Independent variables ($X_{n,i}$ and $Z_{j,i}$) were normalized by dividing by their mean values, so that regression coefficients within each model component (I_i and T_i) can be compared to ascertain the relative influence of variables on recharge. Coefficients cannot be compared between components, however, because I_i is linear and T_i is exponential. To enhance comparability of all variables, we evaluated model sensitivity by relating changes in predicted recharge to incremental changes in the independent variables. We computed ''relative sensitivity'' (RS) as the absolute value of percent change in recharge, in units of ln(cm/yr), for a 1% change in an independent variable while holding the remaining variables constant.

Results and discussion

Medians of measured sediment texture, bulk density, and volumetric moisture content are summarized by NAWQA study area in Table 1. Sediment-texture data reflect regional vari-ations in unsaturated-zone characteristics. The median silt content of sediment cores from WHMI and CNBR is 70% and 78%, respectively (see Table 1 for definition of NAWQA study area acronyms). Wells in CNBR are completed in shallow gla-cial sand lenses and WHMI wells are in relatively impermeable glacial till. In contrast, sediment cores from WMIC, GAFL, PODL, and CONN contain on average 66–89% sand. GAFL wells are completed in the Coastal Plain surficial aquifer and in the Floridan aquifer; PODL wells are completed in the coastal plain sand and gravel aquifer and in the Piedmont and Blue Ridge aquifer; and WMIC and CONN wells are in sand and grav-el aquifers in valley fill glacial outwash. Median sand and silt contents of TRIN cores, in the coastal lowlands, are some-what less (37% and 55%, respectively).

Statistical analysis of recharge estimates

Recharge estimates for all sites are shown in Appendix 1. Estimates of R_{PTF}, R_{SZC}, and R_{UZC} are highly skewed
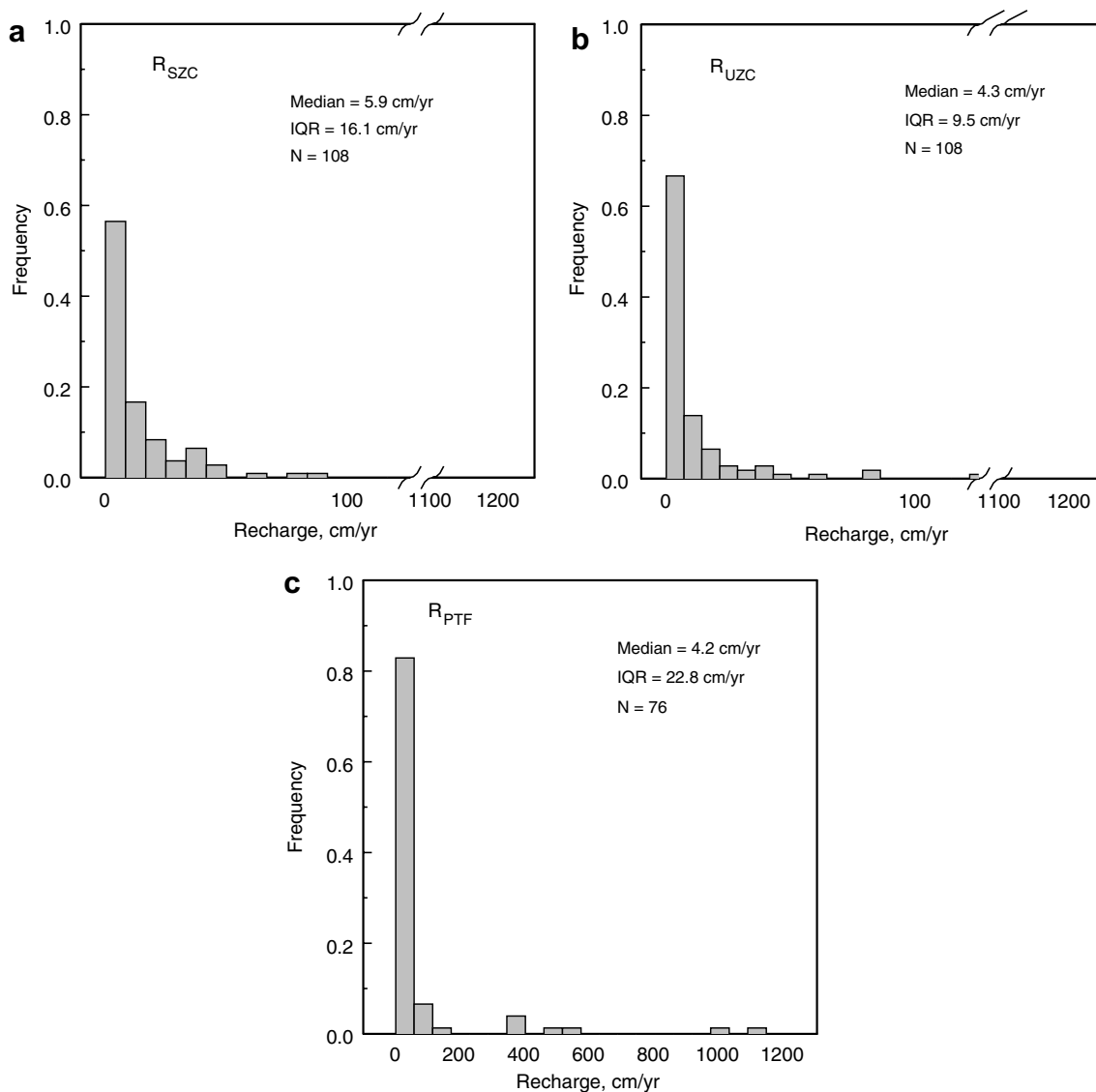
Figure 2 Histograms showing distributions of recharge estimates by (a) saturated-zone chloride tracer (R_{SZC}), (b) unsaturated-zone chloride tracer (R_{UZC}), and (c) the Darcian-pedotransfer method (R_{PTF}).

