Water Resource Report 70

SUMMARY OF GROUNDWATER-RECHARGE ESTIMATES FOR PENNSYLVANIA

by **Stuart O. Reese**
Bureau of Topographic and Geologic Survey

Dennis W. Risser
U.S. Geological Survey

Prepared by the Pennsylvania Geological Survey
in cooperation with the U.S. Geological Survey

PENNSYLVANIA GEOLOGICAL SURVEY

FOURTH SERIES

HARRISBURG

2010

When reproducing material from this publication, please cite the source as follows:

Reese, S. O., and Risser, D. W., 2010, Summary of groundwater-recharge estimates for Pennsylvania: Pennsylvania Geological Survey, 4th ser., Water Resource Report 70, 18 p., 6 plates, scale 1:2,000,000, Portable Document Format (PDF).

Web Site: www.dcnr.state.pa.us/topogeo

CONTENTS

FIGURE

TABLES

PLATES

SUMMARY OF GROUNDWATER-RECHARGE ESTIMATES FOR PENNSYLVANIA

by
Stuart O. Reese and Dennis W. Risser

ABSTRACT

Groundwater recharge is water that infiltrates through the subsurface to the zone of saturation beneath the water table. Because recharge is a difficult parameter to quantify, it is typically estimated from measurements of other parameters like streamflow and precipitation. This report provides a general overview of processes affecting recharge in Pennsylvania and presents estimates of recharge rates from studies at various scales.

The most common method for estimating recharge in Pennsylvania has been to estimate base flow from measurements of streamflow and assume that base flow (expressed in inches over the basin) approximates recharge. Statewide estimates of mean annual groundwater recharge were developed by relating base flow to basin characteristics of HUC10 watersheds (a fifth-level classification that uses 10 digits to define unique hydrologic units) using a regression equation. The regression analysis indicated that mean annual precipitation, average daily maximum temperature, percent of sand in soil, percent of carbonate rock in the watershed, and average stream-channel slope were significant factors in the explaining the variability of groundwater recharge across the Commonwealth.

Several maps are included in this report to illustrate the principal factors affecting recharge and provide additional information about the spatial distribution of recharge in Pennsylvania. The maps portray the patterns of precipitation, temperature, prevailing winds across Pennsylvania's varied physiography; illustrate the error associated with recharge estimates; and show the spatial variability of recharge as a percent of precipitation. National, statewide, regional, and local values of recharge, based on numerous studies, are compiled to allow comparison of estimates from various sources. Together these plates provide a synopsis of groundwater-recharge estimations and factors in Pennsylvania.

Areas that receive the most recharge are typically those that get the most rainfall, have favorable surface conditions for infiltration, and are less susceptible to the influences of high temperatures, and thus, evapotranspiration. Areas that have less recharge in Pennsylvania are typically those with less precipitation, less permeable soils, and higher temperatures that are conducive to greater rates of evapotranspiration.

INTRODUCTION

Recharge refers to water that infiltrates the subsurface of the earth to the zone of saturation where it becomes groundwater. This process takes place over most of Pennsylvania's land surface but occurs irregularly, depending on precipitation events and surface conditions, such as soil properties and land cover.

In a typical year, about 40 inches of precipitation falls upon Pennsylvania. This is equivalent to about 31 and a half *trillion* gallons of water. Of that amount, approximately one-third reaches the saturated zone, and under the influence of gravity and hydraulic head, slowly moves as groundwater toward zones of discharge. Discharge takes place almost continuously but is restricted to springs, streams, wetlands, and areas where groundwater is close to the surface and can be tapped by surficial processes such as evaporation and vegetation growth. Most groundwater discharges to a nearby stream, where it provides sustaining base flow.

The volume of groundwater in Pennsylvania is estimated at over 30 times the volume of surface water (Fleeger, 1999). The subsurface essentially acts as a massive underground reservoir. If there is no change in groundwater storage in that underground reservoir during a period of time, recharge of the watershed is often assumed to be about equal to the base-flow discharge from groundwater, provided that uptake by riparian vegetation, and other subtractions or additions of water are minor in the watershed.

Over the years, numerous investigations have provided estimates of groundwater recharge in Pennsylvania for specific geologic units or watersheds, and recently, recharge rates have been estimated on a statewide basis. This report provides a general overview of processes affecting recharge in Pennsylvania, discusses the estimates of recharge rates from the statewide study of Risser and others (2008), and provides results from other studies for comparison. Maps are presented to show the spatial distribution of recharge and factors affecting its distribution as well as to provide values of recharge based on numerous studies at various scales.

PREVIOUS STUDIES

Numerous publications have defined and discussed groundwater recharge over the years. For discussions of the basics of recharge and its many aspects, refer to, for examples, Theis (1940), Heath (1983), de Vries and Simmers (2002), Scanlon and others (2002), and Delin and Risser (2007). The online table *References, Methods for Estimating Groundwater Recharge in Humid Regions* by the USGS is a handy compendium of information on research and techniques (U.S. Geological Survey, 2009).

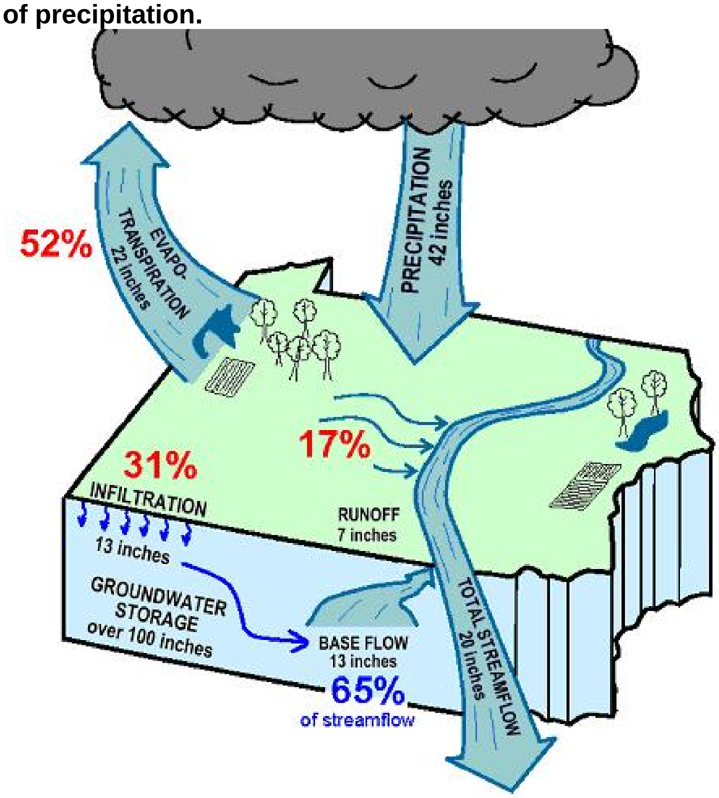
Recharge is nearly impossible to measure directly so many different techniques have been applied for estimating its magnitude. Because most methods have considerable uncertainty, it is often recommended that estimates be made using multiple methods. In Pennsylvania, Risser and others (2005b) compared the results of multiple methods of estimating recharge of a small watershed in Northumberland County, and the online report *Estimates of Ground-Water Recharge Based on Streamflow-Hydrograph Methods: Pennsylvania* compared estimates from two different hydrograph methods for 197 basins in Pennsylvania using streamflow data at gaging stations (Risser and others, 2005a).

Although it is prudent to estimate recharge from multiple methods, in practice, most estimates for watersheds in Pennsylvania have been derived from analysis of stream base flow, with a few others derived from streamflow-recession analysis, water balance, or modeling. Examples of the use of stream base flow include Risser and others (2008), Gerhart and Lazorchick (1988), and Lehigh University (1982). Streamflow-recession analysis has been applied by Gerhart and Lazorchick (1988), and Risser and others (2005b). A water-balance model was used by Risser (2008) to investigate the spatial distribution of recharge for a 76 mi^2 watershed. A surface-watershed model was applied to Pocono Creek watershed to estimate groundwater recharge (Hantush, 2006), and Senior and Goode (1999) used groundwater modeling to estimate groundwater recharge in part of Montgomery County. In a groundwater model of the lower Susquehanna River Basin, Gerhart and Lazorchick (1988) estimated recharge for a wide variety of rock types in south-central Pennsylvania; however, those recharge values were estimated by base-flow analysis and streamflow-recession analysis rather than through model calibration.

In 2008, the USGS released the report *Regression Method for Estimating Long-Term Mean Annual Ground-Water Recharge Rates from Base Flow in Pennsylvania* (Risser and others, 2008). This report provided statewide groundwater-recharge estimates for Pennsylvania through a regression equation. A regression analysis is the study of the relationship between a dependent variable with one or more independent variables. The USGS developed the regression equation to determine the critical variables needed to estimate groundwater recharge. For that study, the dependent variable was the mean annual base flow for a watershed, which was equated with groundwater recharge. Out of 28 variables, five statistically significant variables for recharge were determined at the "HUC11" watersheds. The significant variables in the regression at the 95-percent confidence level included mean annual precipitation, average daily maximum temperature, percent carbonate rock, percent sand in soil, and average stream channel slope. The USGS computed recharge amounts for 352 "HUC11" watersheds across the state based on the regression equation.

Results of the recharge estimates for the HUC11 watersheds show that over 80 percent of the watersheds (about 83 percent of Pennsylvania's land area) have annual recharge values from 10 to 18 inches, with an average annual recharge of 13.7 inches. This is consistent with an average recharge of 13 inches per year for Pennsylvania (Figure 1) reported by Fleeger (1999).

Figure 1. Average annual water budget for Pennsylvania (modified after Fleeger, 1999). Numbers in red indicate percent of precipitation.



Shortly after publication of the statewide estimates of recharge by Risser and others (2008), it was recognized that the "HUC11" watershed layer used to illustrate the distribution of recharge was not available to the public. Because the "HUC11" watershed layer was a temporary product that was never officially distributed, the USGS updated the recharge calculations using the official, published HUC10 watershed delineations (which differed only slightly from the HUC11 delineations) for presentation in this report. The Hydrologic Unit Code (HUC) is a hierarchical numeric code used to delineate and identify watersheds across the United States. In the case of HUC10 watersheds, a unique 10-digit code serves as an identifier. For more information about hydrologic unit codes, see U.S. Geological Survey and U.S. Department of Agriculture (2009).

FACTORS AFFECTING GROUNDWATER RECHARGE AND ITS ESTIMATION

Recharge is controlled by weather, climate, soil, and land-cover characteristics. In addition, recharge also can be affected by human patterns of development and water use. Logically, it is the climatic variables such as precipitation and temperature that have a strong control over the amount of groundwater recharge. Changes to these factors over the long term will affect groundwater recharge.

PRECIPITATION

Risser and others (2008) found that precipitation was the parameter having the strongest positive correlation with groundwater recharge in regression analyses. Plate 1 shows the 30-year patterns of precipitation across Pennsylvania from 1971 to 2000 (PRISM Group, 2006). The precipitation map is based on data derived from the Parameter-elevation Regressions on Independent Slopes Model (PRISM). The PRISM model integrates spatial scale and orographic effects by using digital elevation models combined with station precipitation data.

