Ground-Water Resources Program

Comparison of Methods for Estimating Ground-Water Recharge and Base Flow at a Small Watershed Underlain by Fractured Bedrock in the Eastern United States

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In cooperation with the U.S. Department of Agriculture, Agricultural Research Service

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Conversion Factors and Datum

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter
square foot (ft^2)	0.09290	square meter (m^2)
square inch (in^2)	6.452	square centimeter (cm^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
	Pressure	
bar	100	kilopascal (kPa)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Transmissivity*	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

°C = (°F - 32) / 1.8

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

*Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness [(ft^3/d)/ft^2]ft. In this report, the mathematically reduced form, foot squared per day (ft^2/d), is used for convenience.

Comparison of Methods for Estimating Ground-Water Recharge and Base Flow at a Small Watershed Underlain by Fractured Bedrock in the Eastern United States

By Dennis W. Risser, William J. Gburek, and Gordon J. Folmar

Abstract

This study by the U.S. Geological Survey (USGS), in cooperation with the Agricultural Research Service (ARS), U.S. Department of Agriculture, compared multiple methods for estimating ground-water recharge and base flow (as a proxy for recharge) at sites in east-central Pennsylvania underlain by fractured bedrock and representative of a humid-continental climate. This study was one of several within the USGS Ground-Water Resources Program designed to provide an improved understanding of methods for estimating recharge in the eastern United States.

Recharge was estimated on a monthly and annual basis using four methods—(1) unsaturated-zone drainage collected in gravity lysimeters, (2) daily water balance, (3) water-table fluctuations in wells, and (4) equations of Rorabaugh. Base flow was estimated by streamflow-hydrograph separation using the computer programs PART and HYSEP. Estimates of recharge and base flow were compared for an 8-year period (1994-2001) coinciding with operation of the gravity lysimeters at an experimental recharge site (Masser Recharge Site) and a longer 34-year period (1968-2001), for which climate and streamflow data were available on a 2.8-square-mile watershed (WE-38 watershed).

Estimates of mean-annual recharge at the Masser Recharge Site and WE-38 watershed for 1994-2001 ranged from 9.9 to 14.0 inches (24 to 33 percent of precipitation). Recharge, in inches, from the various methods was: unsaturated-zone drainage, 12.2; daily water balance, 12.3; Rorabaugh equations with PULSE, 10.2, or RORA, 14.0; and water-table fluctuations, 9.9. Mean-annual base flow from streamflow-hydrograph separation ranged from 9.0 to 11.6 inches (21-28 percent of precipitation). Base flow, in inches, from the various methods was: PART, 10.7; HYSEP Local Minimum, 9.0; HYSEP Sliding Interval, 11.5; and HYSEP Fixed Interval, 11.6.

Estimating recharge from multiple methods is useful, but the inherent differences of the methods must be considered when comparing results. For example, although unsaturated-zone drainage from the gravity lysimeters provided the most direct measure of potential recharge, it does not incorporate spatial variability that is contained in watershed-wide estimates of net recharge from the Rorabaugh equations or base flow from streamflow-hydrograph separation. This study showed that water-level fluctuations, in particular, should be used with caution to estimate recharge in low-storage fractured-rock aquifers because of the variability of water-level response among wells and sensitivity of recharge to small errors in estimating specific yield. To bracket the largest range of plausible recharge, results from this study indicate that recharge derived from RORA should be compared with base flow from the Local-Minimum version of HYSEP.

Introduction

Ground-water recharge is a fundamental component in the water balance of any watershed. However, because it is nearly impossible to measure directly, numerous methods, ranging widely in complexity and cost, have been used to estimate recharge (Lerner and others, 1990; Scanlon and others, 2002). Practicing hydrologists typically make the best estimates of recharge possible by the use of methods that are relatively straightforward in their application and require only commonly available hydrologic data. In the humid, eastern United States, where most streams are gaining and the water table is relatively shallow, recharge typically is estimated by an analysis of streamflow records, ground-water levels, or the water balance for a watershed. In some cases, base flow has been used as an approximation of recharge, with the acknowledgement that it is probably less than the amount recharging the ground-water system (Daniel, 1996; Holtschlag, 1997; Szilagyi and others, 2003).

A common recommendation is that recharge should be estimated by the use of multiple methods and the results compared (Nimmo and others, 2003; Healy and Cooke, 2002). This is a prudent approach, though good-quality data usually are not available to make estimates from multiple methods. In east-central Pennsylvania, however, there are two hydrologic research sites where long-term monitoring of climate, ground water, surface water, and the unsaturated zone allows comparison of multiple methods for estimating ground-water recharge with available data. The sites are operated by the U.S. Department of Agriculture, Agricultural Research Service (ARS), as part of their Pasture Systems and Watershed Management Research Unit Research Watershed. Not only do these ARS sites afford long-term, continuous hydrologic records representative of the humid-continental climate of the northeastern United States, they include measurements of unsaturated-zone drainage from gravity-drainage lysimeters (a dataset rarely available) and streamflow data from gages in nested watersheds.

This study was conducted in cooperation with the ARS as part of the U.S. Geological Survey (USGS) Ground-Water Resources Program (Grannemann, 2001). It was one of several studies designed to provide an improved understanding of methods for estimating recharge in the humid, eastern United States.

Purpose and Scope

This report compares four methods for estimating ground-water recharge and four automated techniques for estimating base flow by hydrograph separation and discusses their application and limitations. The methods were evaluated using available data from 1968 to 2001 at the ARS Masser Recharge site, ARS WE-38 experimental watershed, and at two streamflow-gaging stations within the East Mahantango Creek watershed in east-central Pennsylvania.

Estimates of recharge and base flow were developed and compared for an 8-year period (1994-2001) and a 34-year period (1968-2001). The 8-year period was used because it corresponds to the period of record available for the gravity lysimeters at the Masser Recharge Site. The longer 34-year period of record was used to take advantage of the additional data from climatic stations, streamflow-gaging stations, and observation wells at the WE-38 experimental watershed. Streamflow data from gaging stations on East Mahantango Creek were used to evaluate the effects of watershed size on estimates of recharge and base flow.

Description of Study Area

The study area includes two hydrologic research sites operated by the ARS—watershed WE-38 and the Masser Recharge Site (fig. 1). WE-38 is a 2.8-mi^2 sub-watershed of East Mahantango Creek that drains a rural, agricultural watershed of 162 mi^2 in the unglaciated part of the Valley and Ridge Physiographic Province. The Masser Recharge Site is a 2-acre plot in an upland setting about 1 mi west of the WE-38 watershed. Ground water is present in folded and fractured shales, siltstones, and sandstones of the Trimmers Rock Sandstone and Catskill Formation of Devonian and Mississippian age that are overlain by mostly silty loam soils. Depth to ground water ranges from about 80 ft below land surface beneath uplands to only several feet below land surface near streams. The climate of the study area is classified as humid continental. Average monthly temperature ranges from 25°F in January to 72°F in July. Annual precipitation averages about 42 in. and is distributed fairly evenly throughout the year. On average, annual potential evapotranspiration is about 26 in. (Waltman and others, 1997), so annual precipitation exceeds potential evapotranspiration by about 16 in.

The sites have been used in numerous investigations to characterize watershed hydrology and effects of agricultural activities on water quality. A good summary of site conditions and the ground-water system of the WE-38 watershed is contained in Urban (1977) and Gburek and others (1998). At WE-38, the ARS has collected meteorological and streamflow data since 1968 and ground-water data since 1973. WE-38 is nested within two larger gaged watersheds, providing the opportunity to study the effects of watershed scale on estimates of recharge and base flow. The 2.8-mi^2 WE-38 watershed is nested within the 45-mi^2 watershed of East Mahantango Creek upstream of the streamflow-gaging station at Klingerstown and the 162-mi^2 watershed upstream of the USGS streamflow-gaging station 01555500 near Dalmatia (fig. 1). The streamflow-gaging station at Klingerstown has been operated continuously by ARS since 1968 and intermittently by USGS as station 01555400 from 1993-95 and 1997-2000.

The Masser Recharge Site is described in detail in Gburek and Folmar (1999) and Stout and others (1998). At the Masser Recharge Site, unsaturated-zone drainage has been collected by the use of 28 gravity-drainage lysimeters (16 monitored continuously) since 1994. Data from seven of the 24-in. diameter lysimeters were used for this study. The lysimeters collect and monitor percolate at 3.3 ft below a grass-covered field plot.

Methods Investigated

Methods for estimating recharge and base flow in this study are summarized in table 1. Recharge was estimated on a monthly and annual basis by using four methods: (1) unsaturated-zone drainage, (2) a daily water balance, (3) water-table fluctuations (WTF) in wells, and (4) the equations of Rorabaugh (Daniel, 1976; Rorabaugh, 1964). Base flow was estimated from streamflow-hydrograph separation by the use of two computer programs—PART (Rutledge, 1993) and HYSEP (Sloto and Crouse, 1996). Unsaturated-zone drainage, collected by gravity lysimeters at the Masser Recharge Site, provides a direct measurement of downward water flux. The other recharge and base-flow methods were chosen for analysis because they are easy to apply and are widely used by practicing hydrologists in the humid eastern United States.