(Fig. 2). Statistical distributions of R_{SZC} and R_{UZC} (Fig. 2a and b, respectively) appear similar, but the latter has a somewhat lower median (4.3 cm/yr compared with 5.9 cm/yr for R_{SZC}). The greater median and variability of R_{SZC} (IQR = 16.1 versus 9.5 cm/yr for R_{UZC}) may reflect preferential flow, which causes saturated-zone chloride estimates of recharge to exceed unsaturated zone estimates by as much as two orders of magnitude (Scanlon et al., 2002). Saturated zone estimates integrate water fluxes over areas ranging from a few to several thousand square meters, areas much larger than those sampled by unsaturated zone methods (Scanlon et al., 2002). Hence, the R_{SZC} method is more likely than the R_{UZC} method to capture preferential flow, which can occur as focused recharge beneath small-scale topographic depressions at lowland sites that received surface-water run-on (Delin et al., 2000). In contrast, R_{UZC} and R_{PTF} are point estimates. The IQR of R_{PTF} (22.8 cm/yr) is the highest of the three methods, indicating greater variability (Fig. 2c). R_{PTF} statistics are influenced by the maximum value of 1140 cm/yr. Although such a high value might result from focused recharge in topographically low lying areas, it could also result from measurement inaccuracies. The R_{PTF} estimates are highly uncertain because $K(\theta)$ is sensitive to small changes in moisture content, and because the estimated hydraulic parameters are subject to the uncertainty of the Rosetta model. The latter uncertainty arises for several reasons: the estimated hydraulic properties are a function of observed matric potential and soil texture; the number of samples in the Rosetta database varies from about 200 to 2100 depending on the hydraulic property of interest; and, silt and clay textures are somewhat underrepresented in the Rosetta database (Schaap et al., 2001).

Recharge estimates by chloride tracer are significantly correlated with environmental factors (Table 2). Variables with univariate correlations of <-0.3 or >0.3 for R_{UZC} are shown in the table. Spearman correlations are positive for mean annual base flow, runoff, and factors related to coarse-grained soils (such as percent sand and ''soil hydrologic group A''); and negative for Hortonian overland flow and factors related to fine-grained soils (such as percent silt and clay). Soil hydrologic group A is described as ''deep, well drained to excessively drained sands or gravels''; group A/D indicates soils that have a ''very slow rate of water transmission'' in their natural condition but that behave as group A soils when artificially drained (US Department of Agriculture, 2001).

Correlations generally are strongest for R_{UZC}, with $p \leqslant 0.001$ for all variables shown in Table 2. The maximum positive correlation by this method is 0.443. The maximum correlation overall (-0.554) was obtained with R_{SZC}. Although correlations with R_{SZC} generally are weaker, more than half of these have significance level <0.01. Weaker correlations with recharge estimates by this method may reflect preferential flow. Estimates of R_{PTF} yield the weakest correlations with spatial data (Table 2). Only two variables approached the 0.05 significance level: base flow ($p = 0.050$) and shrink—swell potential ($p = 0.054$).

Factors influencing recharge in the study area

The remainder of the paper focuses on R_{SZC}, which is significantly correlated with several potential explanatory vari-

ables in Table 2, has intermediate variability (IQR = 16.1), and performed better than R_{UZC} and R_{PTF} in subsequent empirical models. Results of ANOVA and Tukey's test on ranked data indicate that NAWQA study areas containing coarse-grained or fractured aquifers or with high sand content (those marked ''A'' or ''AB'' in Fig. 3) — with the exception of CONN — have significantly greater recharge than their westernmost counterparts (those marked ''BC'' or ''C'', such as CNBR and TRIN). In the figure, study areas with the same letter are not significantly different at the 0.05 level. Some of the study areas marked ''A'' and AB'' contain sand and gravel aquifers (PODL and GAFL coastal plain surficial aquifers), fractured crystalline rocks (PODL Piedmont and Blue Ridge), or carbonate rocks with karst features (Floridan aquifer in GAFL), which are highly transmissive. This makes sense, because the same hydrogeologic characteristics that lead to high transmissivities in the saturated zone also promote high recharge rates through the unsaturated zone.

Estimates of R_{SZC} in WMIC apparently reflect the high sand content (median = 87.6%) of coarse-grained glacial deposits, although it is hard to generalize because only four estimates were obtained. WHMI is in glacial deposits comprising fine-grained sediment (median silt content = 70.4%), but recharge in the area is enhanced by the presence of numerous tile drains that convey excess water from agricultural fields and thus lower the water table. In the absence of drains, the water table would rise to land surface and could reject additional recharge. We anticipated that CONN sites (median sand content = 86.9%) would have greater median recharge than shown in Fig. 3; these estimates may show effects from road salt, which was assumed negligible compared with fertilizer inputs of chloride. The remaining study areas (TRIN and CNBR) contain fine-grained sediments (median silt content = 55% and 78%) and have comparatively low recharge (Table 1).

Using the NLR model and subsequent sensitivity analysis, we identified factors that most influence the R_{SZC} estimates. The model explains a moderate amount of variation in the data set, based on the coefficient of determination (R^2) of 0.61, and the standard error of regression is 0.942 ln(cm/yr). A plot of predicted versus observed or ''measured'' recharge (R_{SZC}) indicates that the overall model fit is reasonable (Fig. 4a). A probability plot indicates that the residuals are normally distributed, which satisfies regression assumptions regarding hypothesis testing for significance of model coefficients (Fig. 4b).