PHYSIOGRAPHY AND PREVAILING WINDS

Plate 1 shows the orographic effects of topography on precipitation patterns in Pennsylvania. The physiographic regions of Pennsylvania as categorized by Sevon (2000) are also shown on Plate 1. Areas of enhanced precipitation over higher regions and adjacent rain shadows over lower terrain can be observed. Much of the Allegheny Mountain section, northeastern portion of the Appalachian Mountain section, southeastern portion of the Glaciated High Plateau, the Anthracite Upland, Glaciated Pocono Plateau, Blue Mountain sections in eastern Pennsylvania, and the South Mountain region are specific zones of enhanced precipitation. Eastern Pennsylvania is affected by ocean moisture from occasional Atlantic storms. These storms typically have an eastern component of wind, and provide a substantial source of moisture that condenses out as winds ascend topographic highs like the Pocono Plateau. On the other hand, some rain-shadow effects of descending westerly winds off the Appalachian plateaus can be observed in south-central and northern portions of the state.

Plate 1 shows the predominant wind directions, based on data from the Pennsylvania State Climatologist (2007). Resultant wind vectors from approximately 15 years of data for 11 stations are plotted. Based on these data, Pennsylvania has a westerly direction of wind about 60 – 70 percent of the time. All 11 stations show this prevailing wind direction. The rest of the time there is an easterly component of wind. (Calm winds, which occurred from 9 to 31 percent of the time at these stations, were assigned a direction based on the closest in time wind direction to the previous wind measurement.) Most of the stations also have a southerly component of wind direction. The three easternmost stations, however, have a more northerly component of wind direction.

TEMPERATURE

Plate 2 shows the 30-year average (1971 – 2000) maximum daily temperatures for the state. Risser and others (2008) found temperature to be a statistically significant factor in the regression equation for recharge. Higher temperatures allow for increased evaporation of moisture and are thus a limiting factor on recharge. The southern tier counties, and especially the southeast and southwest corners, are the typically warm zones of Pennsylvania. Cooler zones are in the topographically higher areas and, for the most part, the northern third of the state.

CLIMATIC TRENDS

The geologic record indicates that the Earth's climate has undergone numerous swings in temperature and moisture in its long history (American Institute of Professional Geologists, 2005). In the last 15,000 years, the northeastern United States has emerged from glacial and near-glacial conditions to a temperate humid climate. In the past 15 years, the concept of anthropogenic global climate change has gained a foothold. The basis of this concept is that the voluminous industrial emissions of carbon dioxide and other greenhouse gases over the last 150 years have led to an increased warming of the atmosphere. The principal climatic trends in Pennsylvania over the last 110 years lend credit to the idea of climate change.

Important climatic trends in Pennsylvania, based on Historical Climatology Network (HCN) data and a 10-fold climatic division of the state, include the following (Knight, 2008):

- Increased winter (December, January, February) temperatures; increased number of snowy days
- Increase in dew point, and increased intensity and amounts of rainfall across all seasons, especially in the fall (September, October, November)
- Lengthened growing season (last recorded freeze in the spring to the first freeze of the fall)

Although spring (March, April, May), summer (June, July, August), and fall HCN temperatures for Pennsylvania have not increased but have slightly declined for the summer and fall, climate records are consistent with a changing atmosphere that is overall warmer and moister. Higher dew points are consistent with more precipitation and warmer winter nights and with spring, summer, and fall temperatures that have remained steady or slightly fallen during the past 110 years. Higher dew points and more cloud cover will tend to suppress maximum temperatures, and keep wintertime temperatures elevated, especially at night. A substantial increase in precipitation has occurred over the last 11 decades. Precipitation during the fall has increased an average of 0.36 inches per decade (Knight, 2008).

The potential effects on groundwater recharge if these trends continue may include:

- Increases in winter temperatures, number of snowy days, and precipitation amounts may allow more groundwater recharge during the winter months;
- High-intensity rainfall may result in more runoff and reduced recharge, although the general increase in precipitation may offset the intense rainfall; and
- The lengthening of the growing season may reduce recharge as plants intercept more rainfall.

Depending on which factor is the most dominant, climate change could have a positive or negative effect on groundwater recharge.

GEOLOGY AND LAND COVER

Surface factors such as geology, soils, and land cover can affect how recharge occurs by controlling the amount and extent of diffuse, macropore, or preferential flow of infiltrating water (de Vries and Simmers, 2002). The influence of the surface factors is commonly scale dependent, meaning that they might be the principal factors controlling recharge at a local scale, but may not be statistically significant factors at a more regional scale.

On a statewide scale, Risser and others (2008) found that the geologic variables of percentage of carbonate bedrock and percentage of sand in the soil were significant factors in explaining groundwater recharge in the regression analyses. In Pennsylvania, higher percentages of these factors increased conditions that were favorable for infiltration of precipitation into the subsurface, thereby increasing groundwater recharge. Land-cover characteristics were not significant for the regression method on a statewide scale for HUC10 basins, but it is intuitive that land cover affects recharge patterns and amounts at certain scales.

On a local scale, favorable soil or geologic conditions also can have an effect in increasing groundwater recharge. Impervious cover can affect the hydrology of an area by limiting natural recharge. Soils that have a low permeability also will slow recharge at various scales.

RECHARGE VARIABILITY

Because of the intrinsic variability of climatic and surface conditions, variation in recharge rates can occur daily, seasonally, year to year, and over longer periods of time as climate and land-use patterns change. In fact, there is so much variability that exact hydrologic conditions never repeat, though patterns emerge as records are kept. Temporal fluctuations of recharge and discharge rates are normal and represent the dynamic balance between precipitation, infiltration, evaporation, transpiration, runoff, groundwater storage, withdrawal, and base-flow discharge. The season, precipitation timing, and rate of precipitation also will affect the rate of recharge. A slow steady rain is more likely to infiltrate to groundwater than a hard downpour that tends to become runoff.

Seasonal Variability

Despite the fairly even distribution of precipitation throughout the year, recharge is typically subject to a strong seasonal influence, caused primarily by variations in water lost via evapotranspiration. In general, the least amounts of recharge are received during summer months when high temperatures and lush vegetation promote high rates of evapotranspiration. During the summer, dry soil, hard ground surface, and thirsty plants can deflect precipitation before any recharge takes place. Frozen ground in the winter can produce the same results. On the other hand, episodes of steady precipitation across unfrozen ground, outside of the growing season, provide the most conducive circumstances for groundwater recharge. Thus, there are typical seasonal controls that affect recharge amounts.

In 2005, the U.S. Geological Survey (USGS) provided a detailed analysis of groundwater recharge at 197 basins in Pennsylvania using stream-gage data (Risser and others, 2005a). Table 1 shows an average of the percentages of recharge by month for the 197 basins. Based on the above report, March is typically the month with the most recharge. On average, over 40 percent of annual recharge occurs in spring (March, April, May). Over 80 percent of all recharge occurs from November through May. Recharge does not typically occur during a given growing season unless precipitation exceeds absorption by soil and vegetation, allowing water to infiltrate beyond the vadose zone.

Table 1. Seasonal and climatic variability of recharge (percent of annual total) in Pennsylvania (from Risser and others, 2005a).

Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.
10.1	10.2	11.4	18.4	12.9	9.1	4.5	3.4	2.8	3.6	5.0	8.7
	Winter			Spring			Summer			Fall	
	31.7			40.4			10.6			17.3	

Variability over the Years

From year to year, groundwater recharge can vary considerably. Calculations based on Risser and others (2005a) demonstrate that recharge in a wet year can be 3 – 5 times the amount of recharge in a dry year. In essence, the amount of recharge for a particular area ranges between periods of heavy precipitation (especially outside of the growing season) and times of low or no infiltration caused by the lack of precipitation and landcover conditions. The timing of precipitation thus plays a critical role.

Pennsylvania's climate has been subject to precipitation anomalies of wet and dry periods that typically are 28 – 34 months long. In the last 105 years, eight different wet or dry periods occurred over most of the state. Wet periods have been followed by a period of two years where the majority of months are drier than normal conditions (Knight, 2008).

Geographic Variability

Plate 3 demonstrates the geographic variability of recharge. Values range from about 7 to 22 inches. About 8 percent of Pennsylvania has less than 10 inches of annual recharge. Most of these basins are in the western part of the state, although a few are in south-central Pennsylvania. These areas are affected by low precipitation, high evapotranspiration, and soils that have little sand and lack carbonate rocks at the surface. About 3 percent of Pennsylvania receives over 20 inches of annual recharge. These areas are scattered about the state, and are typically zones of abundant rainfall at higher elevations.

Local Variability

Recharge on a local scale can be influenced by numerous factors including topography, the depth to the water table, and characteristics of the surface cover such as vegetation amounts and types, soil permeability, and percent of impervious surfaces. In addition, made-made sources of recharge such as sewage systems and pipelines can affect the calculation of recharge. Water moved from one basin to the next can substantially change the water budget in an area, including recharge amounts.

GROUNDWATER-RECHARGE ESTIMATES

Groundwater-recharge estimates are important elements of a water budget. In the absence of site-specific data, previous studies on a statewide or local basis can be used as a frame of reference or as initial estimates of recharge.

STATEWIDE ESTIMATES

Plate 3 provides statewide recharge estimates for HUC10 watersheds based on the USGS regression equation (Risser and others, 2008). Estimated values of groundwater recharge are intended for use on a HUC10 watershed basis. Most of the 339 watersheds are about 50 to 400 square miles. Forty-one basins, all representing fractional basins along the state border, are less than 50 square miles. Plate 3 can be used to develop regional water budgets and to provide estimates of groundwater recharge. The USGS regression equation also can be used to predict recharge where the characteristics of a basin are known although the basin is ungaged. Plate 3 should not be used to estimate recharge for site-specific locations. It is not intended for use at larger scales (i.e., more detailed) than the original scale of the map (1:2,000,000).

The variability and natural trends of hydrologic conditions, along with the limitations of the data, should be considered when using these (or any) estimates of groundwater-recharge amounts. Also, the regression equation assumes that base flow approximates recharge for a watershed, though that may not always be the case. The regression analysis does not account for heterogeneity within a watershed. Also, the recharge values shown on Plate 3 are long-term averages that do not represent the amount of recharge in any given year; thus, the map serves as a guide on geographic recharge variability and long-term rates.

Predicted Error of Estimates

The error of prediction is one aspect of variability for recharge on a watershed scale. Plate 4 shows the approximate average error range based on a comparison of the predicted recharge using the regression analysis and observed base flow. This error represents the 90-percent prediction interval (Risser and others, 2008). The approximate average error range is shown on Plate 4 because the regression equation was based on log-transformed values, which produced asymmetrical error ranges.

Percentage of Precipitation as Recharge

The patterns of statewide recharge are related to the precipitation amounts and the topography of the state. Prevailing wind directions and sources of moisture also have a strong impact on these patterns. It might be expected that the percent of precipitation that becomes recharge is relatively consistent across the state. However, this is not the case. In some areas, there is twice as much recharge as a percentage of precipitation than in other areas.

The percent of precipitation that becomes recharge (Plate 5) was calculated from the precipitation and estimated recharge values. Areas showing a lower percentage include the southeast and southwest, where it is likely that higher temperatures and a longer growing season draw off more moisture as evapotranspiration compared to other areas. These areas also are lower topographically and typically get less precipitation. Areas that receive greater precipitation are in higher terrain, where temperatures are cooler and evapotranspiration is less. Areas with high amounts of precipitation actually retain even more of a percentage of precipitation in the form of recharge than other areas.