The methods used in this study have inherent differences (summarized in table 1) that need to be considered when comparing their results. Methods in this study are used to estimate either recharge or base flow. The recharge methods attempt to quantify the water added to the water table (recharge), whereas base-flow methods separate part of the streamflow hydrograph attributed to ground-water discharge. The methods have other

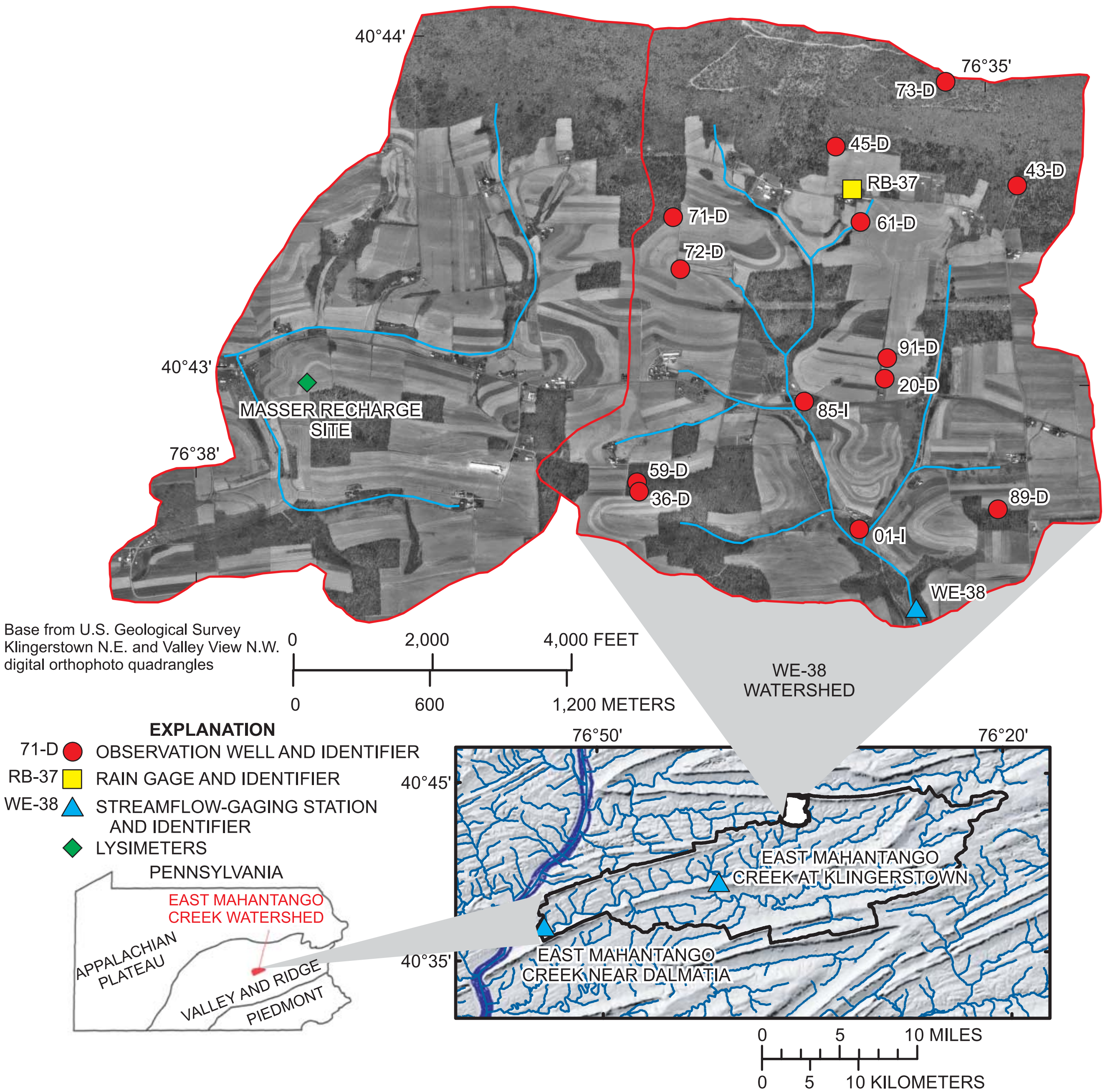

Figure 1. Location of the study area, WE-38, Masser Recharge Site, and East Mahantango Creek watershed, Pennsylvania.

Table 1. Summary of methods investigated in this study for estimating recharge and base flow.

Method	Quantity estimated	Type of estimate	Extent of estimate	Computer program or instrumentation used	Recharge estimated for period	
					1994-2001	1968-2001
Unsaturated-zone drainage	Recharge (potential)	Direct	Point	Measurement of drainage from gravity lysimeters at Masser Recharge Site.	Yes	No
Daily water balance	Recharge (potential)	Indirect	Point	HELP3 Model at Masser Recharge Site using climate, land cover, and soils data.	Yes	No
			Areal	HELP3 Model with GIS at WE-38 watershed using climate, land cover, and soils data.	Yes	Yes
Water-table fluctuation	Recharge	Indirect	Point/Areal[1]	Observation wells at WE-38 watershed.	Yes	No
Rorabaugh equations	Recharge (net)	Indirect	Areal	RORA—Computer program estimates recharge by recession-curve-displacement method from streamflow records.	Yes	Yes
				PULSE—Computer program estimates recharge by trial-and-error matching of simulated ground-water discharge to streamflow records.	Yes	No
Hydrograph separation for base flow	Base flow	Indirect	Areal	HYSEP Program—Local-Minimum version	Yes	Yes
				HYSEP Program—Fixed-Interval version	Yes	Yes
				HYSEP Program—Sliding-Interval version	Yes	Yes
				PART Program	Yes	Yes

[1]This method usually provides a "point" estimate of recharge, but in this study an "areal" estimate was developed from the weighted average of point values from 10 observation wells.

inherent differences—some provide estimates at a point location and others provide a spatially averaged value; some are indirect estimates and some are nearly direct measurements. In addition, estimates of recharge and base flow are derived by the use of differing data sources (streamflow, ground-water levels, or meteorological data); thus, any errors in those datasets are likely to propagate to the estimates of recharge or base flow.

Recharge

Recharge is defined for this study as any water that moves from land surface to the water table (Heath, 1983, p. 4). Although the four methods of estimating recharge in this study (table 1) are widely used, none directly measure the amount of water reaching the water table; thus, each has inherent advantages and disadvantages in its application.

Unsaturated-Zone Drainage

Recharge was estimated in this study from the unsaturated-zone drainage measured in gravity lysimeters. Gravity lysimeters are a method of estimating recharge by directly measuring the vertical flow of water through a large section of the unsaturated zone at a depth below most root systems (Lerner and others, 1990). Unsaturated-zone drainage from gravity lysimeters represents water that has not yet reached the water table, which has been termed "potential" recharge by Scanlon and others (2002). Percolate collected from the lysimeters ideally represents water that passed beneath the root zone and is assumed to closely represent a direct estimate of the volume of recharge reaching the water table, although not necessarily the timing of its arrival. The advantage of gravity lysimeters is that they are one of the few methods that provide an estimate of recharge by direct measurement of vertical water flux. Disadvantages of the lysimeters, in addition to expense and difficulty of installation, are that they provide only a point-estimate of recharge for a specific location and their installation disturbs the soil, which may affect the collection of percolate for several years (Lerner and others, 1990).

Water-Balance Equation

Estimates of recharge from a daily water balance were computed in this study using the computer program *H*ydrologic *E*valuation of *L*andfill *P*erformance (HELP3) (Schroeder and others, 1994a). These estimates are probably best categorized as potential recharge because, as applied in this study, the program only routes water to the base of the root zone. The HELP3 model was used to estimate recharge for the Masser Recharge

Site and the entire WE-38 watershed from the residual term in the general daily water balance:

$$R = P - (ET + RO + \Delta S) \quad (1)$$

where

R is recharge, in inches;
P is precipitation, in inches;
ET is evapotranspiration, in inches;
RO is direct runoff, in inches;

and

ΔS is change in storage, in inches.

HELP3 was developed by the U.S. Army Waterways Experiment Station to compute the water balance of landfills (Schroeder and others, 1994a). It estimates vertical recharge at a point in the watershed, but areal estimates can be obtained by summing recharge rates computed for subdivisions of the watershed with similar physical properties as described by Jyrkama and others (2002). HELP3 is a "quasi-two-dimensional" model that routes precipitation falling on the land to components of evapotranspiration, runoff, storage, and vertical infiltration (recharge) for a layered soil column on a daily basis. The lateral movement of water as overland and subsurface runoff is accounted for by an output from the model, but two-dimensional flow is not explicitly modeled. The model algorithms are described in detail by Schroeder and others (1994b), and limitations are discussed by Berger (2000).

The water-balance method is attractive because it can be applied almost anywhere precipitation data are available. A major drawback of the method is that recharge is estimated as the residual term in an equation where the other budget terms usually are estimated with considerable error, which can result in large errors in the recharge estimate (Nimmo and others, 2003).

The water-balance equation was applied at the Masser Recharge Site and the WE-38 watershed. At the Masser Recharge Site, it was used to estimate recharge at a single point location on the landscape; whereas, spatially variable estimates were derived for the WE-38 watershed.

Water-Table Fluctuations in Wells

Water-table fluctuations (WTF) were used to estimate recharge from the water-level rise in a well multiplied by the specific yield of the aquifer (Rasmussen and Andreasen, 1959). This method actually measures the effect of recharge at the water table, so it should provide estimates that correspond most closely to our definition of recharge; however, the appropriate value of specific yield must be known to translate the measured water-level fluctuations into estimates of recharge.

WTF in wells have been used by hydrologists for many years to estimate recharge (Meinzer and Stearns, 1929; Rasmussen and Andreasen, 1959; Gerhart, 1986). The WTF method assumes that a water-level rise is caused by recharge arriving at the water table and that the specific yield is constant. The method provides a point value of recharge computed from the water-level rise in a well multiplied by the specific yield of the aquifer as:

$$R = \Delta h \times Sy \quad (2)$$

where

R is recharge, in inches;
Δh is change in water-table altitude, in inches;

and

Sy is specific yield.

Although simple in concept, the WTF method has drawbacks in its application (Healy and Cooke, 2002). The method requires an estimate of specific yield and assumes this value is constant with time. Sophocleous (1985) challenged the validity of this assumption on a theoretical basis and Sloto (1990, p. 25) showed that specific yield decreased with water-table depth in an aquifer in southeastern Pennsylvania. The method should work best for wells that show a relatively rapid water-level rise in relation to the rate that water moves away from the water table. Other complications include water-level rises not associated with recharge—such as those caused by changes in atmospheric pressure, earth tides, and entrapped air.