The model comprises water input and transport factors that promote or inhibit transfer of water through the unsaturated zone to the water table. Ten of these are significant at the 0.05 level, and the significance of TWI and precipitation approaches 0.05 (Table 3). This differs from the MLR model attempted for southern New Jersey, for which only measured percent clay ($p = 0.045$) was significant at the 0.05 level (Nolan et al., 2003). The regional scope of the current study facilitates systematic variation in climate and landscape variables, which promotes correlations with recharge. In particular, regional climate patterns and flow processes drive the observed correlations, which are exploited by the NLR model. The NLR model differs from an earlier empirical approach that modeled recharge globally (Doll et al., 2002). They assigned values by expert judg-
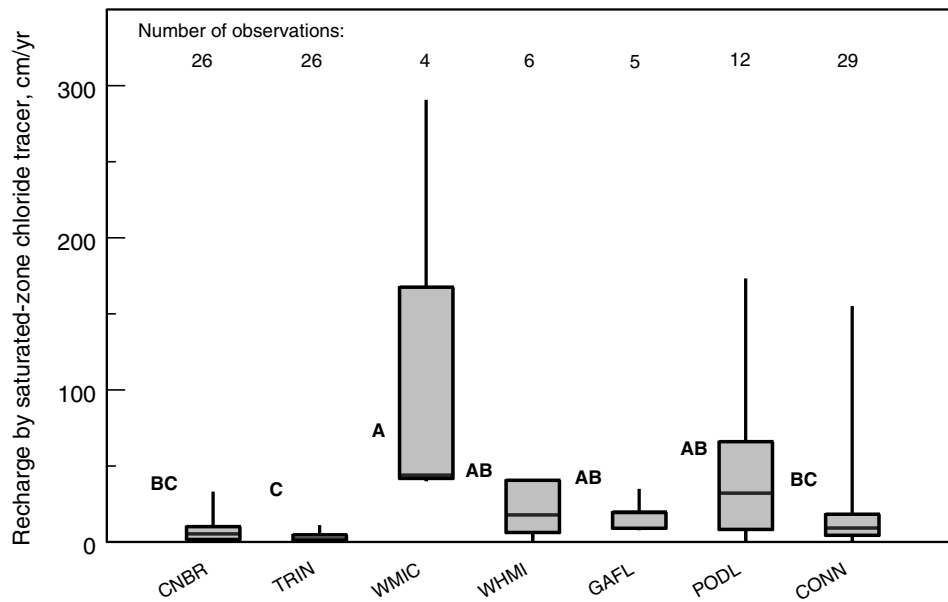
Figure 3 Recharge estimates by saturated-zone chloride tracer (R_{SZC}) for study units of the National Water-Quality Assessment Program, proceeding from west to east in the region. Study unit definitions are: CNBR, Central Nebraska Basins; TRIN, Trinity River Basin; WMIC, Western Lake Michigan Drainages; WHMI, White-Miami River Basins; GAFL, Georgia—Florida Coastal Plain; PODL, Potomac—Delmarva River Basins; CONN, Connecticut, Housatonic, and Thames River Basins. In the figure, study areas with the same letter (e.g., ''A'') are not significantly different at the 0.05 level.
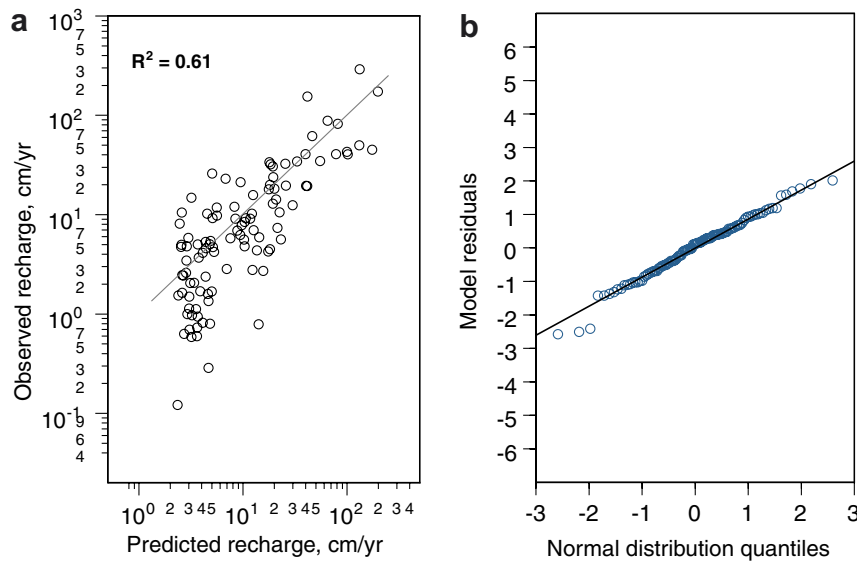
Figure 4 (a) Observed recharge versus that predicted by the nonlinear regression model. Observed recharge refers to estimates by saturated-zone chloride tracer (R_{SZC}). (b) Quantile plot of model residuals. Natural logarithms of model residuals are shown.

ment for factors representing the fraction of total runoff of land areas delivered as recharge, and checked results in iterative fashion. In contrast, NLR transport factors are weighted automatically by model coefficients during calibration.

Factors are shown in Table 3 in decreasing order of influence for components I_i and T_i of the NLR model. Irrigation variables are insignificant in these regressions, so Eq. (4) reduces to a single water-input variable (precipitation). Relative sensitivity values indicate that, overall, mean annual runoff (RS = 1.1), air temperature (RS = 0.80), and precipitation (RS = 0.68), and TWI (RS = 0.63) most influence recharge at sampled sites in the region. For example, recharge predicted by Eq. (3) increases by 0.68% for a 1% increase in mean annual precipitation. The comparatively large influence of the precipitation variable and positive coefficient sign are consistent with prior regression models. Annual precipitation was the most important variable in a MLR model that also included maximum soil-water storage, shallow depth to water table, and spring rainfall rate as

Table 3   Parameters of nonlinear regression model for ground-water recharge

Model parameter	Units[a]	Estimated coefficient[b]	Significance level (p)	Relative sensitivity[c]
Intercept	ln(cm/yr)	0.437	0.174	na
Water input (β)				
Mean annual precipitation	cm/yr	21.4	0.0838	0.68
Water transport factor (α)				
Mean annual runoff	cm/yr	−1.71	0.0007	1.1
Mean annual temperature	°C	−1.25	0.0002	0.80
Topographic wetness index	ln(m)	−0.969	0.0547	0.63
Hortonian overland flow	%	−0.827	0.0032	0.54
Inceptisols	%	0.438	0.0053	0.30
Hydric soils	%	0.426	0.0059	0.30
Measured sand above water table	%	0.398	0.0081	0.28
Subsurface flow contact time	days	0.308	0.0019	0.21
Ultisols	%	0.147	0.0007	0.10
Residential land use[d]	%	−0.147	0.0411	0.10
Soil hydrologic group A	%	0.114	0.0165	0.08
Wetlands[e]	%	−0.0674	0.150	0.05

na: Not applicable; β and α correspond to parameter coefficients in Eqs. (4) and (5), respectively.
[a] Original units before normalization of independent variables.
[b] After normalization; all units of independent variables are dimensionless after dividing by their mean values. Coefficients within the exponential component of the model (α) are directly comparable.
[c] Absolute value of percent change in predicted recharge in units of ln(cm/yr), for 1% change in an independent variable.
[d] NLCDe 92 categories 25 (residential without forest) and 26 (residential with forest).
[e] NLCDe 92 categories 91 (woody wetlands) and 92 (emergent herbaceous wetlands).

explanatory variables (Sophocleous, 1992). Prior researchers observed high correlations between recharge and seasonal precipitation for hydrogeological provinces in India (Rangarajan and Athavale, 2000). Seasonal precipitation amounts were strongly related to recharge in glaciated sediments of north-central Minnesota (Nichols and Verry, 2001). Based on these earlier results, seasonal variables representing spring (March–May), summer (June–August), fall (September–November), and winter (December–February) precipitation were tested with the NLR model, but were statistically insignificant.

Transport factors proportionally increase or decrease water inputs, as indicated by the sign of the model coefficient, in nonlinear fashion. For example, mean annual temperature has a negative coefficient sign, indicating that as temperature increases, recharge decreases, likely because of increased potential for evapotranspiration. Temperature generally increases from north to south in the region; TRIN and GAFL have the warmest mean annual temperature among sampled study areas.