OTHER ESTIMATES

Numerous groundwater reports have included estimates of groundwater recharge for specific areas of Pennsylvania. These recharge values represent different methods, periods of record, climatic conditions, and study scales. These data can be used to approximate the general variability of groundwater-recharge estimates. In general, estimates of recharge are based on the assumption that base flow approximates recharge. Note that, in most cases, Pennsylvania groundwater-recharge estimates in published reports are somewhat less than the statewide estimates in Risser and others (2008). This difference in recharge estimates is due mostly to the different methods used to compute base flow. In the statewide study, the base-flow separation program PART (Rutledge, 1993) yielded larger values than the local minimum method of Pettyjohn and Henning (1979), or similar methods that have been applied in Pennsylvania.

Local Estimates of Recharge or Base Flow

Local estimates of groundwater recharge or base flow are summarized from various previous studies in Table 2. The values are shown on Plate 6 in the approximate location of the studies. For more information about these local estimates, references to the original work are provided in Table 2. These site-specific values can be used to provide another approximation of recharge across Pennsylvania based on reported values of recharge.

Regional Recharge Estimates

Recharge values for Pennsylvania are shown as a base on Plate 6 using information from Wolock (2003), who estimated mean annual ("natural") groundwater recharge for the contiguous United States. Wolock interpolated recharge using point estimates of base flow and a 1-kilometer grid spacing. He assumed that long-term groundwater discharge is equal to recharge. The ratio of base flow to total flow (as a percentage) was multiplied by estimates of mean annual streamflow "runoff" for 1951-80 to estimate recharge. Wolock also assumed that the base-flow ratio characterizes the long-term, natural part of the ground-water discharge of streamflow.

Wolock emphasizes that the values are strictly for the long term, and qualifies the use of the results and method. He notes that actual recharge would be underestimated where groundwater is extracted by evapotranspiration or pumping, or if there was a substantial element of deep flow that bypassed the local water system. Also, actual base-flow ratios may be less where snowmelt is large, or where streams are regulated. Additional sources of error can occur where irrigation adds to recharge. Finally, site-specific recharge values are not expected to be accurate because of the generalization of data over time and space.

SUMMARY

This report provides a general overview of processes affecting recharge in Pennsylvania and discusses the estimates of recharge rates from a statewide study of Risser and others (2008). Maps show the spatial distribution of recharge on a HUC10 watershed basis, and illustrate some of the principal factors affecting its distribution. Estimates of recharge from numerous studies at various scales from national to local are also provided for comparison. Because estimates of recharge have considerable uncertainty, when possible, it is prudent to compare results from various studies using different methods.

Recharge rates in Pennsylvania are variable over time and space. Eighty percent of recharge in Pennsylvania occurs from November to May, with March typically having the greatest amount of recharge. Areas that receive the most recharge are typically those that get the most rainfall, have favorable surface conditions, and are less susceptible to the influences of high

Table 2. Local estimates of groundwater recharge or base flow included on Plate 6.

Plate 6 Key	Rate - inches per year	Location of Study	Years	Method	Term Used	Reference
1	13.6	Basin 3I, White Clay Creek near Landenberg, Chester County	No dates given	Water budget; low flow as base flow	Base-flow discharge	Lehigh University, 1982
2	8.5	Red Clay Creek near Kennett Square, Chester County	No dates given	Water budget; low flow as base flow	Base-flow discharge	Lehigh University, 1982
3	12.3	Neshaminy Creek watershed, which includes most of Basin 2F (predominantly underlain by Stockton Formation), Bucks County	No dates given	Water budget and composite recession-curve method	Base runoff	Lehigh University, 1982
4	12.5	Basin 1F, eastern edge of Great Valley, Martins Creek at East Bangor, Northampton County	No dates given	Interpreted water-budget information	Groundwater contribution to runoff	Lehigh University, 1982
5	16.6	Basin 2B, Carbon County, eastern Schuylkill County, and southwestern Monroe County	1969-1978	Base-flow estimation by composite recession curve of streamflow, Brune method	Recharge	Lehigh University, 1982
6	10.1	Basin 7A, Shermansdale area, Sherman Creek; includes Bixby Run (Johnston, 1973), Perry County	1955-1965	Composite recession curve of streamflow	Base flow	Lehigh University, 1982
7	11.2	Basin 2A, located mostly in the Pocono Plateau; Monroe, Carbon, Luzerne, Lackawanna, and Wayne Counties	1969-1978	Base-flow estimation by composite recession curve of streamflow, Brune method	Recharge	Lehigh University, 1982
8	16	Basin 1C, Pike and Wayne Counties; using Basin 1B as representative	1969-1978	Using basing 1B, base-flow estimation by composite recession curve of streamflow, Brune method	Recharge	Lehigh University, 1982
9	21	Basin 1D, Pike and Monroe Counties; using Bushkill Creek watershed as representative of entire basin	1969-1978	Base-flow estimation by composite recession curve of streamflow, Brune method	Recharge	Lehigh University, 1982
10	19	Basin 1B, central Wayne County, northern Pike County	1969-1978	Base-flow estimation by composite recession curve of streamflow, Brune method	Recharge	Lehigh University, 1982
11	15.5	Basin 4D, portions of Bradford, Susquehanna, and Wyoming Counties	1969-1978	Hydrograph base-flow separation	Recharge	Lehigh University, 1982
12	14	Basin 15,Erie and Crawford Counties; Conneaut Creek, Ohio, and Raccoon Creek, West Springfield	1922-1972; 1961-1972	Water-budget estimate – 60% of runoff	Recharge	Lehigh University, 1982
13	9	Stewartstown, York County	NA	Estimated with water budget for contributing area	Recharge	Barton and others, 1999
14	23.5	Coastal Plain, Delaware River Basin; includes Delaware, Philadelphia, and Bucks Counties	1921-50	Estimate based on base flow (using recession curves), and estimates of groundwater evapotranspiration and outflow percentages	Groundwater recharge or discharge	Parker and others, 1964
15	6	West Conewago Creek, Manchester, York County	1931-1976; 1966, 1972	Water-budget estimate, in which base flow was calculated as an average between a dry year (1966) and a wet year (1972), no actual method stated	Base flow as recharge	Wood, 1980
16	18.8	Bushkill, Monroe and Pike Counties	Average of 3 years: 1963, 1969, and 1973	Water budget and streamflow hydrographs (procedure by Linsley and others, 1958)	Recharge - groundwater contribution	Carswell and Lloyd, 1979
	19.6	Brodhead Creek, Monroe County				
	17.6	Lehigh River, Monroe, Lackawanna, and Wayne Counties				
	20.8	Tobyhanna Creek, Monroe County				
	19.2	Pohopoco Creek, Monroe County				
	18.1	Aquashicola Creek, Monroe County				
17	8.2	Bixler Run, Perry County	1955-1965	Hydrograph base-flow separation	Base flow	Johnston, 1973
18	15.3	Fishing Creek, western Columbia County, Catskill Formation	Average of 1964, 1970, and 1973	Hydrograph base-flow separation	Groundwater contribution to runoff (under "Recharge")	Williams and Eckhardt, 1987
	8.3	East Branch Chillisquaque Creek, Montour County, Devonian shales				
19	10.0	Juniata River at Newport	1945, 1947, 1949, 1953, 1958	Hydrograph base-flow separation; average over 5 different years	Groundwater discharge	Taylor and others, 1982
	11.6	Juniata River at Huntingdon				
	9.7	Raystown Branch of the Juniata River at Saxton				
	13.8	Kishacoquillas Creek at Reedsville				
	9.7	Tuscarora Creek at Port Royal				
20	15	Buried valley sediments, Susquehanna River, Luzerne County, between West Pittston and Kingston	No year given	Calculation of groundwater discharge to river	Recharge, based on discharge	Hollowell, 1971
21	19.2	Pike County, interpreting Bushkill basin as representative of the county	Average of 1965, 1970, and 1973	Hydrograph base-flow separation using method by Pettyjohn and Henning; plus interpretation of basin conditions	Groundwater discharge	Davis, 1989
22	21	Glacial drift valleys, Bradford and Tioga Counties, including valley floors and adjacent upland	None provided	Water-budget estimations	Recharge	Williams and others, 1998
23	12.4	Laurel Run basin, northeastern Cambria County	1983-1984	Hydrograph base-flow separation	Base flow	McElroy, 1998
	9.1	Little Laurel Run basin, northeastern Cambria County	1983-1984	Hydrograph base-flow separation	Base flow	
24	11.3	Stony Creek River basin, south-central Fayette County	1960-1993	Hydrograph base-flow separation using local minimum method (HYSEP)	Base flow	McElroy, 2000
	20.3	Blue Hole Creek basin along Laurel Hill, upper and lower basins, western Somerset County	1993-1995		Base flow	

Plate 6 Key	Rate - inches per year	Location of Study	Years	Method	Term Used	Reference
25	8.1	Cherry Run basin, central Indiana County	1987	Hydrograph base-flow separation using fixed interval method (HYSEP)	Groundwater discharge	Williams and McElroy, 1997
	12.4	Little Yellow Creek, eastern Indiana County				
	9.7	Little Mahoning Creek, northern Indiana County				
	11.5	South Branch Plum Creek, northern Indiana County				
26	15.8	West Branch Susquehanna at Karthaus, Clearfield County	1961-1980	Hydrograph base-flow separation	Groundwater discharge	Taylor and others, 1983
	12.7	Spring Creek near Axemann, Centre County	1961-1980			
	15.4	Lycoming Creek near Trout Run, Lycoming County	1961-1980			
27	8.0	South Fork Tenmile Creek, Greene County	1942, 1948, 1981	Base-flow separation from streamflow (average of 3 separate water years)	base flow	Stoner et al., 1987
	10.1	Enlow Fork, Green County	1980-1981			
28	11.1	Unit 1. Western Great Valley and Eastern Great Valley shales with substantial graywacke	Model calcs; stream years not given for base flow estimate for sub-basins	Groundwater modeling estimates of recharge for hydrogeologic units; based on streamflow and base-flow estimations using hydrograph-separation techniques, groundwater and surface-water conditions, and defined hydrogeologic unit characteristics	Recharge assumed to equal average annual base flow	Gerhart and Lazorchick, 1988
	14.3	Unit 2. Eastern Lebanon Valley carbonate rocks				
	11.6	Unit 3. Eastern Piedmont metamorphic rocks				
	15.8	Unit 4. Cumberland Valley carbonate rocks				
	7.1	Unit 5. Western Triassic sedimentary rocks				
	10.5	Unit 6. Eastern Triassic sedimentary rocks				
	10.5	Unit 7. Conestoga Valley carbonate rocks				
	6.7	Unit 8. Conestoga Valley metamorphic rocks west of Susquehanna River				
	14.7	Unit 9. Northern Conestoga Valley carbonate rocks east of Susquehanna River				
	10.1	Unit 10. Central Piedmont metamorphic rocks				
	10.1	Unit 11. Southern Piedmont metamorphic rocks				
	9.0	Unit 12. Great Valley shales on flanks of South Mountain				
	4.2	Unit 13. Combination unit of 5 and 6, and diabase				
	8.2	Unit 14. Combination unit of 7 and 8				
	11.1	Unit 15. Northern Conestoga Valley shales				
	14.1	Unit 16. Combination unit of 9 and 17				
	14.5	Unit 17. Southern Conestoga Valley metamorphic rocks east of Susquehanna River				
	4.0	Unit 18. Triassic conglomerates				
	5.0	Unit 19. Combination unit of 18 and 5 and 6				
	10.5	Unit 20. Western Lebanon Valley carbonate rocks				
	9.2	Unit 21. Eastern Great Valley shales, no substantial graywacke				
29	14.8	Yellow Breeches Creek, near Shippensburg, Cumberland and Franklin Counties	1912-1916, 1955-1958, and 1968-2003	Hydrograph separation	Base flow as Recharge	Lindsey, 2005
	9.5	Conodoguinet Creek, near Shippensburg, Cumberland and Franklin Counties				
30	9.5-13	Martinsburg area, southern Blair County	NA	Selected groundwater model MODFLOW recharge values; based on local base-flow values and similar hydrogeology	Modeled Recharge	Lindsey and Koch, 2004
31	13.0	Kishacoquillas Creek, at Reedsville, Mifflin County	1941-1970	Hydrograph separation – fixed interval method	Base flow (groundwater discharge)	Becher, 1996
32	8.3	Lansdale area, Montgomery County	Aug 1996 flow condition	Calibrated groundwater model; estimated by adding base flow and volumes of groundwater pumped	Recharge	Senior and Goode, 1999
33	7-19	Northern portion, Pocono Creek watershed, Monroe County	October 2004	Calibrated numerical groundwater-flow model for subwatersheds	Recharge	Sloto, 2008
	19-27	Southern portion, Pocono Creek watershed, Monroe County				
34	11.3-13.0	Big Elk Creek basin, Chester County, and into Maryland	1998-1999	Water budgets equation and estimates	Recharge	Sloto, 2002
35	14.3	French Creek basin, northern Chester and southern Berks Counties	1969-2001	Water budgets equation and estimates	Recharge	Sloto, 2004
36	5.9-26.6 (statewide range)	Statewide – at specified stream gage locations; values are color coded on Map 8	Various	PART hydrograph-separation method	Base flow	Risser and others, 2005a
37	7.7-29.3 (statewide range)	Statewide – at specified stream gage locations; values are color coded on Map 8	Various	RORA recession-curve-displacement method	Recharge	Risser and others, 2005a