Rorabaugh Equations

Equations described in Rorabaugh (1964) and Daniel (1976) were used to estimate recharge by analysis of streamflow records using two approaches—the computer programs RORA (Rutledge, 1993; 1998) and PULSE (Rutledge, 1997; 2002). RORA provides estimates of ground-water recharge from the displacement of the streamflow-recession curve using an equation developed by Rorabaugh (1964). PULSE uses equations developed by Rorabaugh (1964) and Daniel (1976) to compute the ground-water discharge to a stream following an instantaneous pulse of recharge to the water table. Although ground-water recharge is not computed by the PULSE program, it can be obtained from the PULSE file of user-specified recharge that is created by adjusting recharge by trial and error until the PULSE program simulates a ground-water discharge hydrograph that is a good match to recession periods of gaged streamflow. Because the discharge recorded at a streamflow-gaging station does not always include all recharge from the watershed, these estimates might appropriately be termed "net" recharge (Rutledge, 2000, p. 23).

RORA and PULSE have the advantage of being able to estimate recharge from the Rorabaugh equations with the use of daily values of streamflow from any streamflow-gaging station. However, the PULSE program was not designed to analyze long periods of record, so it is generally impractical to estimate more than a few years of record with this method. The methods assume that streamflow recessions represent ground-water discharge from areal precipitation to the aquifer. Snowmelt runoff, streamflow regulation, and storage and release of water from wetlands or bank storage could be other sources that affect the shape of the recession curve. The methods estimate values of recharge for individual events on a daily basis, but Rutledge (2000, p. 31) recommends reporting results for RORA at no smaller than a seasonal (3-month) time scale.

Although RORA and PULSE use streamflow data to estimate ground-water recharge, they are not "hydrograph-separation" techniques. They are based on a one-dimensional analytical model of ground-water discharge to a fully penetrating stream in an idealized, homogenous aquifer with uniform recharge (Mau and Winter, 1996). Because of the simplifying assumptions inherent in the equations, Halford and Mayer (2000) suggest that RORA may not provide reasonable estimates of recharge for some watersheds.

Application of both RORA and PULSE requires an estimate of the slope of the streamflow-recession curve (recession constant K) representing periods when all streamflow is from ground-water discharge. The recession index is computed by constructing a master-recession curve from the streamflow record by use of the program RECESS (Rutledge, 1993).

Base Flow as a Proxy for Recharge

Base flow is that part of streamflow usually attributed to ground-water discharge (U.S. Geological Survey, 1989). Although base flow is not recharge, it is sometimes used as an approximation of recharge when underflow, evapotranspiration from riparian vegetation, and other losses of ground water from the watershed are thought to be minimal. When used as a proxy for recharge, base flow has sometimes been referred to as "effective recharge" (Daniel, 1996), "base recharge" (Szilagyi and others, 2003), or "observable recharge" (Holtschlag, 1997) to acknowledge that it probably represents some amount less than that which recharged the aquifer.

The major assumptions in using base flow for estimating recharge are that base flow equals ground-water discharge, and that ground-water discharge is approximately equal to recharge. Implicit is the assumption that ground-water losses from the gaged watershed caused by underflow, ground-water evapotranspiration, and exports of ground water are minimal. If these conditions are met, base flow may provide a reasonable estimate of recharge for long time periods (1 year or more). Ultimately, though, different methods for separating base flow will provide different results and the user is left to determine which estimate (if any) is most representative of recharge.

Streamflow-Hydrograph Separation—PART and HYSEP Programs

Methods for separating streamflow hydrographs into components of base flow and direct runoff have been available for many years (Hall, 1968), and more recently, computer programs have automated the separation procedures (Pettyjohn and Henning, 1979; Nathan and McMahon, 1990; Rutledge, 1993; Arnold and others, 1995; Wahl and Wahl, 1988). Two computer programs for hydrograph separation—PART (Rutledge, 1993), and HYSEP (Sloto and Crouse, 1996)—were selected for investigation because they are automated computer programs that are widely used and are readily available from the USGS Internet software page (*http://water.usgs.gov/software*).

PART and HYSEP separate or "scalp" base flow from a streamflow hydrograph using somewhat arbitrary (though different) criteria. PART separates base flow by equating streamflow to base flow on those days after a storm meeting a requirement of antecedent-recession length greater than N and rate of recession less than 0.1 log cycle per day and uses linear interpolation to connect across periods that do not meet those tests. N is the approximate duration of surface runoff from Linsley and others (1982):

$$N = (A)^{0.2}, \tag{3}$$

where

N is the time after which surface runoff ceases, in days;

and

A is the watershed area, in square miles.

HYSEP uses three different versions developed by Pettyjohn and Henning (1979) to separate base flow—Local Minimum, Fixed Interval, and Sliding Interval. Each version searches the hydrograph for the minimum streamflow during an interval 2N* days. The width of the interval 2N* used for hydrograph separation in HYSEP is the nearest odd integer (between 3 and 11) to twice the value of N. The "*" notation is used by the authors of HYSEP to signify that the interval used is not exactly equal to twice the value of N.

Sloto and Crouse (1996) describe the three different HYSEP algorithms. The Local-Minimum version centers the interval 2N* on the day of interest. If it is the minimum streamflow within the interval, it is assigned as a local minimum and is connected by straight lines to adjacent local minimums. Base flow for days between local minimums is estimated by linear interpolation. The Fixed-Interval version assigns the lowest discharge to all days in the interval 2N*, starting with the first day of streamflow record; then the analysis is moved forward 2N* days, and the process is repeated. The Sliding-Interval version centers the interval 2N* on the day of interest. Base flow for that day is assigned the minimum streamflow within the interval; then the interval is moved forward 1 day, and the process is repeated.

Recharge and Base-Flow Estimates

The methods for estimating recharge and base flow (as a proxy for recharge) were applied at the Masser Recharge Site, WE-38 watershed, and East Mahantango Creek Watershed. Use of the methods at these sites provided insights into the benefits as well as possible shortcomings and limitations of each method.

Masser Recharge Site

Two methods were used to estimate recharge at the Masser Recharge Site—(1) unsaturated-zone drainage from lysimeters and (2) a water-balance equation (HELP3). Both methods provide a point estimate of infiltration below the root zone that is categorized as potential recharge for this study (table 1).

Unsaturated-Zone Drainage

Unsaturated-zone drainage was used to estimate recharge from direct measurements of percolate collected in zero-tension gravity-drainage lysimeters at the Masser Recharge Site during 1994-2001 (table 2). The seven lysimeters at the Masser Recharge Site used to estimate recharge were selected because they had a relatively uninterrupted, continuous record of percolate. For periods of missing record at individual lysimeters, the monthly percolate volume was estimated from the operational lysimeter that correlated most closely. During three periods—June through August 2000, October 2000, and September through November 2001—none of the lysimeters were available because they were being used for other experiments or were not functioning. For those months, a qualitative amount of percolate was estimated from precipitation and ground-water fluctuations. The estimated percolate was 1.04 in. for June-August 2000, 0.1 in. for October 2000, and 0.00 in. for September-November 2001. Because the missing record was during dry periods, annual estimates of recharge were not affected greatly.

The gravity lysimeters provide an estimate of recharge at a depth of 3.3 ft beneath the 3.1-ft^2 surface area enclosed by each lysimeter. Variability of percolate collected among the seven lysimeters within the small (approximately 100 ft^2) plot from 1994 to 2001 is illustrated in figure 2. Although the general seasonal trends of recharge are represented similarly in all lysimeters, the volume of percolate collected by individual lysimeters varied. The mean-annual percolate from the seven lysimeters for the period 1994-2001 was 12.2 in. (table 2), although it varied by individual lysimeter from 10.8 to 13.1 in., indicating either the inherent spatial variability of the soils or differences caused by the lysimeters installation.

The variability of annual percolate among the seven lysimeters was largest during the first 3 years of operation (1994-96). The variability, expressed as standard deviation, ranged from 2.4 to 3.9 in/yr from 1994 to 1996, but was only about 1 in/yr from 1997 to 2001 (fig. 3). The greater variability during the first few years of operation may be the result of the disruption of natural conditions caused by lysimeter installation in 1992. The variability does not seem directly related to the amount of percolate collected.

On a monthly basis, the variability in percolate among the seven lysimeters from 1994 to 2001 is shown in figure 4. The volume of percolate collected by the lysimeters varied most during the winter months January through March (standard deviation 0.26-0.45 in/month) and least during July and August (standard deviation 0.05-0.07 in/month). However, when the standard deviation is viewed relative to the magnitude of monthly percolate using the coefficient of variation, the lysimeter response is shown to be most variable during the summer months, June through August.

Water-Balance Equation

The HELP3 model was used to estimate recharge for conditions at the Masser Recharge Site for the period 1994-2001 for which concurrent data were available from the gravity-drainage lysimeters. Mean-annual recharge for the period was 12.3 in. (table 2). Input data used by the model in this study were daily precipitation, daily temperature, average seasonal wind speed and relative humidity, soil properties, and land cover. Solar radiation was synthesized by HELP3 from the WGEN weather-generation model of the U.S. Department of Agriculture (Richardson and Wright, 1984). The data used by the model for simulation of the Masser Recharge Site are summarized in table 3. The total depth of the soil profile corresponds to the 3.3-ft depth of the gravity lysimeters, and the soil properties were obtained directly or computed from properties measured at the Masser Recharge Site (Stout and others, 1998) or listed in the Northumberland County soil survey (Eckenrode, 1985) (table 2).

WE-38 Watershed

Four methods were used to estimate recharge or base flow at the WE-38 watershed—(1) daily water-balance equation, (2) water-table fluctuations in wells, (3) Rorabaugh equations (RORA and PULSE), and (4) streamflow-hydrograph separation of base flow. The methods each provide an areal estimate of recharge or base flow for the 2.8-mi^2 watershed (table 2).