Some model coefficients have a different sign than obtained with univariate correlations. The univariate correlation coefficient for mean annual runoff is positive (Table 2), but this factor has a negative coefficient sign in the NLR model (Table 3). The positive sign in the univariate case is reasonable because runoff by this method (Gebert et al., 1987) is calculated as stream flow divided by basin area. Base flow is a component of stream flow. The base-flow index (used to compute base flow) is assumed to represent, over the long term, the percentage of natural ground-water discharge to streams (Wolock, 2003b). Long-term discharge should resemble long-term average natural ground-water

recharge. In the multi-variate NLR model, however, runoff appears to explain residual variation in recharge that is not accounted for by other variables in the model. Factors such as precipitation and sandy, well-drained soils represent infiltration and are positively related to recharge as well. Therefore in the multi-variate case, runoff appears more related to overland water movement to streams, which is expected to have a negative relation with recharge. The negative sign for Hortonian overland flow (RS = 0.54) provides additional evidence of such a relation.

Similarly, subsurface contact time (positive coefficient sign, RS = 0.21) may explain residual variation in the NLR model, given that TWI is also in the model. Topographic wetness index (negative sign, RS = 0.63) is a terrain metric that depends on drainage area and slope and indicates the potential for ground-water exfiltration. Thus, high values of TWI represent ground-water discharge areas, and would be expected to be inversely related to recharge. Subsurface contact time is positively related to TWI and negatively related to the lateral hydraulic conductivity of the aquifer (Vitvar et al., 2002). Because both contact time and TWI are in the model, the former may reflect lateral residence time, with greater times associated with more opportunity for vertical movement of infiltrating water.

Soil characteristics, sediment texture, and land use have small RS values (0.30 or less) and, therefore, less influence on the recharge estimates. Some of these factors likely represent combined effects of sediment texture and climate on recharge. Hydric soils (positive sign, RS = 0.30) represent saturated, flooded, or ponding conditions and commonly are anaerobic near the surface. Ultisols (RS = 0.10) are highly weathered soils that contain oxidized iron and alumi-

Table A1 Sources of spatial data used in statistical analyses of ground-water recharge estimates (NA, not applicable)

Variable	Reference	Internet source of data
Climate/hydrology		
Mean annual precipitation, 1980–1997, cm/yr	Thornton and Running (1999)	http://www.daymet.org/
Mean annual temperature, 1980—1997, °C	Thornton and Running (1999)	http://www.daymet.org/
Potential evapotranspiration, cm/yr	Daly et al. (2002), Hamon (1961)	http://www.ocs.oregonstate.edu/prism/
Mean annual base-flow, cm/yr	Wolock (2003a), Gebert et al. (1987)	http://water.usgs.gov/lookup/getspatial?rech48grd
Hortonian overland flow, %	Beven and Kirkby (1979), Wolock (1993)	http://water.usgs.gov/lookup/getspatial?ieof48
Dunne overland flow, %	Beven and Kirkby (1979), Wolock (1993)	http://water.usgs.gov/lookup/getspatial?satof48
Mean annual runoff (1951–1980), in/yr	Gebert et al. (1987)	http://water.usgs.gov/lookup/getspatial?runoff
Slope from 1 km digital elevation maps	Wolock, written commun. (2002)	NA
Topographic wetness index, ln(m)	Wolock and McCabe (1995)	NA
Subsurface flow contact time, d	Wolock (1997), US Geological Survey (1987)	NA
Land cover		
Open water, %	Vogelmann et al. (2001), USGS (1990), Nakagaki and Wolock (2005)	http://edc.usgs.gov/products/landcover/nlcd.html, http://edc.usgs.gov/products/landcover/lulc.html
Commercial/industrial/transportation, %	Vogelmann et al. (2001), USGS (1990), Nakagaki and Wolock (2005)	http://edc.usgs.gov/products/landcover/nlcd.html, http://edc.usgs.gov/products/landcover/lulc.html
Low-intensity residential, %	Vogelmann et al. (2001), USGS (1990), Nakagaki and Wolock (2005)	http://edc.usgs.gov/products/landcover/nlcd.html, http://edc.usgs.gov/products/landcover/lulc.html
High-intensity residential, %	Vogelmann et al. (2001), USGS (1990), Nakagaki and Wolock (2005)	http://edc.usgs.gov/products/landcover/nlcd.html, http://edc.usgs.gov/products/landcover/lulc.html
LULC Residential with NLCD forest, %	Vogelmann et al. (2001), USGS (1990), Nakagaki and Wolock (2005)	http://edc.usgs.gov/products/landcover/nlcd.html, http://edc.usgs.gov/products/landcover/lulc.html
LULC Residential without NLCD forest, %	Vogelmann et al. (2001), USGS (1990), Nakagaki and Wolock (2005)	http://edc.usgs.gov/products/landcover/nlcd.html, http://edc.usgs.gov/products/landcover/lulc.html
Bare rock/sand/clay, %	Vogelmann et al. (2001), USGS (1990), Nakagaki and Wolock (2005)	http://edc.usgs.gov/products/landcover/nlcd.html, http://edc.usgs.gov/products/landcover/lulc.html
Quarries/strip mines/gravel pits, %	Vogelmann et al. (2001), USGS (1990), Nakagaki and Wolock (2005)	http://edc.usgs.gov/products/landcover/nlcd.html, http://edc.usgs.gov/products/landcover/lulc.html
Transitional, %	Vogelmann et al. (2001), USGS (1990), Nakagaki and Wolock (2005)	http://edc.usgs.gov/products/landcover/nlcd.html, http://edc.usgs.gov/products/landcover/lulc.html
Deciduous forest, %	Vogelmann et al. (2001), USGS (1990), Nakagaki and Wolock (2005)	http://edc.usgs.gov/products/landcover/nlcd.html, http://edc.usgs.gov/products/landcover/lulc.html
Evergreen forest, %	Vogelmann et al. (2001), USGS (1990), Nakagaki and Wolock (2005)	http://edc.usgs.gov/products/landcover/nlcd.html, http://edc.usgs.gov/products/landcover/lulc.html

Table A1 (*continued*)