Plate 6 Key	Rate - inches per year	Location of Study	Years	Method	Term Used	Reference
38	15.1	Spring Creek Basin, Centre County	1968-2002	Local-minimum method of hydrograph separation of base flow	Groundwater Recharge	Fulton and others, 2005
39	15.8	East Mahantango Creek at Klingerstown, Schuylkill County	1968-2001	Rorabaugh equations with RORA	Recharge	Risser and others, 2005b
39	10.3	East Mahantango Creek at Klingerstown, Schuylkill County	1968-2001	HYSEP hydrograph-separation program – local minimum	Base flow	Risser and others, 2005b
39	11.9	East Mahantango Creek at Klingerstown, Schuylkill County	1968-2001	HYSEP hydrograph-separation program – sliding interval	Base flow	Risser and others, 2005b
39	11.8	East Mahantango Creek at Klingerstown, Schuylkill County	1968-2001	HYSEP hydrograph-separation program – fixed interval	Base flow	Risser and others, 2005b
39	12.7	East Mahantango Creek at Klingerstown, Schuylkill County	1968-2001	PART hydrograph-separation program	Base flow	Risser and others, 2005b
40	15.6	East Mahantango Creek near Dalmatia, Northumberland County	1968-2001	Rorabaugh equations with RORA	Recharge	Risser and others, 2005b
40	10.8	East Mahantango Creek near Dalmatia, Northumberland County	1968-2001	HYSEP hydrograph-separation program – local minimum	Base flow	Risser and others, 2005b
40	12.3	East Mahantango Creek near Dalmatia, Northumberland County	1968-2001	HYSEP hydrograph-separation program – sliding interval	Base flow	Risser and others, 2005b
40	12.2	East Mahantango Creek near Dalmatia, Northumberland County	1968-2001	HYSEP hydrograph-separation program – fixed interval	Base flow	Risser and others, 2005b
40	12.9	East Mahantango Creek near Dalmatia, Northumberland County	1968-2001	PART hydrograph-separation program	Base flow	Risser and others, 2005b
41	15	Bushkill Creek watershed and parts of Monocacy Creek watersheds, Northampton County	Base measure Jul 2005; base flow 1967-2005	Estimated recharge for groundwater-flow model; within range of PART and RORA estimates	Recharge	Risser, 2006
42	9.2 – 10.5	Swatara Creek basin, Dauphin, Lebanon, Berks, and Schuylkill Counties, Hydrologic zone 1	1920-1960	Recession hydrographs, empirical formulas for ground-water discharge, and flow-duration data	Groundwater discharge	Stuart and others, 1967
42	7.7 – 10.3	Hydrologic zone 2	1920-1960	Recession hydrographs, empirical formulas for ground-water discharge, and flow-duration data	Groundwater discharge	Stuart and others, 1967
42	8.6 – 9.9	Hydrologic zone 3	1920-1960	Recession hydrographs, empirical formulas for ground-water discharge, and flow-duration data	Groundwater discharge	Stuart and others, 1967
42	6.7 – 9.2	Hydrologic zone 4	1920-1960	Recession hydrographs, empirical formulas for ground-water discharge, and flow-duration data	Groundwater discharge	Stuart and others, 1967
42	6.7 – 8.0	Hydrologic zone 5	1920-1960	Recession hydrographs, empirical formulas for ground-water discharge, and flow-duration data	Groundwater discharge	Stuart and others, 1967
42	7.4 – 8.2	Hydrologic zone 6	1920-1960	Recession hydrographs, empirical formulas for ground-water discharge, and flow-duration data	Groundwater discharge	Stuart and others, 1967
42	8.6 – 12.6	Hydrologic zone 7	1920-1960	Recession hydrographs, empirical formulas for ground-water discharge, and flow-duration data	Groundwater discharge	Stuart and others, 1967
42	11.3 – 12.6	Hydrologic zone 8	1920-1960	Recession hydrographs, empirical formulas for ground-water discharge, and flow-duration data	Groundwater discharge	Stuart and others, 1967
43	12.3	Jordan Creek Watershed, Lehigh County	1951-2000	Hydrological Evaluation of Landfill Performance (HELP) water-budget model simulating landscape units	Recharge	Risser, 2008
44	12.2 – 12.3	Masser Site watershed, East Mahantango Creek watershed, Northumberland County	1968-2001	Range of recharge values from different methods	Recharge	Risser and others, 2005b
44	12.2	Masser (not included on Plate 6)	1994-2001	unsaturated-zone drainage collected in gravity lysimeters	Recharge	Risser and others, 2005b
44	12.3	Masser (not included on Plate 6)	1994-2001	Daily water balance (HELP3 model)	Recharge	Risser and others, 2005b
44	9.0 – 15.8	WE-38 watershed, East Mahantango Creek watershed, Northumberland County	1968-2001	Range of recharge and base-flow values from different methods	Recharge and base flow	Risser and others, 2005b
44	11.7	WE-38 (not included on Plate 6)	1968-2001	Daily water balance (HELP3 model)	Recharge	Risser and others, 2005b
44	9.9	WE-38 (not included on Plate 6)	1994-2001	water-table fluctuations in wells	Recharge	Risser and others, 2005b
44	15.8	WE-38 (not included on Plate 6)	1968-2001	Rorabaugh equations with RORA	Recharge	Risser and others, 2005b
44	14.0	WE-38 (not included on Plate 6)	1994-2001	Rorabaugh equations with RORA	Recharge	Risser and others, 2005b
44	10.2	WE-38 (not included on Plate 6)	1994-2001	Rorabaugh equations with PULSE	Recharge	Risser and others, 2005b
44	9.0	WE-38 (not included on Plate 6)	1994-2001	HYSEP hydrograph-separation program – local minimum	Base flow	Risser and others, 2005b
44	11.5	WE-38 (not included on Plate 6)	1994-2001	HYSEP hydrograph-separation program – sliding interval	Base flow	Risser and others, 2005b
44	11.6	WE-38 (not included on Plate 6)	1994-2001	HYSEP hydrograph-separation program – fixed interval	Base flow	Risser and others, 2005b
44	10.7	WE-38 (not included on Plate 6)	1994-2001	PART hydrograph-separation program	Base flow	Risser and others, 2005b
44	10.2	WE-38 (not included on Plate 6)	1968-2001	HYSEP hydrograph-separation program – local minimum	Base flow	Risser and others, 2005b
44	13.1	WE-38 (not included on Plate 6)	1968-2001	HYSEP hydrograph-separation program – fixed interval	Base flow	Risser and others, 2005b
44	13.1	WE-38 (not included on Plate 6)	1968-2001	HYSEP hydrograph-separation program – sliding interval	Base flow	Risser and others, 2005b
44	12.3	WE-38 (not included on Plate 6)	1968-2001	PART hydrograph-separation program	Base flow	Risser and others, 2005b
45	5.3	Mesozoic lowlands of the Monocacy River and Catoctin Creek basins; Adams County part of study area and into Maryland	1960-2002	Estimated groundwater-recharge values using base-flow statistics and multiple regression analysis applied to hydrogeomorphic subbasins (2-year recurrence interval)	Recharge	Schultz and others, 2005
45	8.5	Blue Ridge portion of the Monocacy River and Catoctin Creek basins; Adams County part of study area into Maryland	1960-2002	Estimated groundwater-recharge values using base-flow statistics and multiple regression analysis applied to hydrogeomorphic subbasins (2-year recurrence interval)	Recharge	Schultz and others, 2005

Plate 6 Key	Rate - inches per year	Location of Study	Years	Method	Term Used	Reference
46	14.4	Delaware County, based on Chester, Darby Creek, and Cobbs basins	1960-2002	Estimated groundwater recharge from hydrograph separations; based on an average of 4 gaging stations in Delaware County for a "normal" water year; report includes values by gages	Recharge	Balmer and Davis, 1996
47	10.9	Redstone Creek basin, western Fayette County	1947, 1959, 1967	Water-budget calculations	Base flow as groundwater availability	McElroy, 1988
	15.4	Stony Fork basin, eastern Fayette County	1978-1980			
48	10.3	Towanda Creek Basin, Bradford County (primarily Lock Haven Formation)	1961-1980	Hydrograph base-flow separation	Groundwater discharge as base flow, and as recharge to specific rock units	Taylor, 1984
	14.2	Wapwollopen Creek basin, Luzerne County (Valley and Ridge sandstone and shale)	1961-1980			
	12.0	Tunkhannock Creek basin, Lackawanna Susquehanna, and Wyoming Counties (primarily Catskill Formation)	1961-1980			
49	11	Lebanon County	NA	Approximate annual average for county based on water-budget information	Groundwater discharge	Royer, 1983
50	12.4	Shales, Conodoguinet Creek basin, Cumberland County	1968-1974	Streamflow analysis and water-budget information	Groundwater discharge	Becher and Root, 1981
	18.1	Carbonate rocks, Conodoguinet Creek basin, Cumberland County				
51	11.3	Back Creek basin, Franklin County (Martinsburg Formation)	1977-1978	Streamflow analysis and water-budget information	Groundwater discharge	Becher and Taylor, 1982
	14.1	Antietam Creek basin, Franklin County	1966-1978			
	13.2	Conococheague Creek basin, Franklin County	1966-1978			

temperatures and thus evapotranspiration. Areas that have less recharge in Pennsylvania are typically those with less precipitation, less permeable soils, and higher temperatures that are conducive to greater rates of evapotranspiration.

In summary, any assessment of groundwater recharge should consider the inherent variability of natural processes and prediction methods. The use of predicted recharge must consider the variability of the parameters in terms of equation sensitivity and error associated with the regression equation. Recharge is nearly impossible to measure directly, so many different techniques have been applied for estimating its magnitude. Consideration should be given to specific methods and assumptions that are used when applying recharge values for a specific area.