Table 2. Estimates of mean-monthly and mean-annual recharge and base flow, in inches, at Masser Recharge Site and WE-38 watershed for 1968-2001 and 1994-2001.

Method	Computer program or instrumentation	Location	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean annual, in inches and (as percent of precipitation)[1]
1968-2001															
Recharge															
Daily water balance	HELP3 Model	WE-38	0.96	0.61	1.79	2.37	1.38	0.81	0.63	0.43	0.29	0.40	0.60	1.41	11.7 (28)
Rorabaugh equations	RORA	WE-38	1.69	1.91	2.72	1.84	1.66	.92	.33	.32	.60	.75	1.48	1.60	15.8 (38)
Base flow															
Hydrograph separation with HYSEP	Local Minimum	WE-38	1.03	1.15	1.76	1.54	1.07	.60	.39	.24	.25	.43	.66	1.05	10.2 (24)
	Sliding Interval	WE-38	1.29	1.50	2.19	1.86	1.38	.83	.44	.30	.37	.60	.97	1.38	13.1 (31)
	Fixed Interval	WE-38	1.30	1.45	2.17	1.90	1.39	.81	.44	.30	.38	.61	1.02	1.38	13.1 (31)
Hydrograph separation with PART	PART program	WE-38	1.19	1.41	2.10	1.82	1.37	.74	.43	.28	.29	.55	.85	1.29	12.3 (29)
1994-2001															
Recharge															
Unsaturated-zone drainage	Mean from 7 gravity-drainage lysimeters	Masser	1.68	1.25	2.83	1.55	.69	.43	.06	.12	.63	.60	.90	1.49	12.2 (29)
Daily water balance	HELP3 Model	Masser	.48	.72	3.03	2.07	.91	.56	.44	.52	.59	.63	1.01	1.35	12.3 (29)
Rorabaugh equations	PULSE program	WE-38	1.24	1.39	2.00	1.47	.83	.56	.31	.20	.27	.35	.67	.88	10.2 (24)
	RORA program	WE-38	2.10	1.91	3.10	1.48	.96	.87	.22	.22	.51	.47	1.09	1.12	14.0 (33)
Water-table fluctuations	Weighted average from 10 wells	WE-38	1.59	1.22	1.48	1.13	.62	.73	.24	.24	.47	.48	.78	.96	9.9 (24)
Base flow															
Hydrograph separation with HYSEP	Local Minimum	WE-38	1.07	1.11	2.18	1.24	.77	.45	.28	.16	.19	.27	.54	.76	9.0 (21)
	Sliding Interval	WE-38	1.46	1.46	2.49	1.64	.98	.61	.32	.19	.25	.40	.71	.97	11.5 (27)
	Fixed Interval	WE-38	1.57	1.44	2.41	1.63	1.03	.59	.30	.19	.26	.40	.82	.96	11.6 (28)
Hydrograph separation with PART	PART program	WE-38	1.18	1.42	2.39	1.65	.95	.55	.31	.19	.21	.36	.61	.86	10.7 (25)

[1]Precipitation as measured at meteorological station RB-37.

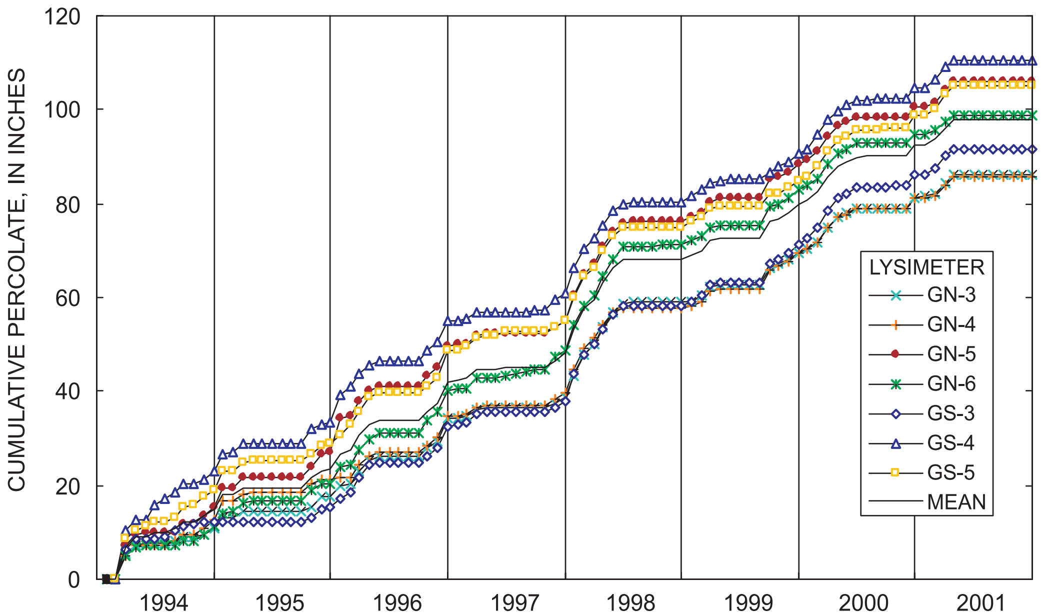

Figure 2. Cumulative percolate collected from seven gravity lysimeters at the Masser Recharge Site, 1994-2001.

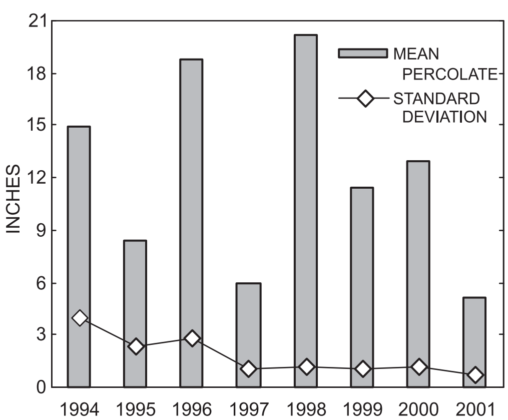

Figure 3. Annual mean percolate and standard deviation for seven gravity lysimeters at the Masser Recharge Site, 1994-2001.

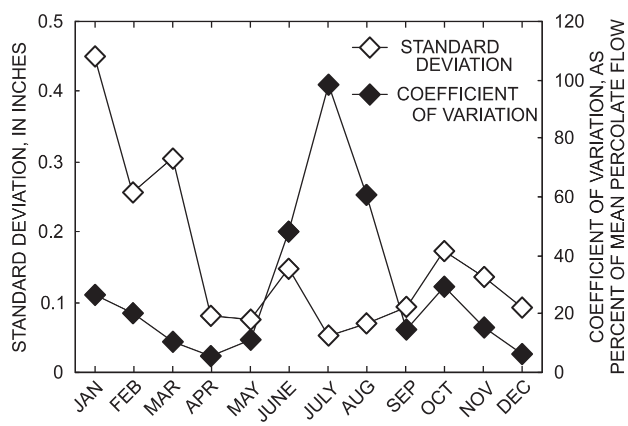

Figure 4. Variability of mean-monthly percolate for seven gravity lysimeters at the Masser Recharge Site, 1994-2001.

Table 3. HELP3 model input parameters used to simulate recharge at Masser Recharge Site, 1994-2001.

[vol, volume]

Model Input—General Data			
Daily Precipitation and Temperature = Masser Recharge Site meteorological station			
Daily Solar Radiation = Synthesized by HELP3 using temperature and precipitation data			
Soil Profile Depth = 3.3 feet			
Number of Soil Layers = 4			
Slope = 0%			
Natural Resources Conservation Service Runoff Curve Number (CU) = 61			
Leaf-Area Index = 3			
Maximum Rooting Depth = 3.3 feet			
Wilting Point = 0.085 vol/vol for all soil layers. Corresponds to moisture storage at suction of 15 bars			
Soil Hydraulic Conductivity = 3.6 feet per day			
Quarterly Relative Humidity = 69, 70, 78, 75 percent			
Model Input—Data for Specific Soil-Profile Layers			
Soil profile layer	Layer thickness (feet)	Porosity (vol/vol)	Field capacity (vol/vol)
1	0.7	0.502	0.191
2	.5	.426	.134
3	1.3	.385	.139
4	.8	.351	.128

Water-Balance Equation

The HELP3 model was used to estimate potential recharge for the entire WE-38 watershed from 1968 to 2001 in an approach similar to that described by Jyrkama and others (2002). A geographic information system (GIS) was used to divide the watershed into 26 landscape units on the basis of similar land cover, hydrologic soil group, and slope (fig. 5A-C). HELP3 provided estimates of recharge for each of the landscape units, which were weighted by their percentage of the WE-38 watershed, then summed to provide an estimate of average recharge for the watershed. Mean annual recharge for the period was 11.7 in. (table 2).

The properties used in the HELP3 model for each landscape unit are shown in table 4. Land cover was categorized as woods, crop, grass, or “developed” (farmlots and roadways) from the 1990 land-cover dataset of WE-38 compiled by ARS. Soils were categorized by hydrologic soil group B, C, or D (group C/D was lumped with D); and slopes were categorized as 0-8, 8-25, and 25-80 percent from the Northumberland County soil survey (Eckenrode, 1985). Of the possible 36 landscape units, only 26 were present within the WE-38 watershed. Runoff curve numbers were estimated from Natural Resources Conservation Service technical report TR-55 (U.S. Department of Agriculture, 1986, table 2). Soil properties were estimated from HELP3 default soil types and the county soil survey. Leaf area index was estimated using guidance in the HELP3 documentation (Schroeder and others, 1994b) and values from a worldwide survey of leaf-area index (Scurlock and others, 2001). Maximum depth of evapotranspiration was estimated for various crop types and hydrologic soil group from values given in Charles and others (1993, table 2). Daily precipitation and temperature data were used from the RB-37 meteorological station (fig. 1), and solar radiation was synthesized by HELP3.