Variable	Reference	Internet source of data
Mixed forest, %	Vogelmann et al. (2001), USGS (1990), Nakagaki and Wolock (2005)	http://edc.usgs.gov/products/landcover/nlcd.html, http://edc.usgs.gov/products/landcover/lulc.html
Shrubland, %	Vogelmann et al. (2001), USGS (1990), Nakagaki and Wolock (2005)	http://edc.usgs.gov/products/landcover/nlcd.html, http://edc.usgs.gov/products/landcover/lulc.html
Orchards/vineyards/other, %	Vogelmann et al. (2001), USGS (1990), Nakagaki and Wolock (2005)	http://edc.usgs.gov/products/landcover/nlcd.html, http://edc.usgs.gov/products/landcover/lulc.html
Orchards/vineyards/ other (LULC), %	Vogelmann et al. (2001), USGS (1990), Nakagaki and Wolock (2005)	http://edc.usgs.gov/products/landcover/nlcd.html, http://edc.usgs.gov/products/landcover/lulc.html
Grasslands/herbaceous, %	Vogelmann et al. (2001), USGS (1990), Nakagaki and Wolock (2005)	http://edc.usgs.gov/products/landcover/nlcd.html, http://edc.usgs.gov/products/landcover/lulc.html
Tundra (LULC), %	Vogelmann et al. (2001), USGS (1990), Nakagaki and Wolock (2005)	http://edc.usgs.gov/products/landcover/nlcd.html, http://edc.usgs.gov/products/landcover/lulc.html
Pasture/hay, %	Vogelmann et al. (2001), USGS (1990), Nakagaki and Wolock (2005)	http://edc.usgs.gov/products/landcover/nlcd.html, http://edc.usgs.gov/products/landcover/lulc.html
Row crops, %	Vogelmann et al. (2001), USGS (1990), Nakagaki and Wolock (2005)	http://edc.usgs.gov/products/landcover/nlcd.html, http://edc.usgs.gov/products/landcover/lulc.html
Small grains, %	Vogelmann et al. (2001), USGS (1990), Nakagaki and Wolock (2005)	http://edc.usgs.gov/products/landcover/nlcd.html, http://edc.usgs.gov/products/landcover/lulc.html
Fallow, %	Vogelmann et al. (2001), USGS (1990), Nakagaki and Wolock (2005)	http://edc.usgs.gov/products/landcover/nlcd.html, http://edc.usgs.gov/products/landcover/lulc.html
Urban/recreational grasses, %	Vogelmann et al. (2001), USGS (1990)	http://edc.usgs.gov/products/landcover/nlcd.html, http://edc.usgs.gov/products/landcover/lulc.html
Woody wetlands, %	Vogelmann et al. (2001), USGS (1990), Nakagaki and Wolock (2005)	http://edc.usgs.gov/products/landcover/nlcd.html, http://edc.usgs.gov/products/landcover/lulc.html
Emergent herbaceous wetlands, %	Vogelmann et al. (2001), USGS (1990), Nakagaki and Wolock (2005)	http://edc.usgs.gov/products/landcover/nlcd.html, http://edc.usgs.gov/products/landcover/lulc.html
Population data		
1990 population density, people/km^2	US Bureau of the Census (1991)	http://water.usgs.gov/lookup/getspatial?uspop90
Public or private water source, % of housing units	US Bureau of the Census (1992)	http://factfinder.census.gov/servlet/DatasetMainPageServlet?_program=DEC&_lang=en
Individual well, drilled, % of housing units	US Bureau of the Census (1992)	http://factfinder.census.gov/servlet/DatasetMainPageServlet?_program=DEC&_lang=en
Individual well, dug, % of housing units	US Bureau of the Census (1992)	http://factfinder.census.gov/servlet/DatasetMainPageServlet?_program=DEC&_lang=en
Other water source, % of housing units	US Bureau of the Census (1992)	http://factfinder.census.gov/servlet/DatasetMainPageServlet?_program=DEC&_lang=en
Public sewer, % of housing units	US Bureau of the Census (1992)	http://factfinder.census.gov/servlet/DatasetMainPageServlet?_program=DEC&_lang=en

Variable	Source	Link/Media
Septic tank, % of housing units	US Bureau of the Census (1992)	http://factfinder.census.gov/servlet/DatasetMainPageServlet?_program=DEC&_lang=en
Other disposal method, % of housing units	US Bureau of the Census (1992)	http://factfinder.census.gov/servlet/DatasetMainPageServlet?_program=DEC&_lang=en
Irrigation water use		
Total fresh ground water, MGD	Solley et al. (1998)	http://water.usgs.gov/lookup/getspatial?ofr99-78_cowu95
Total ground water, MGD	Solley et al. (1998)	http://water.usgs.gov/lookup/getspatial?ofr99-78_cowu95
Total fresh surface water, MGD	Solley et al. (1998)	http://water.usgs.gov/lookup/getspatial?ofr99-78_cowu95
Total saline surface water, MGD	Solley et al. (1998)	http://water.usgs.gov/lookup/getspatial?ofr99-78_cowu95
Total surface water, MGD	Solley et al. (1998)	http://water.usgs.gov/lookup/getspatial?ofr99-78_cowu95
Total fresh, MGD	Solley et al. (1998)	http://water.usgs.gov/lookup/getspatial?ofr99-78_cowu95
Total saline, MGD	Solley et al. (1998)	http://water.usgs.gov/lookup/getspatial?ofr99-78_cowu95
Total, MGD	Solley et al. (1998)	http://water.usgs.gov/lookup/getspatial?ofr99-78_cowu95
Consumptive use, fresh, MGD	Solley et al. (1998)	http://water.usgs.gov/lookup/getspatial?ofr99-78_cowu95
Consumptive use, saline, MGD	Solley et al. (1998)	http://water.usgs.gov/lookup/getspatial?ofr99-78_cowu95
Consumptive use total, MGD	Solley et al. (1998)	http://water.usgs.gov/lookup/getspatial?ofr99-78_cowu95
Conveyance losses, MGD	Solley et al. (1998)	http://water.usgs.gov/lookup/getspatial?ofr99-78_cowu95
Irrigated acres, sprinkler systems, km^2	Solley et al. (1998)	http://water.usgs.gov/lookup/getspatial?ofr99-78_cowu95
Irrigated acres, micro irrigation systems, km^2	Solley et al. (1998)	http://water.usgs.gov/lookup/getspatial?ofr99-78_cowu95
Irrigated acres, surface (flood) systems, km^2	Solley et al. (1998)	http://water.usgs.gov/lookup/getspatial?ofr99-78_cowu95
Irrigated acres, total, km^2	Solley et al. (1998)	http://water.usgs.gov/lookup/getspatial?ofr99-78_cowu95
Reclaimed wastewater, MGD	Solley et al. (1998)	http://water.usgs.gov/lookup/getspatial?ofr99-78_cowu95
National resources inventory		
Areas with well as irrigation source, km^2	USDA (1995)	CD-ROM
Areas with pond, lake, or reservoir as irrigation source, km^2	USDA (1995)	CD-ROM
Areas with stream, ditch, or canal as irrigation source, km^2	USDA (1995)	CD-ROM
Areas with lagoon or other waste water as irrigation source, km^2	USDA (1995)	CD-ROM
Combination of irrigation sources, km^2	USDA (1995)	CD-ROM
Gravity irrigated, km^2	USDA (1995)	CD-ROM
Pressure irrigation systems, km^2	USDA (1995)	CD-ROM
Gravity and pressure irrigated, km^2	USDA (1995)	CD-ROM
Waste management system, km	USDA (1995)	CD-ROM
Irrigation, canal or lateral, km^2	USDA (1995)	CD-ROM
Conservation tillage system, km^2	USDA (1995)	CD-ROM
Contour farming, km^2	USDA (1995)	CD-ROM
Irrigation water conveyance, ditch and canal, km^2	USDA (1995)	CD-ROM
Irrigation water conveyance, pipeline, km^2	USDA (1995)	CD-ROM
Irrigation system, tailwater recovery, km^2	USDA (1995)	CD-ROM
Irrigation water management, km^2	USDA (1995)	CD-ROM
Irrigation land leveling, km^2	USDA (1995)	CD-ROM
Terrace, km^2	USDA (1995)	CD-ROM