REFERENCES

American Institute of Professional Geologists, 2005, Global climate change, AIPG Fact Sheet FS-04-004, 2 p.

Balmer, W. T., and Davis, D. K., 1996, Groundwater resources of Delaware County, Pennsylvania, Pennsylvania Geological Survey, 4th Ser., Water Resource Report 66, 67 p.

Barton, G. J., Risser, D. W., Galeone, D. G., and Conger, R. W., 1999, Case study for delineating a contributing area to a water-supply well in a fractured crystalline-bedrock aquifer, Stewartstown, Pennsylvania, USGS Water Resources Investigations Report 99-4047.

Becher, A. E., 1996, Ground-water resources of Cambrian and Ordovician carbonate rocks in the Valley and Ridge Physiographic Province of Pennsylvania: U.S. Geological Survey Open-File Report 90-109, 134 p.

Becher, A. E., and Root, S. I., 1981, Groundwater and geology of the Cumberland Valley, Cumberland County, Pennsylvania, Pennsylvania Geological Survey, 4th Ser., Water Resource Report 50, 95 p.

Becher, A. E., and Taylor, L. E., 1982, Groundwater resources in the Cumberland and contiguous Valleys of Franklin County, Pennsylvania, Pennsylvania Geological Survey, 4th Ser., Water Resource Report 53, 67 p.

Carswell, L. D., and Lloyd, B. L., 1979, Geology and groundwater resources of Monroe County, Pennsylvania, Pennsylvania Geological Survey, 4th Ser., Water Resource Report 47, 60 p.

Davis, D. K., 1989, Groundwater resources of Pike County, Pennsylvania, Pennsylvania Geological Survey, 4th Ser., Water Resource Report 65, 63 p.

Delin G. N., and Risser, D. W., 2007, Ground-water recharge in humid areas of the United States—a summary of ground-water resources program studies, 2003-06, U.S. Geological Survey Fact Sheet 2007-3007, 4 p., pubs.usgs.gov/fs/2007/3007 (accessed on August 4, 2009).

de Vries, J. J., and Simmers, I., 2002, Groundwater recharge: an overview of processes and challenges, Hydrogeology Journal, vol. 10., p 5-17.

Fleeger, G. M., 1999, The geology of Pennsylvania's groundwater, Pennsylvania Geological Survey, 4th Ser., Educational Series 3, 34 p., www.dcnr.state.pa.us/topogeo/education/es3.pdf (accessed on May 8, 2009).

Fulton, J. W., Koerkle, E. H., McAuley, S. D., Hoffman, S. A., and Zarr, L. F., 2005, Hydrogeologic setting and conceptual hydrologic model of the Spring Creek Basin, Centre County, Pennsylvania, June 2005: U.S. Geological Survey Scientific Investigations Report 2005-5091, 83 p., pubs.usgs.gov/sir/2005/5091/sir2005-5091.pdf (accessed on August 3, 2009).

Gerhart, J. M., and Lazorchick, G. J., 1988, Evaluation of the ground-water resources of the lower Susquehanna River Basin: U.S. Geological Survey Water-Supply Paper 2284, 128 p., pubs.er.usgs.gov/usgspubs/wsp/wsp2284 (accessed on August 3, 2009).

Hantush, M. M., 2006, Impact of urbanization on the hydrology of Pocono Creek Watershed: A model study: Environmental Protection Agency report EPA/600/R-07/006, 57 p.

Heath, R. C., 1983, Basic ground-water hydrology: U.S. Geological Survey Water-Supply Paper 2220, 84 p.

Hollowell, J. R., 1971, Hydrology of the Pleistocene sediments in the Wyoming Valley, Luzerne County, Pennsylvania, Pennsylvania Geological Survey, 4th Ser., Water Resource Report 28, 77 p.

Johnston, H. E., 1970, Ground-water resources of the Loysville and Mifflintown quadrangles in south-central Pennsylvania, Pennsylvania Geological Survey, 4th Ser., Water Resource Report 27, 96 p.

Knight, P., 2008, Pennsylvania's changing climate, Pennsylvania State Climate Office, talk given April 14, 2008, Rachel Carson State Office Building, Harrisburg, Pa.

Lehigh University, 1982, Aquifer designation study: ground-water basins, Volumes 1-4, Department of Environmental Resources Project No. ME79506, 1205 p.

Lindsey, B. D., and Koch, M. L., 2004, Determining sources of water and contaminants to wells in a carbonate aquifer near Martinsburg, Blair County, Pennsylvania, by use of geochemical indicators, analysis of anthropogenic contaminants, and simulation of ground-water flow: U.S. Geological Survey Scientific Investigations Report 2004-5124, 46 p., pubs.usgs.gov/sir/2004/5124/pdf/sir2004-5124.pdf (accessed on August 4, 2009).

Lindsey, B. D., 2005, Hydrogeology and simulation of source areas of water to production wells in a colluvium-mantled carbonate-bedrock aquifer near Shippensburg, Cumberland and

Franklin Counties, Pennsylvania: U.S. Geological Survey Scientific Investigations Report 2005-5195, 49 p., pubs.usgs.gov/sir/2005/5195/sir2005-5195.pdf (accessed on August 3, 2009).

McElroy, T. A., 1988, Groundwater resources of Fayette County, Pennsylvania, Pennsylvania Geological Survey, 4th Ser., Water Resource Report 60, 57 p.

McElroy, T. A., 1998, Groundwater resources of Cambria County, Pennsylvania, Pennsylvania Geological Survey, 4th Ser., Water Resource Report 67, 49 p.

McElroy, T. A., 2000, Groundwater resources of Somerset County, Pennsylvania, Pennsylvania Geological Survey, 4th Ser., Open-File Report 2000-02.

Parker, G. G. , Hely, A. G., Keigliton, W. B., Olmsted, F. H., and others, 1964, Water resources of the Delaware River basin, U.S. Geological Survey Professional Paper 381, 200 p., pa.water.usgs.gov/reports/pp_381.html (accessed October 29, 2009).

Pennsylvania State Climatologist, 2007, Pennsylvania wind roses: Wind roses for 11 secondary Pennsylvania airports, climate.met.psu.edu/features/_PA_WIND_ROSES/windrose.php (accessed November 19, 2009).

Pettyjohn, W. A., and Henning, R., 1979, Preliminary estimate of ground-water recharge rates, related streamflow and water quality in Ohio: Ohio State University Water Resources Center Project Completion Report Number 552, 323 p.

PRISM Group, 2006, United States average monthly or annual precipitation, 1971–2000: Oregon State University, digital dataset: www.prismclimate.org (accessed July 13, 2009).

Risser, D. W., 2006, Simulated water budgets and ground-water/surface-water interactions in Bushkill and parts of Monocacy Creek watersheds, Northampton County, Pennsylvania—A preliminary study with identification of data needs: U.S. Geological Survey Open-File Report 2006-1143, 31 p., pubs.usgs.gov/of/2006/1143/pdf/ofr2006-1143.pdf (accessed on August 3, 2009).

Risser, D. W., 2008, Spatial distribution of ground-water recharge estimated with a water-budget method for the Jordan Creek watershed, Lehigh County, Pennsylvania: U.S. Geological Survey Scientific Investigations Report 2008-5041, 26 p., pubs.usgs.gov/sir/2008/5041/pdf/sir2008-5041.pdf (accessed on August 3, 2009).

Risser, D. W., Conger, R. W., Ulrich, J. E., and Asmussen, M. P., 2005a, Estimates of ground-water recharge based on streamflow-hydrograph methods: Pennsylvania: U.S. Geological Survey Open-File Report 2005-1333, 30 p., pa.water.usgs.gov/recharge (accessed May 7, 2009).

Risser, D. W., Gburek, W. J., and Folmar, G. J., 2005b, Comparison of methods for estimating ground-water recharge and base flow at a small watershed underlain by fractured bedrock in the eastern United States: U.S. Geological Survey Scientific Investigations Report 2005-5038, 31 p., pubs.usgs.gov/sir/2005/5038/pdf/sir2005-5038.pdf (accessed July 8, 2009).

Risser, D. W., Thompson, R. E., and Stuckey, M. H., 2008, Regression method for estimating long-term mean annual ground-water recharge rates from base flow in Pennsylvania: U.S. Geological Survey Scientific Investigations Report 2008-5185, 23 p., pubs.usgs.gov/sir/2008/5185/ (accessed July 13, 2009).

Royer, D. W., 1983, Groundwater resources of Lebanon County, Pennsylvania, Pennsylvania Geological Survey, 4th Ser., Water Resource Report 55, 84 p.

Rutledge, A. T., 1993, Computer programs for describing the recession of ground-water discharge and for estimating mean ground-water recharge and discharge from streamflow records: U.S. Geological Survey Water-Resources Investigations Report 93-4121, 45 p.

Scanlon, B. R., Healy, R. W., and Cook, P. G., 2002, Choosing appropriate techniques for quantifying groundwater recharge: Hydrogeology Journal, v. 10, p. 18-39.

Schultz, C., Tipton, D., Palmer, J., 2005, Annual and seasonal water budgets for the Monocacy/ Catoctin drainage area - final report, Interstate Commission on the Potomac River Basin, ICPRB Report No. 04-04, 56 p.

Senior, L. A., and Goode, D. J., 1999, Ground-water system, estimation of aquifer hydraulic properties, and effects of pumping on ground-water flow in Triassic sedimentary rocks in and near Lansdale, Pennsylvania: U.S. Geological Survey Water-Resources Investigations Report 99-4228, 112 p., pa.water.usgs.gov/reports/wri994228 (accessed on August 4, 2009).

Sevon, W. D., 2000, Physiographic provinces of Pennsylvania, Pennsylvania Geological Survey, 4th Ser., Map 13, scale 1:2,000,000, www.dcnr.state.pa.us/topogeo/maps/map13.pdf (accessed July 13, 2009).

Sloto, R. A., 2008, Effects of land-use changes and ground-water withdrawals on stream base flow, Pocono Creek watershed, Monroe County, Pennsylvania: U.S. Geological Survey Scientific Investigations Report 2008-5030, 38 p.

Sloto, R. A., 2004, Geohydrology of the French Creek basin and simulated effects of drought and ground-water withdrawals, Chester County, Pennsylvania, USGS Water-Resources Investigations Report 03-4263, 82 p.

Sloto, R. A., 2002, Ground-water resources of Big Elk Creek Basin, Pennsylvania and Maryland: U.S. Geological Survey Fact Sheet 019-02, 6 p.

Stuart, W. T., Schneider, W. J., and Crooks, J. W., 1967, Swatara Creek basin of southeastern Pennsylvania, an evaluation of its hydrologic system, U.S. Geological Survey Water-Supply Paper 1829, 79 p._

Stoner J. D., Williams D. R., Buckwalter T. F., Felbinger, J. K., and Pattison, K. L., 1987, Water resources and the effects of coal mining, Greene County, Pennsylvania, U. S. Geological Survey and Pennsylvania Geological Survey, 4th Ser., Water Resource Report 63, 166 p.

Taylor, L. E., Werkheiser, W. H. duPont, N. S., and Kriz, M. L., 1982, Groundwater resources of the Juniata River basin, Pennsylvania, Pennsylvania Geological Survey, 4th Ser., Water Resource Report 54, 131 p.

Taylor, L. E., Werkheiser, W. H., and Kriz, M. L., 1983, Groundwater resources of the West Branch Susquehanna River basin, Pennsylvania: Pennsylvania Geological Survey, 4th ser., Water Resource Report 56, 143 p.