There are several limitations in the application of HELP3 at the watershed scale. Mean-annual recharge simulated by the HELP3 model for the WE-38 watershed during 1968-2001 ranged from 10.7 to 13.6 in. across the 26 landscape units (fig. 5D and table 4), and averaged 11.7 in. for the watershed as a whole. These estimates are similar to estimates determined by other methods; however, because HELP3 does not route water from landscape units to a stream, it is difficult to compare model results directly to observations of streamflow on an event basis. For the period 1968-2001, the HELP3 model simulated 3.0 in/yr of direct runoff, making the sum of simulated recharge plus runoff equal to 14.7 in/yr. Streamflow at the WE-38 gage was 20.1 in. during the same period, which suggests that evapotranspiration may be overestimated by HELP3 because the sum of annual recharge and direct runoff (14.7 in.) should approximately equal measured streamflow (20.1 in.) for this 34-year period.

Another questionable result is that the two landscape units having the greatest simulated ground-water recharge were those that represented developed areas within the WE-38 watershed. The implication of this result is that increased development will lead to increased ground-water recharge because evapotranspiration from vegetation is lessened. The large simulated recharge rates for some developed areas were caused by highly permeable soils in those areas and parameterization of the landscapes in HELP3 with a low leaf-area index (2), shallow limit of evapotranspiration (12 in.), and a runoff curve number (80) that might have been too small. Because it is difficult to know if these parameters are assigned properly and because the model is sensitive to these parameters (Jyrkama and others, 2002), accuracy of the spatial distribution of recharge computed from HELP3 is difficult to evaluate.

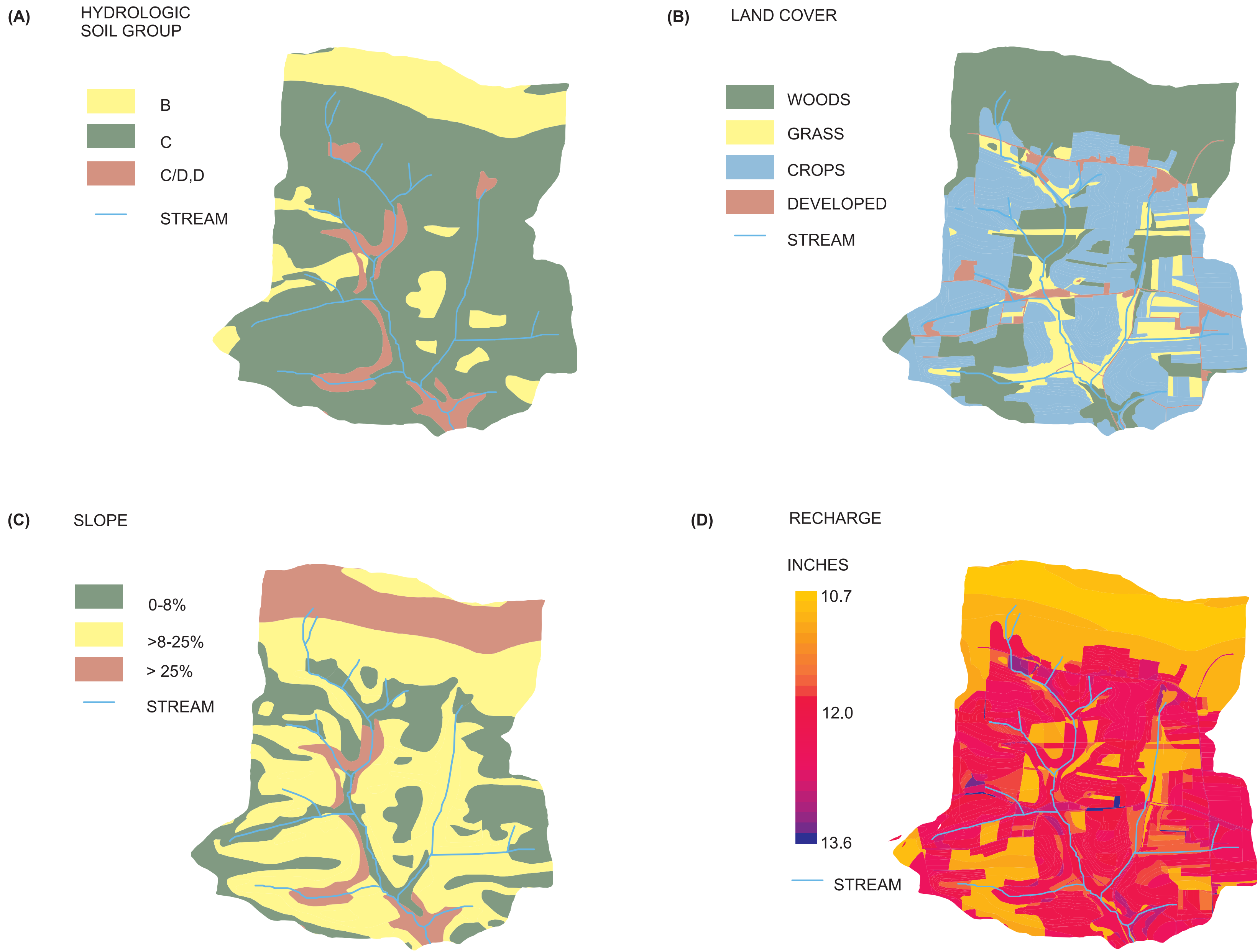

Figure 5. (A) Soil group, (B) land cover, and (C) slope categories used to define landscape units within the WE-38 watershed and resulting estimates of (D) ground-water recharge, 1968-2001, from the HELP3 water-balance model.

Table 4. Properties of landscape units used in the HELP3 water-balance model of the WE-38 watershed and simulated recharge for 1968-2001.

[vol, volume]

Landscape unit	Categories used to define landscape units			HELP3 model input parameters										Simulated recharge, inches
	Land cover category	Hydrologic soil group	Slope category, percent	Number of soil profile layers	Bottom of soil profile layer, inches below land surface	Slope value used in HELP3, percent[1]	Natural Resources Conservation Service runoff curve number[2]	Leaf-area index[3]	Maximum depth of evapotranspiration, in inches[4]	Saturated hydraulic conductivity, feet per day	Total porosity (vol/vol)	Field capacity (vol/vol)	Wilting point (vol/vol)[5]	
1	Crop	B	0 to 8	4	8/45/60/72	4	70	4	39.6	6.6	0.453	0.190	0.085	12.14
2	Crop	B	8 to 25	4	8/45/60/72	17	70	4	39.6	6.6	.453	.190	.085	12.11
3	Grass	B	0 to 8	4	8/45/60/72	4	59	3	50.4	6.6	.453	.190	.085	11.70
4	Grass	B	8 to 25	4	8/45/60/72	17	59	3	50.4	6.6	.453	.190	.085	11.68
5	Woods	B	0 to 8	4	8/45/60/72	4	55	5	72.0	6.6	.453	.190	.085	10.76
6	Woods	B	8 to 25	4	8/45/60/72	17	55	5	72.0	6.6	.453	.190	.085	10.76
7	Woods	B	25 to 80	4	8/45/60/72	55	55	5	72.0	6.6	.453	.190	.085	10.69
8	Developed	B	0 to 8	4	8/45/60/72	4	80	2	12.0	6.6	.453	.190	.085	13.64
9	Developed	B	8 to 25	4	8/45/60/72	17	80	2	12.0	6.6	.453	.190	.085	13.54
10	Crop	C	0 to 8	4	10/24/32/72	4	77	4	32.4	3.6	.501	.284	.135	12.29
11	Crop	C	8 to 25	4	10/24/32/72	17	77	4	32.4	3.6	.501	.284	.135	12.20
12	Grass	C	0 to 8	4	10/24/32/72	4	72	3	39.6	3.6	.501	.284	.135	12.16
13	Grass	C	8 to 25	4	10/24/32/72	17	72	3	39.6	3.6	.501	.284	.135	12.10
14	Woods	C	0 to 8	4	10/24/32/72	4	70	5	63.6	3.6	.501	.284	.135	10.84
15	Woods	C	8 to 25	4	10/24/32/72	17	70	5	63.6	3.6	.501	.284	.135	10.79
16	Woods	C	25 to 80	4	10/24/32/72	55	70	5	63.6	3.6	.501	.284	.135	10.74
17	Developed	C	0 to 8	4	10/24/32/72	4	85	2	12.0	3.6	.501	.284	.135	12.48
18	Developed	C	8 to 25	4	10/24/32/72	17	85	2	12.0	3.6	.501	.284	.135	12.35
19	Crop	D	0 to 8	3	7/15/72	4	80	4	20.4	6.6	.471	.342	.210	12.74
20	Crop	D	25 to 80	3	7/15/72	55	80	4	20.4	6.6	.471	.342	.210	12.58
21	Grass	D	0 to 8	3	7/15/72	4	79	3	26.4	6.6	.471	.342	.210	13.34
22	Grass	D	25 to 80	3	7/15/72	55	79	3	26.4	6.6	.471	.342	.210	12.25
23	Woods	D	0 to 8	3	7/15/72	4	77	5	46.8	6.6	.471	.342	.210	12.34
24	Woods	D	25 to 80	3	7/15/72	55	77	5	46.8	6.6	.471	.342	.210	12.26
25	Developed	D	0 to 8	3	7/15/72	4	90	2	12.0	6.6	.471	.342	.210	11.29
26	Developed	D	25 to 80	3	7/15/72	55	90	2	12.0	6.6	.471	.342	.210	10.95

[1] Slope is averaged value from county soil survey (Eckenrode, 1985).

[2] Runoff curve number from U.S. Department of Agriculture (1986, table 2).

[3] Leaf-area index estimated from HELP3 documentation (Schroeder and others, 1994b).

[4] Maximum depth of evapotranspiration estimated from Charles and others (1993, table 2).