Table A1 (*continued*)

Variable	Reference	Internet source of data
Subsurface drain, km²	USDA (1995)	CD-ROM
Surface drainage, field ditch, km²	USDA (1995)	CD-ROM
Surface drainage, main or lateral, km²	USDA (1995)	CD-ROM
Soils data		
Soil hydrologic group A, %	Wolock, written commun. (2004)	http://www.ncgc.nrcs.usda.gov/products/datasets/statsgo/index.html
Soil hydrologic group B, %	Wolock, written commun. (2004)	http://www.ncgc.nrcs.usda.gov/products/datasets/statsgo/index.html
Soil hydrologic group C, %	Wolock, written commun. (2004)	http://www.ncgc.nrcs.usda.gov/products/datasets/statsgo/index.html
Soil hydrologic group D, %	Wolock, written commun. (2004)	http://www.ncgc.nrcs.usda.gov/products/datasets/statsgo/index.html
Soil hydrologic group AD, %	Wolock, written commun. (2004)	http://www.ncgc.nrcs.usda.gov/products/datasets/statsgo/index.html
Soil hydrologic group BD, %	Wolock, written commun. (2004)	http://www.ncgc.nrcs.usda.gov/products/datasets/statsgo/index.html
Soil hydrologic group CD, %	Wolock, written commun. (2004)	http://www.ncgc.nrcs.usda.gov/products/datasets/statsgo/index.html
Soil hydrologic group AC, %	Wolock, written commun. (2004)	http://www.ncgc.nrcs.usda.gov/products/datasets/statsgo/index.html
Soil hydrologic group BC, %	Wolock, written commun. (2004)	http://www.ncgc.nrcs.usda.gov/products/datasets/statsgo/index.html
Land surface slope, %	Wolock (1997)	http://water.usgs.gov/lookup/getspatial?muid
Depth to seasonally high water table, ft	Wolock (1997)	http://water.usgs.gov/lookup/getspatial?muid
Total soil thickness examined, in.	Wolock (1997)	http://water.usgs.gov/lookup/getspatial?muid
Permeability, in./hr	Wolock (1997)	http://water.usgs.gov/lookup/getspatial?muid
Available water capacity, fraction	Wolock (1997)	http://water.usgs.gov/lookup/getspatial?muid
Bulk density, g/cm³	Wolock (1997)	http://water.usgs.gov/lookup/getspatial?muid
Organic matter content, % by weight	Wolock (1997)	http://water.usgs.gov/lookup/getspatial?muid
Percent by weight of soil material less than 3 in. in size and passing a No. 4 sieve (5 mm)	Wolock, written commun. (2004)	http://www.ncgc.nrcs.usda.gov/products/datasets/statsgo/index.html
Percent by weight of soil material less than 3 in. in size and passing a No. 200 sieve (0.074 mm)	Wolock, written commun. (2004)	http://www.ncgc.nrcs.usda.gov/products/datasets/statsgo/index.html
Percent by weight of soil material less than 3 in. in size and passing a No. 10 sieve (2 mm)	Wolock, written commun. (2004)	http://www.ncgc.nrcs.usda.gov/products/datasets/statsgo/index.html
Soil erodibility factor	Wolock (1997)	http://water.usgs.gov/lookup/getspatial?muid
Soil erodibility factor of uppermost soil horizon	Wolock, written commun. (2004)	http://www.ncgc.nrcs.usda.gov/products/datasets/statsgo/index.html
Soil loss tolerance factor	Wolock (1997)	http://water.usgs.gov/lookup/getspatial?muid
Wind erodibility group	Wolock (1997)	http://water.usgs.gov/lookup/getspatial?muid
Shrink–swell potential	Wolock, written commun. (2004)	http://www.ncgc.nrcs.usda.gov/products/datasets/statsgo/index.html
Vertical permeability, in./hr	Wolock, written commun. (2004)	http://www.ncgc.nrcs.usda.gov/products/datasets/statsgo/index.html
Permeability of the least permeable soils layer, in./hr	Wolock, written commun. (2004)	http://www.ncgc.nrcs.usda.gov/products/datasets/statsgo/index.html
Depth of the least permeable layer, in.	Wolock, written commun. (2004)	http://www.ncgc.nrcs.usda.gov/products/datasets/statsgo/index.html
Soil drainage class	Schwartz and Alexander (1995)	http://water.usgs.gov/lookup/getspatial?ussoils
Hydric soils, %	Wolock, written commun. (2004)	http://www.ncgc.nrcs.usda.gov/products/datasets/statsgo/index.html
Soil order A Alfisols, %	Wolock, written commun. (2004)	http://www.ncgc.nrcs.usda.gov/products/datasets/statsgo/index.html

Variable	Source	Reference/URL
Soil order C Andisols, %	Wolock, written commun. (2004)	http://www.ncgc.nrcs.usda.gov/products/datasets/statsgo/index.html
Soil order D Aridisols, %	Wolock, written commun. (2004)	http://www.ncgc.nrcs.usda.gov/products/datasets/statsgo/index.html
Soil order E Entisols, %	Wolock, written commun. (2004)	http://www.ncgc.nrcs.usda.gov/products/datasets/statsgo/index.html
Soil order H Histosols, %	Wolock, written commun. (2004)	http://www.ncgc.nrcs.usda.gov/products/datasets/statsgo/index.html
Soil order I Inceptisols, %	Wolock, written commun. (2004)	http://www.ncgc.nrcs.usda.gov/products/datasets/statsgo/index.html
Soil order M Mollisols, %	Wolock, written commun. (2004)	http://www.ncgc.nrcs.usda.gov/products/datasets/statsgo/index.html
Soil order O Oxisols, %	Wolock, written commun. (2004)	http://www.ncgc.nrcs.usda.gov/products/datasets/statsgo/index.html
Soil order S Spodosols, %	Wolock, written commun. (2004)	http://www.ncgc.nrcs.usda.gov/products/datasets/statsgo/index.html
Soil order U Ultisols, %	Wolock, written commun. (2004)	http://www.ncgc.nrcs.usda.gov/products/datasets/statsgo/index.html
Soil order V Vertisols, %	Wolock, written commun. (2004)	http://www.ncgc.nrcs.usda.gov/products/datasets/statsgo/index.html
Glacial deposits aquifers, presence or absence	US Geological Survey, (2003)	NA
Northern Atlantic Coastal Plain aquifer system, presence or absence	US Geological Survey (2003)	NA
Surficial aquifer system, presence or absence	US Geological Survey (2003)	NA
Floridan aquifer system, presence or absence	US Geological Survey (2003)	NA
Piedmont and Blue Ridge crystalline-rock and carbonate-rock aquifers, presence or absence	US Geological Survey (2003)	NA
Coastal lowlands aquifer system, presence or absence	US Geological Survey (2003)	NA

num, and have positive coefficient sign in the model (Table 3). They are found in moist areas with considerable precipitation and likely represent leaching conditions indicative of recharge. Sampled areas with high percentages of hydric soils are in TRIN and GAFL, and those with high percentages of Ultisols are primarily in the southeast (PODL and GAFL).