Taylor, L. E., 1984, Groundwater resources of the Upper Susquehanna River basin, Pennsylvania, Pennsylvania Geological Survey, 4th Ser., Water Resource Report 58, 136 p.

Theis, C. V., 1940, The source of water derived from wells: Essential factors controlling the response of an aquifer to development, Civil Engineering, vol. 10, no. 5, p. 277-280.

U.S. Geological Survey, 2009, References, methods for estimating groundwater recharge in humid regions, online table, water.usgs.gov/ogw/gwrp/methods/references/ (accessed July 13, 2009).

U.S. Geological Survey and U.S. Department of Agriculture, Natural Resources Conservation Service, 2009, Federal guidelines, requirements, and procedures for the national Watershed Boundary Dataset: U.S. Geological Survey Techniques and Methods 11–A3, 55 p., ftp://ftp-fc.sc.egov.usda.gov/NCGC/products/watershed/hu-standards.pdf (accessed October 9, 2009).

Williams, D. R. and McElroy, T. A., 1997, Water resources of Indiana County, U. S. Geological Survey Water-Resources Investigations Report 95-4164, 105 p., 2 plates.

Williams, J. H., Taylor, L. E., and Law, D. J., 1998, Hydrogeology and groundwater quality of the glaciated valleys of Bradford, Tioga, and Potter Counties, Pennsylvania, Pennsylvania Geological Survey, 4th Ser., Water Resource Report 68, 89 p.

Williams, J. H. and Eckhardt, D. A., 1987, Groundwater resources of the Berwick-Bloomsburg-Danville area in east-central Pennsylvania, U.S. Geological Survey and Pennsylvania Geological Survey, Water Resource Report 61, 76 p.
Wolock, D. M., 2003, Estimated mean annual natural ground-water recharge in the conterminous United States: U.S. Geological Survey Open-File Report 03–311, digital data set: water.usgs.gov/lookup/getspatial?rech48grd (accessed July 13, 2009).
Wood, C. R., 1980, Groundwater resources of the Gettysburg and Hammer Creek Formations, southeastern Pennsylvania, Pennsylvania Geological Survey, 4th Ser., Water Resource Report 49, 87 p.
Wolock, D. M., 2003, Estimated mean annual natural ground-water recharge in the conterminous United States: U.S. Geological Survey Open-File Report 03–311, digital data set: water.usgs.gov/lookup/getspatial?rech48grd (accessed July 13, 2009).

ACKNOWLEDGMENTS

This report was prepared in cooperation with the U.S. Geological Survey, Pennsylvania Water Science Center, New Cumberland, Pennsylvania. Plate 3 is based on the regression equation used in Scientific Investigations Report 2008-5185 by Dennis W. Risser, Ronald E. Thompson, and Marla H. Stuckey: *Regression Method for Estimating Long-Term Mean Annual Ground-Water Recharge Rates from Base Flow in Pennsylvania*, 2008, available online at pubs.usgs.gov/sir/2008/5185. HUC 10 boundaries, released after the 2008 report, were used with the regression equation to generate the updated recharge values of Plate 3.

The authors gratefully acknowledge the assistance of the following: Tammy Zimmerman, U.S. Geological Survey; Nathan Morrow (intern), Gary Fleeger, Kristin Carter, and John Harper of the Pennsylvania Geological Survey.

PLATE CREDITS

All or Multiple Plates

- Cartography and design of plates by Stuart O. Reese of the Pennsylvania Geological Survey, 2009
- Coordinate system for plates is Albers equal area conic projection, standard parallels 40ºN and 42ºN, and center 78º W., North American Datum 1983, scale 1:2,000,000
- County boundaries from Pennsylvania Department of Transportation dataset, 2009
- Physiographic sections boundaries based on unpublished datasets, Pennsylvania Geological Survey, 2002
- Shaded relief developed from modified 30-meter Digital Elevation Model data for Pennsylvania, National Elevation Dataset layer, 1999

Plate 1

- Resultant wind vectors, wind rose data, and station locations for 11 regional airports from the Pennsylvania State Climatologist, 2007, climate.met.psu.edu/_www_prod/features/wind_roses/ [accessed July 29, 2009]
- Precipitation data derived from "Parameter-elevation Regressions on Independent Slopes Model" by PRISM Group, 2006, Oregon State University, www.prismclimate.org [accessed April 29, 2009]

Plate 2

- Temperature data derived from "Parameter-elevation Regressions on Independent Slopes Model" by PRISM Group, 2006, Oregon State University, www.prismclimate.org [accessed April 29, 2009]

Plate 3

- Groundwater recharge data based on revised calculations from regression equation published in Risser and others, 2008b, pubs.usgs.gov/sir/ 2008/5185 (accessed November 20, 2009)

Plate 4

- Approximate average error of recharge values based on revised calculations from regression equation published in Risser and others, 2008b, pubs.usgs.gov/sir/2008/5185 (accessed November 20, 2009)

Plate 5

- Mean annual groundwater recharge as a percentage of precipitation based on precipitation data and recharge values of HUC10 watersheds

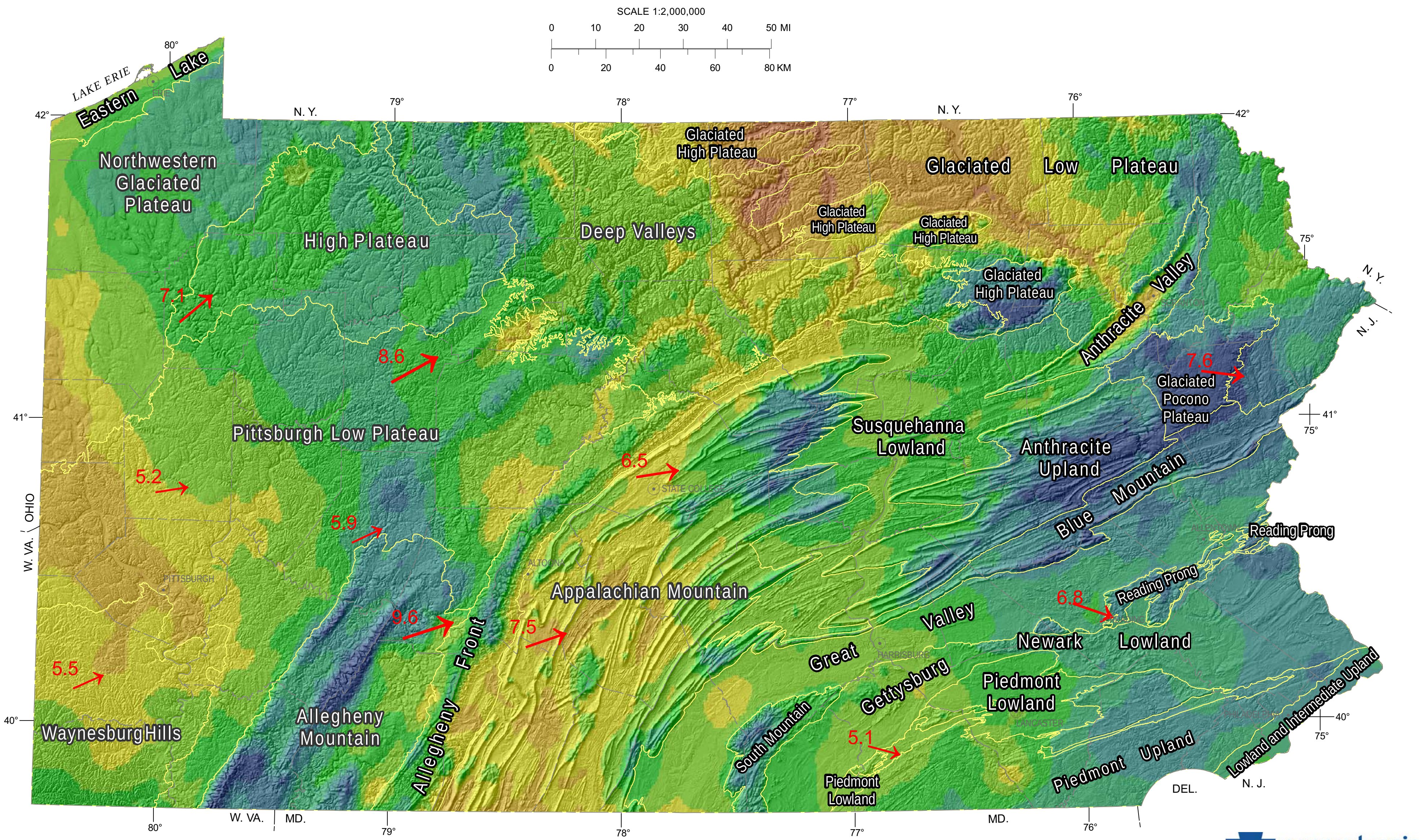
Plate 6

- Recharge and base flow values from various groundwater reports in Table 2
- Basemap of recharge values from Wolock, 2003

WATER RESOURCES REPORT 70
PLATE 1

PRECIPITATION, PHYSIOGRAPHY, AND PREVAILING WIND DIRECTIONS OF PENNSYLVANIA

COMMONWEALTH OF PENNSYLVANIA
DEPARTMENT OF
CONSERVATION AND NATURAL RESOURCES
BUREAU OF TOPOGRAPHIC AND GEOLOGIC SURVEY
www.dcnr.state.pa.us/topogeo



MEAN ANNUAL PRECIPITATION (1971 - 2000, INCHES)

31.38 - 33
33.01 - 35
35.01 - 37
37.01 - 39
39.01 - 41
41.01 - 43
43.01 - 45
45.01 - 47
47.01 - 49
49.01 - 51
51.01 - 64

7.1 Resultant airport wind vector (1991 - 2005) and average wind speed (miles per hour)

Resultant wind vectors from wind rose data for 11 regional airports, Pennsylvania State Climatologist, 2007, climate.met.psu.edu/www_prod/features/wind_roses/ (accessed November 19, 2009].
Precipitation data derived from PRISM Group, 2006, Oregon State University, www.prismclimate.org (accessed April 29, 2009).