[5] Wilting point is defined as the lowest moisture storage by soil at a suction of 15 atmospheres.

Water-Table Fluctuations in Wells

A nearly continuous record of ground-water levels is available since 1973 from 13 shallow wells within the WE-38 watershed (fig. 1). The WTF method was used to estimate mean-monthly and annual recharge for the watershed by analyzing hydrographs from 10 wells in upland settings (near-stream wells 01-I, 61-D, and 85-I were omitted) for 1994-2001. Mean annual recharge for the period was 9.9 in. (table 2). The water-table rise was computed graphically as the difference between the peak water level during a recharge event and the predicted level to which water levels would have declined if the recharge event had not occurred as illustrated in figure 6. For wells having incomplete water-level record, the monthly water-level rise was estimated from the well in which water levels correlated most closely. The average specific yield of the watershed was estimated from the watershed-wide water-table decline measured during periods of streamflow recession.

Variability in Water-Table Fluctuations

The response of water levels in observation wells varies within the WE-38 watershed as illustrated for several of the observation wells in figure 7. For comparison purposes, water-level data for each observation well shown in figure 7 were adjusted to zero on January 1, 1999, so the hydrographs show the water-level fluctuations relative to that date. In general, wells in upland settings have the largest water-level fluctuations.

The mean-annual sum of all water-table rises determined by the procedure shown in figure 6 during 1994-2001 ranged from as little as 8.2 ft at well 61-D to 368 ft at well 91-D (fig. 8). The mean-annual sum of all water-table rises for a well was determined by adding the water-table rise for each individual recharge event during 1994-2001, then dividing by the 8 years of record. For example, for well 43-D, the sum of all water-table rises during 1994-2001 was 1,201 ft, so the annual water-table rise averaged 150 ft (1,201 ft / 8 yr) as shown in figure 8. Therefore, if recharge is estimated by multiplying the water-level rise times the specific yield at each well, rates across the watershed would vary greatly (by a factor of about 45). Although recharge can vary spatially, the variability in water-level rise exhibited by these wells is mostly the result of location of the well within the watershed with respect to streams and the degree to which the well is connected to the aquifer through fractures intercepted by the well.

To illustrate the effect of location relative to a stream boundary on the water-table rise caused by a recharge event, a cross-sectional MODFLOW (McDonald and Harbaugh, 1998) model was constructed having a length of 1,000 ft, transmissivity of 1,000 ft^2/d, specific yield of 0.01, and recharge rate of 1 ft/yr. Although the model is general in nature, its properties were chosen to be representative of the WE-38 watershed (Gburek and others, 1998; table 4). Recharge of 0.1 ft was added to the model (in addition to the 1 ft/yr steady rate) for a period of 1 day and the resulting water-table rise was plotted for

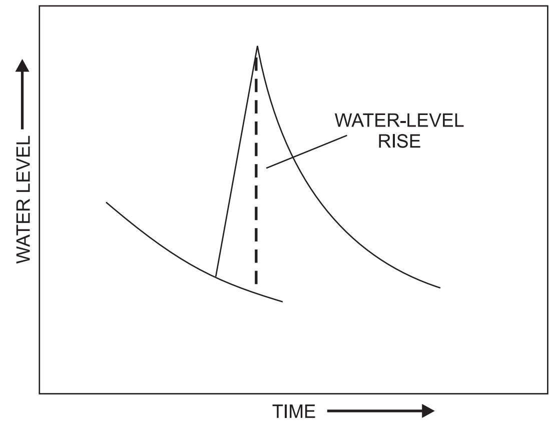

Figure 6. Determination of water-level rise in an observation well.

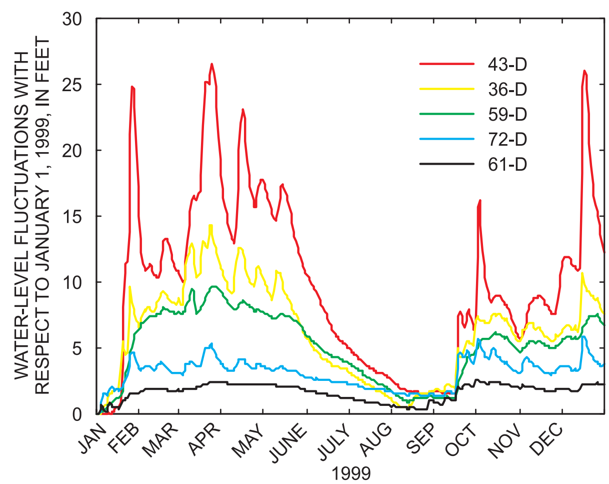

Figure 7. Comparison of water-level fluctuations for 1999 relative to levels on January 1, in five observation wells in the WE-38 watershed.

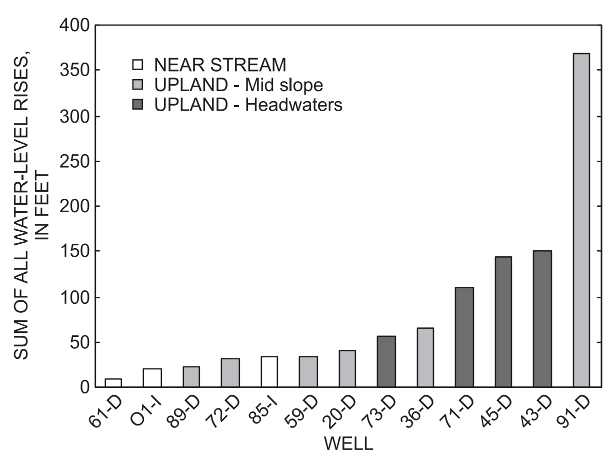

Figure 8. Mean-annual sum of all water-level rises in observation wells in the WE-38 watershed, 1994-2001.

headwaters, mid-slope, and near-stream well locations (fig. 9). A water-table rise of 10 ft is predicted by the WTF method for a recharge event of 0.1ft in an aquifer with specific yield of 0.01 (eqn. 2). As expected, a water-level rise of about 10 ft was simulated for the upland well location, but water levels at the mid-slope and valley locations rose less—only 8 and 1.8 ft, respectively. This result is caused by the movement of water away from the water table during the 1-day period of recharge, which is most rapid near the stream boundary. Such conditions are most pronounced for aquifers with high hydraulic diffusivity (transmissivity/storage coefficient) and high stream density (short distance from streams to divides), which are characteristics of many fractured-rock aquifers in the Valley and Ridge Physiographic Province. Thus, if all other factors are equal, wells in upland settings will be the best candidates for use in estimating ground-water recharge by the WTF method.

Measurement of the water-table rise in a fractured-bedrock aquifer is further complicated by the well/aquifer hydraulic connection. The degree to which an observation well is connected to conditions at the water table depends on the hydraulic connections provided by fractures that intercept the well. The hydrographs from wells in the WE-38 watershed exemplify some of this complexity. For example, wells 36-D and 59-D are only 158 ft apart, yet figure 7 shows that the water-level fluctuations measured in 59-D are significantly less than in 36-D. This difference is not because of well location relative to streams but likely is the result of differing hydraulic properties of fractures connecting each well to the bedrock aquifer.

The importance of the well/aquifer hydraulic connection is further illustrated by changes in the water-level hydrograph of observation well 45-D following hydraulic testing. In 1992, the ARS conducted hydraulic testing of most of their observation wells by isolating depth intervals with packers and injecting water. Subsequent to the testing, the general water-level altitude and magnitude of fluctuations changed in many of the wells. The hydrograph of well 45-D is an example of the most extreme change probably caused by the testing (fig. 10). Most likely, the hydraulic testing acted as a well-development mechanism, causing the well-aquifer connection to improve. If the entire period of record for this well were used to estimate recharge by the WTF method, it is not clear how to deal with the change in magnitude of water-level fluctuations beginning in 1992.

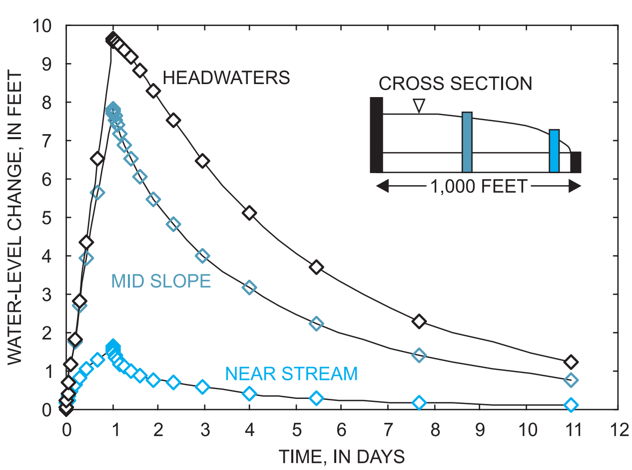

Figure 9. Simulated water-level rise for wells in headwaters, mid-slope, and near-stream locations.

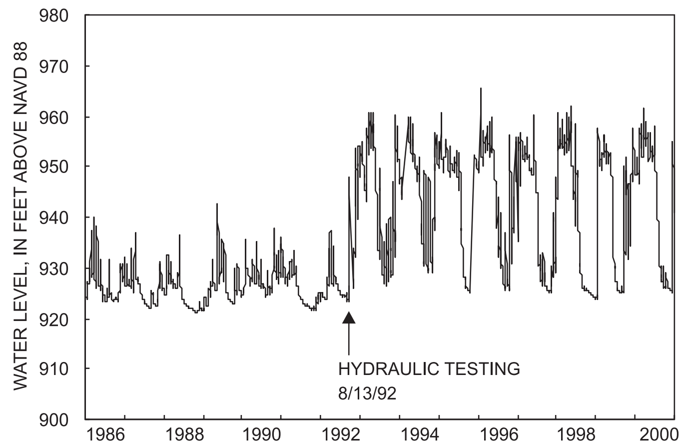

Figure 10. Change in water-level fluctuations in well 45-D in the WE-38 watershed probably caused by hydraulic testing in 1992.