Other factors, such as measured sand (positive sign, RS = 0.28) above the water table and soil hydrologic group A (positive sign, RS = 0.08), indicate primarily a textural effect. These results corroborate an earlier model that predicts that higher recharge when soils in the upper 30 cm of the profile are coarse-textured (Doll et al., 2002). Greater recharge is expected in areas with coarse-textured soils, which promote rapid infiltration of water.

Land-use factors may represent effects of humans or natural conditions on recharge. Residential land use (negative slope coefficient, RS = 0.10) comprises NLCDe 92 categories 25 (NLCD nonforested/LULC residential) and 26 (NLCD forested/LULC residential), and might indicate areas with relatively impervious surfaces from housing, roads, and other suburban development. High percentages of this combined residential land use are present sporadically throughout the region, particularly in TRIN and CONN. Wetlands (negative slope coefficient, RS = 0.05) is the least important variable in the model but is retained because it is reasonable from a conceptual standpoint. It likely indicates ground-water exfiltration areas, where the water table intersects the land surface.

Conclusions

Estimates of ground-water recharge were obtained for selected locations in the eastern US by Darcian and chloride-tracer methods. Recharge estimates by chloride tracer are significantly correlated with factors representing climate, hydrology, land use, and soil properties. We emphasized the ground-water chloride tracer (R_{SZC}) estimates in this research because they had intermediate variability and performed best in the nonlinear regression model. Although the R_{SZC} methods produced the best results in this study, that may not always be the case. Use of multiple methods is beneficial, because each method has advantages and disadvantages. Explanatory variables that commonly vary over large distances (e.g., mean annual temperature and precipitation) likely led to the improved regression results for the R_{SZC} method, which provides recharge estimates that are integrated over much larger areas than the R_{UZC} and R_{PTF} methods.

We evaluated R_{SZC} using analysis of variance, multiple comparison tests, and an exploratory nonlinear regression (NLR) model. For the most part, recharge was significantly higher in areas with well-drained soils or those comprising coastal plain surficial aquifers, fractured crystalline rocks, and carbonate rocks. Westernmost portions of the study area have high silt content and comparatively low recharge.

The NLR model comprises precipitation and transport factors and identifies those, in a multi-variate context, that most influence recharge in the region. Sensitivity analysis indicated that, of the more than 100 variables screened in the model, mean annual runoff, air temperature, precipitation, and topographic wetness index had the most influence

Table A2 Recharge estimates (cm/yr) by the Darcian-pedotransfer, unsaturated-zone chloride tracer, and saturated-zone chloride tracer methods

NAWQA study unit	Station identifier	Sample identifier	Darcian-pedotransfer method (R_{PTF})	Chloride tracer in unsaturated zone (R_{UZC})	Chloride tracer in saturated zone (R_{SZC})
CNBR	411733096185501	DG-23	—	—	1.5
CNBR	413302097090530	K-7	47.2	3.6	10.2
CNBR	413348096324801	FP3	0.0	11.0	4.8
CNBR	413853096483801	D-22	1.9	0.4	0.7
CNBR	413919096531401	DO-12	3.8	4.9	—
CNBR	414141096371701	D-26	0.0	4.0	4.8
CNBR	414343096595801	CO-13	57.2	2.0	5.8
CNBR	414401096531301	D-21	2.0	1.5	2.1
CNBR	414527097094101	S-11	393.2	11.3	14.8
CNBR	414948097212601	S-01	0.0	0.3	0.6
CNBR	415458097142201	S-R2	512.2	8.5	15.8
CNBR	415558096434501	CU-20	32.1	3.2	11.8
CNBR	415918096350501	CU-29	0.4	6.4	23.9
CNBR	420024096485901	CU-19	0.4	7.7	9.1
CNBR	420248096300901	CU-30	21.8	4.6	7.8
CNBR	420425097101301	S-10	0.0	2.4	6.9
CNBR	420526096543901	W-14	17.7	1.4	2.8
CNBR	421149097121301	W-09	4.2	2.4	5.6
CNBR	421303097011601	W-15	1.5	3.3	5.9
CNBR	421357097243201	P-02	0.0	3.1	1.4
CNBR	421445097123801	W-RI	0.1	1.4	5.0
CNBR	421829097112401	W-08	1.6	2.2	32.5
CNBR	422156097314301	P-03	13.9	1.3	1.7
CNBR	422441097404601	P-04	1.1	2.0	4.6
CNBR	422756097334901	K-05	1.3	1.9	1.6
CNBR	422802097031601	CE-17	—	0.7	0.9
CNBR	422947097142701	CE-06	0.0	2.6	12.9
CONN	413122073122401	CONNCL2	—	5.7	5.6
CONN	413126073121101	CONNCL4	13.5	22.4	18.0
CONN	413127073122401	CONNCL3	—	8.0	7.3
CONN	413128073120000	CONNCL5	0.0	0.7	10.2
CONN	413129073122001	CONNCL1	0.0	82.4	4.3
CONN	413130073115801	CONNBR1	537.7	17.1	15.6
CONN	413130073120401	CONNSW2	—	24.2	21.3
CONN	413137073120000	CONNSW4	1026.5	12.0	9.2
CONN	413138073121201	CONNSW1	—	6.4	5.3
CONN	413144073115701	CONNSW3	—	16.3	4.2
CONN	413925072544401	CONNRB	—	1.6	19.5
CONN	414332072555401	CONNSB	—	33.9	18.3
CONN	414815072335701	CONNWM	—	8.3	2.8
CONN	414826072290901	CONNMP	—	10.4	154.5
CONN	414917072403501	CONNWC	—	6.1	61.8
CONN	415035072293801	CONNVR	—	6.1	32.1
CONN	415101072314901	CONNMRS	—	4.1	2.7
CONN	415107072333101	CONNOC	4.1	5.2	—
CONN	415148072325601	CONNNS	—	3.7	4.5
CONN	415336072414801	CONNBW	—	57.7	12.4
CONN	415446072364501	CONNEI	—	11.0	7.0
CONN	415453072482901	CONNMS	—	39.1	10.5
CONN	415535072475701	CONNKG	—	5.8	5.8
CONN	420027072262001	CONNBS	—	5.9	0.8
CONN	420339072411701	CONNPD	—	1.6	33.7
CONN	420400072370201	CONNFH	158.8	5.5	4.4
CONN	420550072434601	CONNWM	0.7	6.1	9.2
CONN	420757072390101	CONNNW	—	9.3	22.9