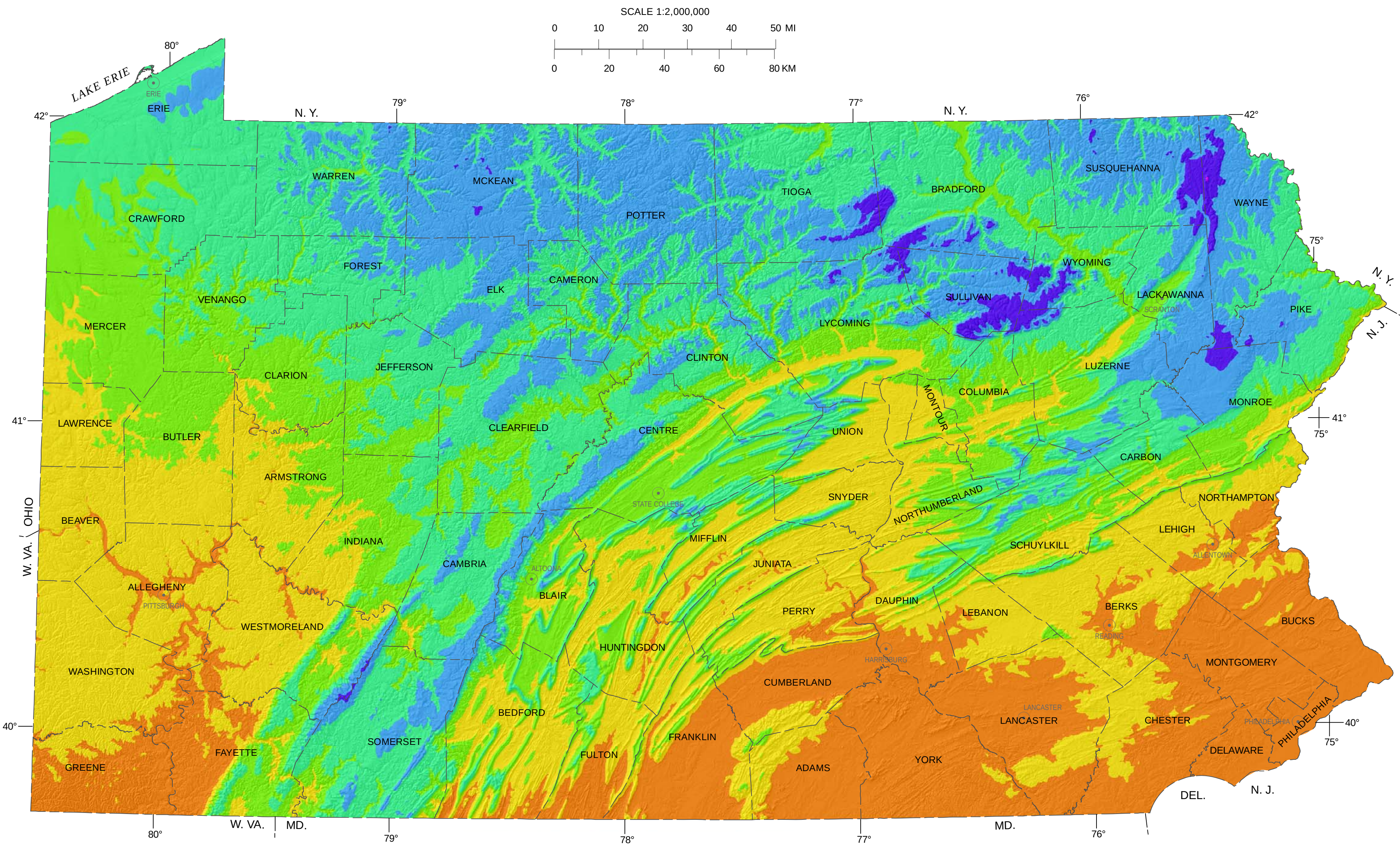
pennsylvania
DEPARTMENT OF CONSERVATION AND NATURAL RESOURCES

USGS
science for a changing world

WATER RESOURCES REPORT 70
PLATE 2

AVERAGE DAILY MAXIMUM TEMPERATURE (DEGREES FAHRENHEIT), 1971 – 2000

COMMONWEALTH OF PENNSYLVANIA
DEPARTMENT OF
CONSERVATION AND NATURAL RESOURCES
BUREAU OF TOPOGRAPHIC AND GEOLOGIC SURVEY
www.dcnr.state.pa.us/topogeo



MEAN ANNUAL TEMPERATURE (DEGREES FARHENHEIT)

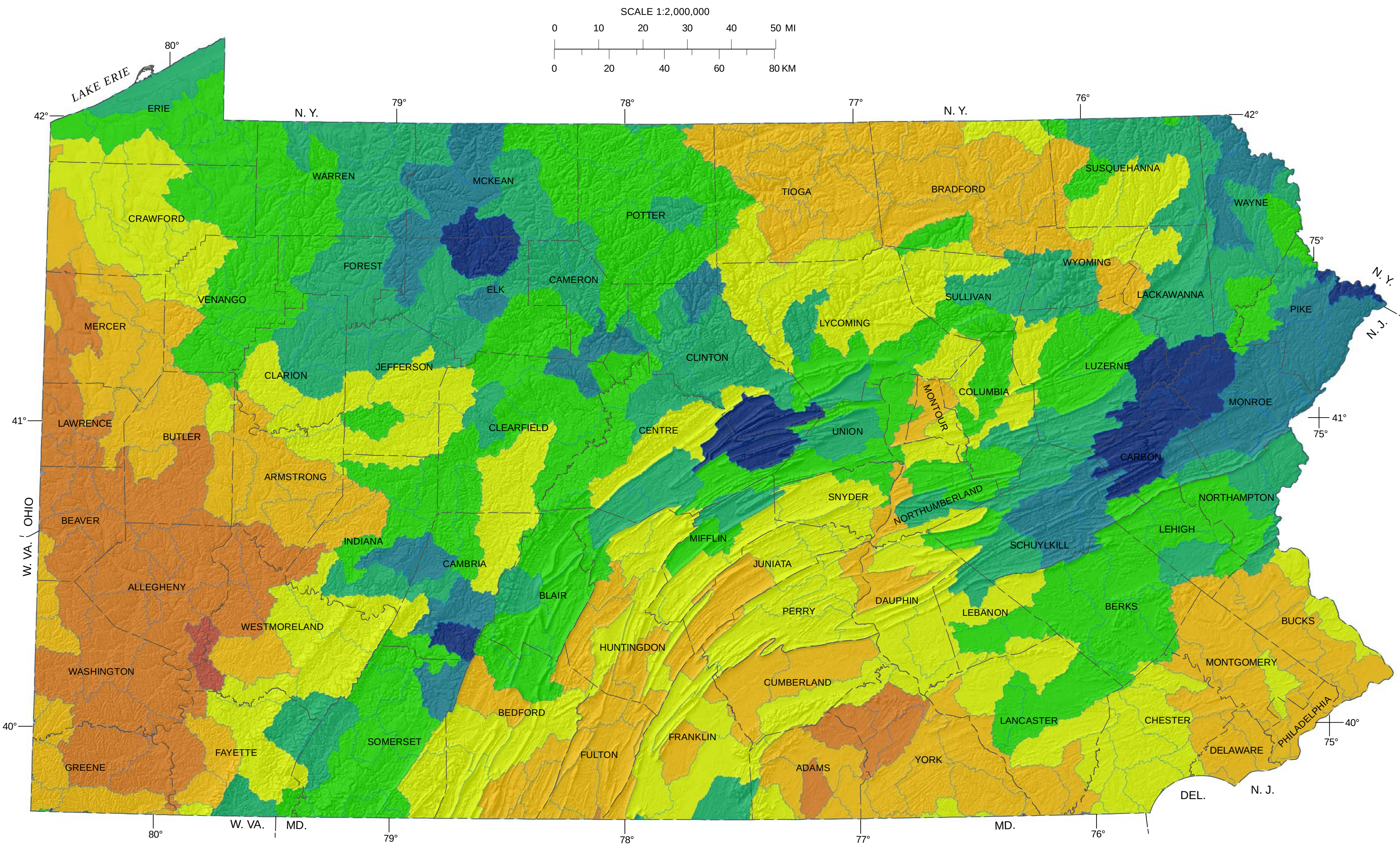
- 49.7 - 52
- 52.1 - 54
- 54.1 - 56
- 56.1 - 58
- 58.1 - 60
- 60.1 - 62
- 62.1 - 65.1

Temperature data derived from "Parameter-elevation Regressions on Independent Slopes Model" by PRISM Group, 2006, Oregon State University, www.prismclimate.org (accessed April 29, 2009).

WATER RESOURCES REPORT 70
PLATE 3

COMMONWEALTH OF PENNSYLVANIA
DEPARTMENT OF
CONSERVATION AND NATURAL RESOURCES
BUREAU OF TOPOGRAPHIC AND GEOLOGIC SURVEY
www.dcnr.state.pa.us/topogeo

MEAN ANNUAL GROUNDWATER-RECHARGE ESTIMATES OF PENNSYLVANIA WATERSHEDS, 1971 – 2000



MEAN ANNUAL RECHARGE (INCHES)

- 7.31 - 8
- 8.01 - 10
- 10.01 - 12
- 12.01 - 14
- 14.01 - 16
- 16.01 - 18
- 18.01 - 20
- 20.01 - 22.21

Groundwater recharge data based on revised calculations from regression equation published in Risser and others, 2008a, pubs.usgs.gov/sir/2008/5185 (accessed November 20, 2009).

Hydrologic unit boundary

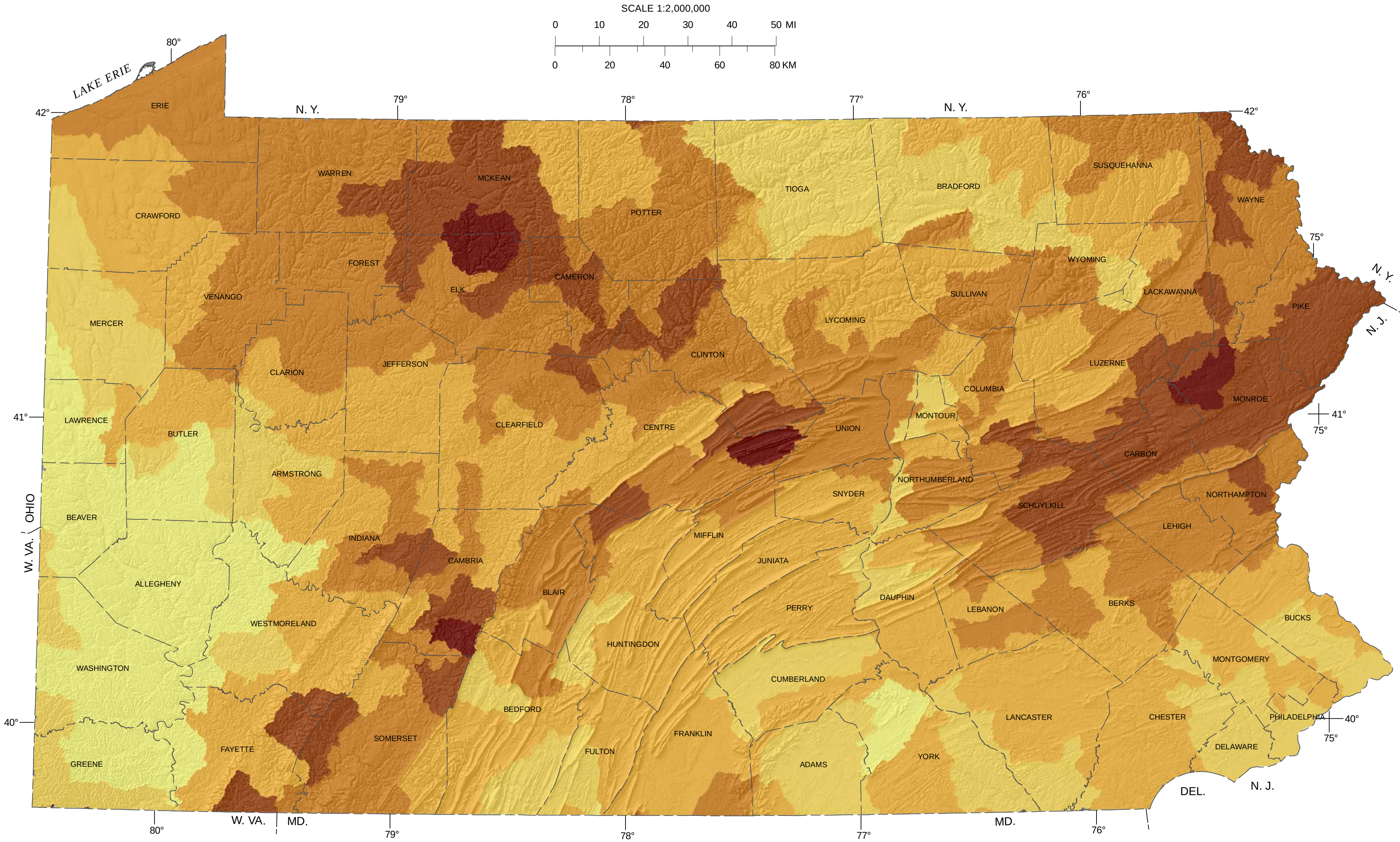
pennsylvania
DEPARTMENT OF CONSERVATION AND NATURAL RESOURCES