Determining a Representative Specific-Yield Value

Specific yield was computed by dividing the average water-table decline in the WE-38 watershed by the streamflow during recession periods when ground-water discharge was the only source of streamflow. The average water-table decline was estimated from a weighted average of water-level declines measured in 13 observation wells in the WE-38 watershed; streamflow volume was measured at the WE-38 streamflow-gaging station at the outlet of the watershed. Specific yield was computed as:

$$Sy = S / \Delta h \tag{4}$$

where:

Sy is specific yield;
S is streamflow volume during a recession period consisting of only ground-water discharge, in inches over the watershed area; and
Δh is the average decline in water-table altitude during the recession period, in inches.

This approach, described by Olmsted and Hely (1962, p. A-16), has the potential to underestimate specific yield because complete drainage of the geologic material is probably not attained during most recession periods. However, this estimate of specific yield may be appropriate for the purpose of estimating recharge with the WTF method because it is just as unlikely that the geologic materials are completely drained immediately prior to periods of water-table rise.

Specific yield was computed by the use of equation 4 for 11 periods of streamflow recession from 1993 to 2001 during the months of October through May when evapotranspiration from ground water was expected to be minimal. The average specific yield for the watershed using this method was 0.013, which is nearly the same as the value of about 0.01 determined by Gburek and Folmar (1999) from water-table rises and lysimeter percolate at the Masser Recharge Site. Recharge determined from equation 2, using a specific yield of 0.013 and the water-level rises for upland (mid-slope and headwaters) wells shown in figure 8 indicate recharge ranged from 3.4 to 57 in. using this approach.

An alternate approach for use of the WTF method also was tested. Instead of using a uniform value of specific yield of 0.013 for the entire WE-38 watershed, the apparent specific yield for each well was used in equation 2. The apparent specific yield was determined by applying equation 4 for the water-level decline at each well instead of for the watershed average. Three wells (61-D, O1-I, and 85-I) were not used because of their proximity to streams. Apparent specific yields for the remaining 10 individual upland wells (mid-slope or headwater settings) ranged from 0.0035 to 0.035. The apparent specific yields for each of the 10 upland wells was multiplied by the water-level rise on a monthly basis to compute monthly and annual recharge for the WE-38 watershed during 1994-2001 (table 2). Estimates of mean-annual recharge computed from the individual upland wells ranged from 7.6 to 15.4 in. (fig. 11).

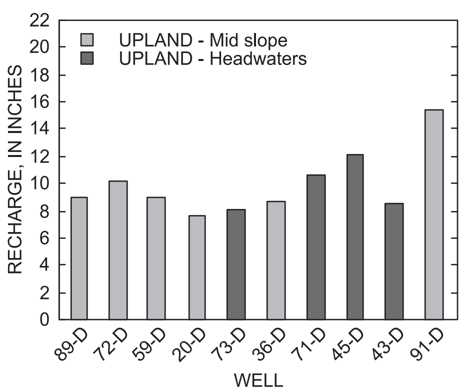

Figure 11. Recharge estimated from the WTF method at upland wells in the WE-38 watershed, 1994-2001.

Rorabaugh Equations with RORA and PULSE

Monthly and annual recharge were estimated with the RORA and PULSE programs using streamflow data from the WE-38 streamflow-gaging station. Mean-annual recharge for 1994-2001 was 14.0 in. from the RORA program and 10.2 in. from the PULSE program (table 2). Monthly and annual recharge also were estimated by the RORA program for the longer period 1968-2001 by the use of streamflow data from the WE-38 streamflow-gaging station. Mean-annual recharge for the period was 15.8 in. The PULSE program was not designed to analyze long periods of record, so it was impractical to estimate 34 years of record with that method.

The basic premise of the Rorabaugh equations is that recharge events occur concurrently with peaks in streamflow (Rutledge, 1998, p. 3). To verify that this assumption was reasonable, the coincidence of precipitation, unsaturated-zone drainage, ground-water rise, and streamflow peaks in 1998 at the WE-38 watershed and the Masser Recharge Site were plotted (fig. 12). All the major recharge events, as documented by lysimeter percolate, are represented by a corresponding increase in ground-water level or streamflow. The general minimal response to precipitation at the lysimeters, wells, and streamflow-gaging station during August-December consistently indicates a lack of ground-water recharge during those months. Such correspondence indicates an ideal situation for application of the RORA program, which is confirmed by examining the days on which RORA simulated recharge of greater than 0.1 in. (shown as triangles on the plot of streamflow in figure 12). The timing of the simulated recharge by RORA corresponds well to all the major recharge events as documented by the lysimeters, wells, and streamflow-gaging station.

Determining the Recession Index (K)

The recession index (K) was determined from streamflow records at the WE-38 gaging station from 1968 to 2001 by use of the RECESS program (Rutledge, 1993). Twenty recession segments were selected during the months of September through May to exclude periods of significant evapotranspiration from ground water. The recession index for the 20 individual segments ranged from 15.9 to 53.2 days. The median value of 26.9 days was used for application of the Rorabaugh equations. The master-recession curve computed from RECESS is shown in figure 13, which compares closely to the master recession curve constructed for a wider range of discharge by Gburek and others (1998, fig. 5). The curve shows some non-linearity, which deviates from the assumptions of the Rorabaugh equation.

The sensitivity of the computed value of recharge to the recession index was tested by applying the RORA program using the minimum, median, and maximum recession indices from the RECESS program. Mean-annual recharge computed for 1968-2001 was 15.8 in. when the median recession index of 26.9 days was used. Estimates of mean-annual recharge varied from 14.2 to 16.1 in. for recession indices of 53.2 and 15.9 days, respectively, which indicates that the results are not very sensitive to the value of K, given the extreme values used for this test.

If the aquifer properties within the watershed can be determined, the recession index can be computed directly and compared to the value from analysis of the master-recession curve. Ideally, the result computed from aquifer properties should compare closely to that from the master-recession curve. The equation for the recession index derived from Rorabaugh and Simons (1966, p. 12) is:

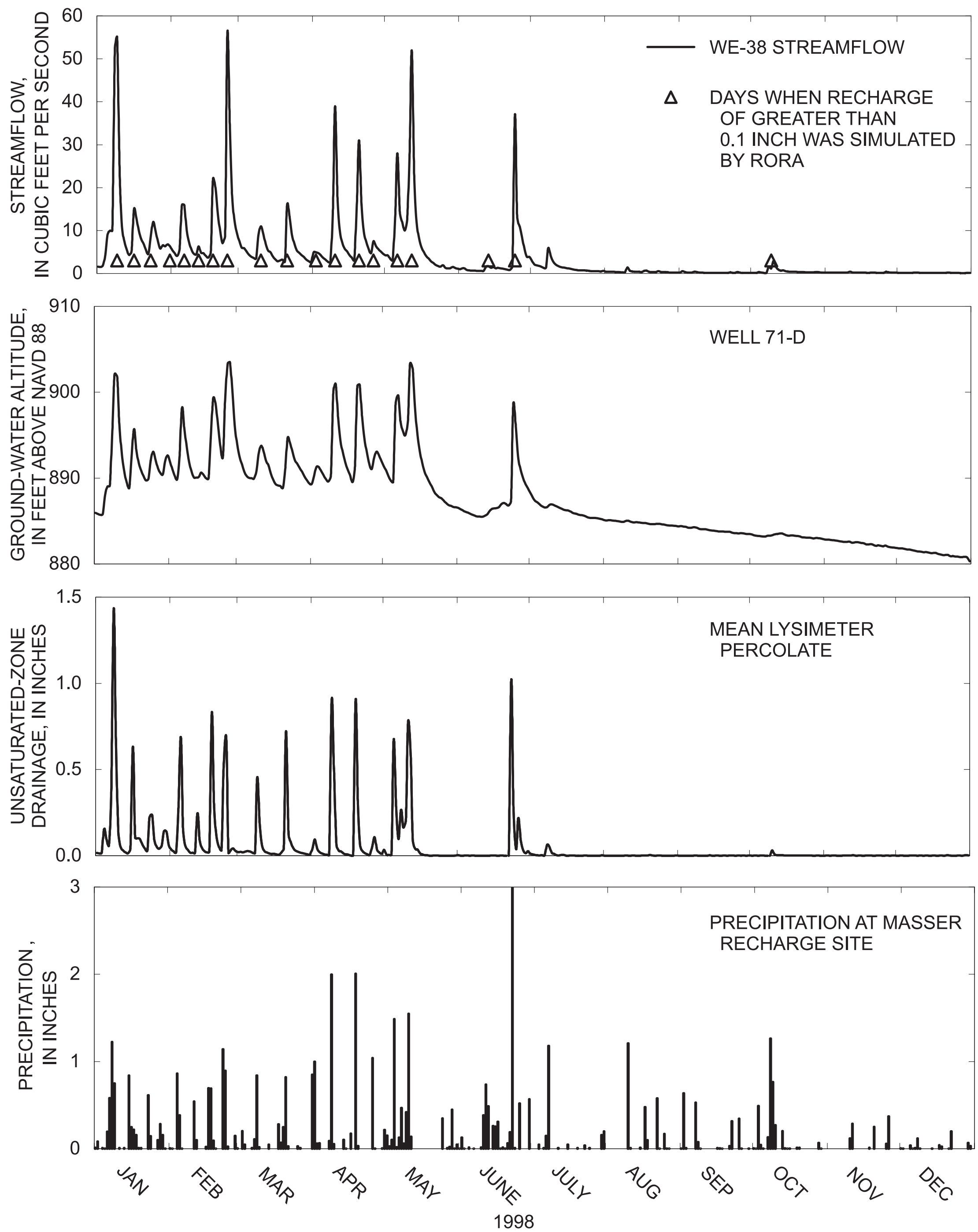

Figure 12. Days recharge was simulated by RORA with measurements of precipitation, unsaturated-zone drainage, ground-water altitude, and streamflow at the WE-38 watershed and Masser Recharge Site, 1998.