Table A2 (continued)

NAWQA study unit	Station identifier	Sample identifier	Darcian-pedotransfer method (R_{PTF})	Chloride tracer in unsaturated zone (R_{UZC})	Chloride tracer in saturated zone (R_{SZC})
CONN	421031072311601	CONNSV	0.0	2.2	3.0
CONN	421118072410401	CONNHG	20.2	18.9	12.0
CONN	421137072385801	CONNHC	—	1.3	—
CONN	421216072411501	CONNBL	0.0	0.7	—
GAFL	280241082224403	FL-4403	11.5	4.4	8.4
GAFL	280247082231901	FL-31901	23.7	14.6	19.6
GAFL	280249082220703	FL-20703	—	124.1	9.2
GAFL	280253082223803	FL-803	57.1	84.1	34.3
GAFL	280301082222702	FL-2702	21.1	43.7	19.4
GAFL	280846082134402	HILLS	—	9.4	—
PODL	383653077203701	PODL87	0.2	4.1	49.8
PODL	384956077250301	PODL3849	12.9	0.6	30.6
PODL	385305077162101	PODL46	0.6	3.7	14.2
PODL	385311077215001	PODL47	23.9	2.1	20.0
PODL	385930077215901	PODL35	361.2	1.1	2.4
PODL	390533077125201	PODL28	390.0	1.9	2.1
PODL	390812077051001	PODL15	57.8	2.3	0.8
PODL	390906077145601	PODL16	19.4	—	—
PODL	391102077101901	PODL05	1.0	16.1	88.2
PODL	391657076003601	TRI-1	—	—	—
PODL	391659076001800	FS1-1	—	23.2	33.7
PODL	391659076001801	PODLFS1-1	107.6	—	—
PODL	391700076002501	FS1-2	3.1	—	34.6
PODL	391701076003201	FS1-3	93.3	5.6	172.7
PODL	391710075584001	AS1	—	—	82.4
TRIN	294405095412301	Ref 1	—	0.3	1.5
TRIN	294503095373201	MW29	—	—	3.5
TRIN	294620095440501	MW17	—	—	1.0
TRIN	294657095412701	MW30	60.7	—	—
TRIN	294800095415801	MW28A	1.3	—	0.7
TRIN	294801095425701	MW28	—	0.5	—
TRIN	294807095452701	MW27	—	1.5	1.1
TRIN	294919095320501	MW25	—	6.5	4.7
TRIN	294957095310801	MW26	1.8	1.5	5.0
TRIN	295049095253101	MW23	3.3	0.1	2.4
TRIN	295150095302401	MW20	—	3.1	3.7
TRIN	295232095294101	MW21	—	36.5	8.1
TRIN	295249095411301	MW16	3.5	—	2.6
TRIN	295358095374101	MW18	2.5	0.4	1.7
TRIN	295421095305801	MW19	0.9	4.8	4.7
TRIN	295557095360901	MW11	1.9	0.2	1.6
TRIN	295633095335201	MW12	—	0.3	0.8
TRIN	295711095222301	MW07	18.3	8.7	5.0
TRIN	295714095361701	MW09	3.0	0.1	—
TRIN	295720095290001	MW08	—	3.0	4.1
TRIN	300011095251801	MW10	—	0.8	10.5
TRIN	300026095225401	MW06	—	2.7	2.5
TRIN	300044095312001	MW01	—	0.1	1.0
TRIN	300155095200201	MW05	0.0	0.1	1.5
TRIN	300351095232601	MW02	—	0.5	0.6
TRIN	300825095274801	MW14	12.2	0.6	0.1
TRIN	301008095302901	MW13	—	142.8	0.6
TRIN	301220095305501	MW15	7.3	1.3	1.1
TRIN	301716095400501	Ref03	0.1	4.7	5.4
WHMI	393230085375302	TP-2	1.9	11.7	26.0
WHMI	395025085493501	Uuk	—	34.7	6.2

Table A2 (*continued*)

NAWQA study unit	Station identifier	Sample identifier	Darcian-pedotransfer method (R_{PTF})	Chloride tracer in unsaturated zone (R_{UZC})	Chloride tracer in saturated zone (R_{SZC})
WHMI	395045085510933	svz	1143.6	—	—
WHMI	395151085504501	2D	15.2	20.0	40.7
WHMI	395159086171501	WHMI	12.1	0.4	0.3
WHMI	400717085032801	TP-10	7.7	13.6	9.8
WHMI	400836085205901	TP-9	12.9	13.6	40.6
WMIC	443317089211701	wmicfss4	0.7	3.5	290.0
WMIC	443320089212301	wmicfss3	51.9	15.5	43.0
WMIC	443328089213601	wmicfss2	47.5	6.2	40.6
WMIC	443338089221501	wmicfss1	12.6	37.0	45.0

Study unit definitions are: CNBR, Central Nebraska Basins; CONN, Connecticut, Housatonic, and Thames River Basins; GAFL, Georgia—Florida Coastal Plain; PODL, Potomac—Delmarva River Basins; TRIN, Trinity River Basin; WMIC, Western Lake Michigan Drainages; WHMI, White-Miami River Basins.

on predictions. Some of the variables, such as runoff and subsurface contact time, are difficult to interpret and may explain residual variation not accounted for by other variables in the model; however, their inclusion results in significant model improvement. Soil characteristics such as measured percent sand have less influence on predicted recharge but nonetheless are highly significant in the model (p generally <0.01). Additionally, measured bulk physical properties (texture, moisture content, and bulk density) were key to estimating recharge by the Darcian-pedotransfer method.

Although the NLR model fits the existing data set reasonably well, we consider it exploratory and refrained from using it to predict recharge throughout the region. Sampling was sparse overall, with only 108 estimates of R_{SZC} available for the eastern US. Future work could involve hundreds or even thousands of R_{SZC} estimates using ground water and atmospheric chemistry data that are readily available in national databases. An enhanced data set may improve model fit, reduce variability, and enable prediction in unsampled areas.

Appendix 1

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