USGS
science for a changing world

WATER RESOURCES REPORT 70
PLATE 4

APPROXIMATE AVERAGE ERROR OF RECHARGE ESTIMATES FOR PENNSYLVANIA WATERSHEDS, 1971 – 2000

COMMONWEALTH OF PENNSYLVANIA
DEPARTMENT OF
CONSERVATION AND NATURAL RESOURCES
BUREAU OF TOPOGRAPHIC AND GEOLOGIC SURVEY
www.dcnr.state.pa.us/topogeo



APPROXIMATE AVERAGE ERROR (INCHES)

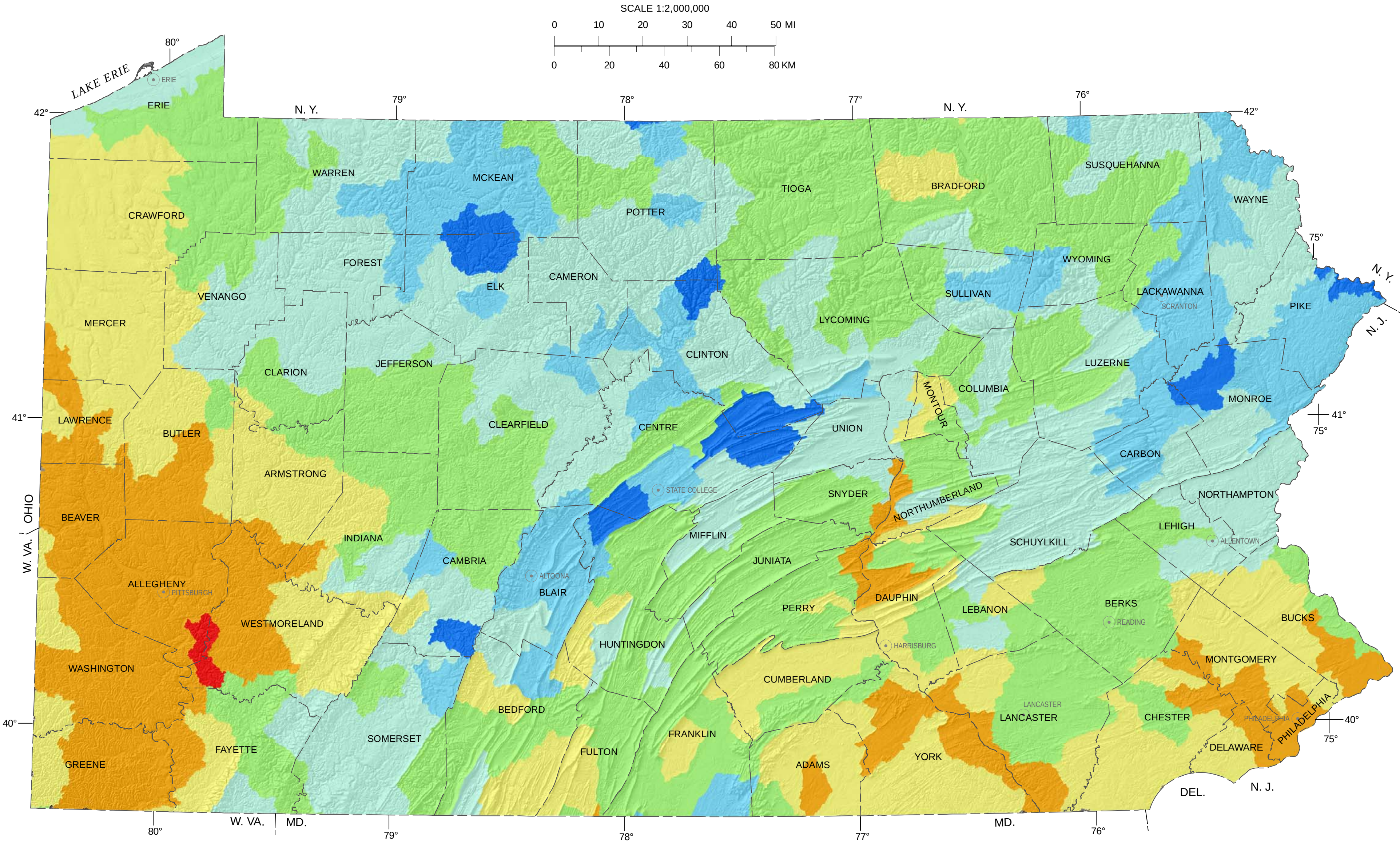
1.26 - 1.69	2.01 - 2.50	3.01 - 3.50
1.70 - 2.00	2.51 - 3.00	3.51 - 3.83

Approximate average error of recharge values based on revised calculations from regression equation published in Risser and others, 2008a, pubs.usgs.gov/sir/2008/5185 (accessed November 20, 2009).

WATER RESOURCES REPORT 70
PLATE 5

MEAN ANNUAL RECHARGE AS A PERCENTAGE OF PRECIPITATION, 1971 – 2000

COMMONWEALTH OF PENNSYLVANIA
DEPARTMENT OF
CONSERVATION AND NATURAL RESOURCES
BUREAU OF TOPOGRAPHIC AND GEOLOGIC SURVEY
www.dcnr.state.pa.us/topogeo



MEAN ANNUAL RECHARGE AS A PERCENTAGE OF PRECIPITATION

- 19 - 20
- 20 - 25
- 25 - 30
- 30 - 35
- 35 - 40
- 40 - 45
- 45 - 49.2

Recharge as a percentage of precipitation was determined using recharge and precipitation values calculated for HUC10 watersheds. For each watershed, recharge was divided by precipitation and multiplied by 100 to produce the percentage of average annual precipitation that is groundwater recharge (1971-2000).

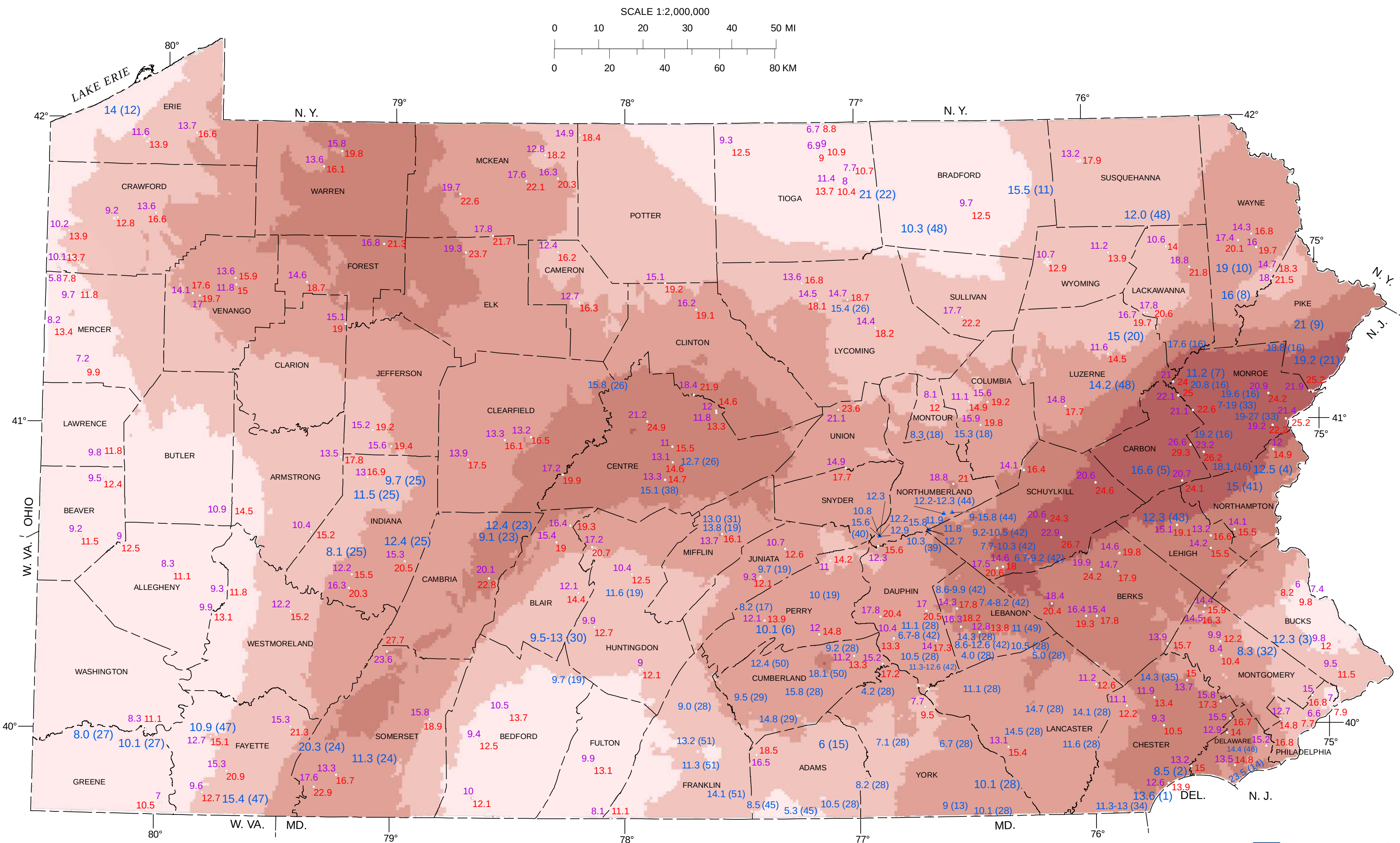
pennsylvania
DEPARTMENT OF CONSERVATION AND NATURAL RESOURCES

USGS
science for a changing world

WATER RESOURCES REPORT 70
PLATE 6

COMMONWEALTH OF PENNSYLVANIA
DEPARTMENT OF
CONSERVATION AND NATURAL RESOURCES
BUREAU OF TOPOGRAPHIC AND GEOLOGIC SURVEY
www.dcnr.state.pa.us/topogeo

GROUNDWATER RECHARGE AND BASE-FLOW ESTIMATES FROM OTHER GROUNDWATER REPORTS



REPORTED GROUNDWATER RECHARGE OR BASE-FLOW VALUES (INCHES)

Groundwater-recharge estimates from Wolock (2003)

4.7 - 7.0	10.6 - 13.0
7.0 - 9.0	13.0 - 16.9
9.0 - 10.6	

13.4 (12) — Report value (Table 2 reference number in parentheses)

10.7 / 12.4 — Stream gage value, PART (purple label) and RORA (red label)

Data are from reports listed in Table 2 of text, which provides summary information on study location and methods. Stream gage points show U.S. Geological Survey PART and RORA base flow and recharge calculations, respectively, for upstream watersheds (from Risser and others, 2005a). See Table 2, map key numbers 36 and 37.

pennsylvania DEPARTMENT OF CONSERVATION AND NATURAL RESOURCES
USGS science for a changing world