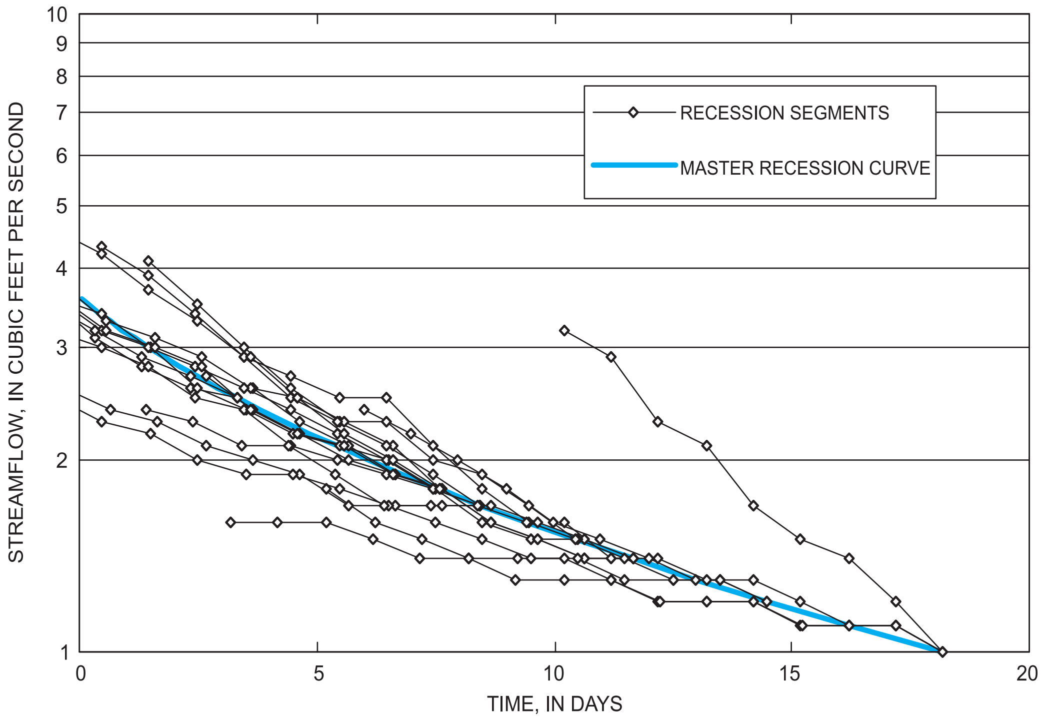

Figure 13. Master recession curve for 20 recession segments from streamflow records from the WE-38 streamflow-gaging station, 1968-2001.

$$K = 0.93\,(a^2)\,S/T \qquad (5)$$

where:

- K is the recession index, in days;
- a is average distance from stream to the hydrologic divide, in feet;
- S is the average storage coefficient; and
- T is average transmissivity, in feet squared per day.

For the WE-38 watershed, the average distance "*a*" from streams to ground-water divides was estimated to be about 1,000 ft as computed from 1/(2 * drainage density). The average storage coefficient (specific yield) of about 0.01 was determined by Gburek and Folmar (1999) and this study. Transmissivity of 470 ft^2/day was used, which is the sum of transmissivity of all layers except the overburden from the calibrated ground-water flow model of Gburek and others (1998). Using these values, the computed recession index is about 20 days. Given the great uncertainty in values of aquifer properties, this result compares reasonably well to the median recession index of 26.9 days from the master-recession curve.

To further evaluate the recession index, master-recession curves were constructed for the 13 observation wells using water-level data from 1993 to 2001. Data prior to 1993 were not used because the well response might have been affected by aquifer-isolation (packer) tests conducted in 1992. Rorabaugh (1960) showed that the recession slopes of ground-water hydrographs should have the same recession index as the streamflow master-recession curve if water levels are referenced to altitude above stream level. Unfortunately, it is not usually apparent how to determine the appropriate stream altitude to use as a base reference. In the WE-38 watershed, water levels were referenced to the nearest stream intercepted along a hypothetical flowpath between the well and stream. Examination of the master-recession curves for the wells shows that the slopes are much less than indicated by the recession index of 26.9 days from the streamflow data. Recession indices from the wells ranged from about 50 to greater than 1,000 days. Although there is considerable ambiguity about the proper stream altitude that should be used as a reference for each well, reasonable stream altitudes could not be found that allowed the ground-water master-recession curves to have recession indices as small as 26.9 days. The very large recession indices suggest that the complexity of the layered, fractured-bedrock hydrogeologic framework of the WE-38 watershed described in Gburek and others (1998) and Burton and others (2002) is significantly different than the simple strip aquifer assumed for the Rorabaugh equations.

The Evapotranspiration Issue

Rutledge (1993, p. 40) noted that RORA gives estimates of recharge that are greater than the estimates of base flow from the hydrograph separation by PART. Rutledge suggested the difference might be the result of ground-water evapotranspiration, which would lower the quantity of base flow estimated from PART but might not affect recharge estimates from RORA. Subsequently, Rutledge (2000, p. 23) has indicated that estimates of recharge from RORA also are probably affected by evapotranspiration from ground water, so the reason for the higher estimates from RORA are not clear.

A comparison was made of mean-monthly recharge estimates from the WE-38 watershed for 1994-2001 by the use of RORA and PULSE (fig. 14). Recharge is estimated from PULSE by taking the user-supplied estimates of ground-water recharge that produced a simulated ground-water discharge hydrograph from PULSE fitting the recession segments of the streamflow hydrograph at the WE-38 streamflow-gaging station. Because the procedure involves fitting simulated discharge to the streamflow hydrograph, which is affected to some extent by ground-water evapotranspiration in summer months, monthly estimates of recharge from PULSE were expected to be less than estimates from RORA during summer months (if estimates from RORA are only minimally affected by ground-water evapotranspiration). However, figure 14 shows that RORA produces greater estimates of mean-monthly recharge for all months, with the greatest differences during winter months when ground-water evapotranspiration is small. Thus, it is unlikely that the higher estimates from RORA (compared to base flow determined from PART) can be attributed to evapotranspiration from ground water in the WE-38 watershed.

Base Flow from Streamflow Hydrograph Separation

Base flow was estimated from daily values of streamflow recorded at the outlet of the 2.8-mi^2 WE-38 watershed. Values of monthly and annual base flow were estimated by streamflow-hydrograph separation using the PART and HYSEP programs (table 2). Missing streamflow record at the WE-38 streamflow-gaging station was estimated from the complete record near Dalmatia based on the drainage area upstream of each gage. Application of PART and HYSEP was straightforward, requiring no user input other than the drainage area.

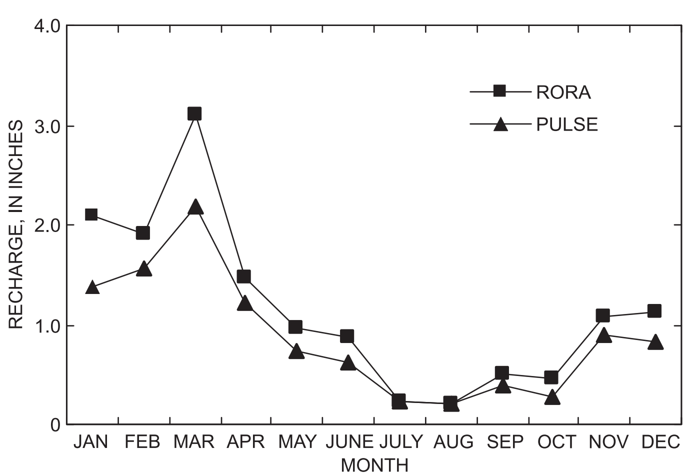

Figure 14. Mean-monthly recharge estimates from RORA and PULSE at the WE-38 watershed, 1994-2001.

Mean-annual base flow at the WE-38 streamflow-gaging station during 1994-2001 was 10.7 in. from the PART program. Estimates from the HYSEP program were 9.0 in. (Local-Minimum version), 11.5 in. (Sliding-Interval version), and 11.6 in. (Fixed-Interval version). Mean-annual base flow for the longer period 1968-2001 was 13-15 percent greater than for 1994-2001.

Because base flow does not account for losses of recharge caused by evapotranspiration of ground water, it might be reasonable to add an estimate of evapotranspiration from riparian vegetation to base flow as an approximation of ground-water recharge. Assuming that riparian vegetation extracted ground water from 50 to 100 ft on each side of streams within the WE-38 watershed at the rate of potential evapotranspiration, the loss would be on the order of 1.3 to 2.5 in/yr. Adding this to the base-flow estimates for the WE-38 watershed during 1994-2001 gives a range for recharge from 10.3 (HYSEP Local-Minimum version) to 14.1 in/yr (HYSEP Fixed-Interval version). For the period 1968-2001, the range would be 11.5 to 15.6 in.

East Mahantango Creek Watershed

Recharge and base flow were estimated from daily values of streamflow during 1968-2001 at streamflow-gaging stations on East Mahantango Creek at Klingerstown and near Dalmatia to compare results from watersheds of different size. Recharge was estimated from the Rorabaugh equations using the RORA program, and base flow was estimated by streamflow-hydrograph separation using the PART and HYSEP programs. Missing streamflow record at the Klingerstown streamflow-gaging station was estimated from the complete record near Dalmatia based on the drainage area upstream of each gage. The methods provide estimates of net recharge or base flow averaged over the watershed area upstream of each streamflow-gaging station—45 mi^2 for the Klingerstown station and 162 mi^2 for the Dalmatia station (table 5).

Rorabaugh Equations with RORA

Values of monthly and annual recharge during 1968-2001 estimated from the RORA program are summarized in table 5. Median recession indices (K) of 31.4 and 46.6 days were determined by use of the RECESS program for streamflow-gaging stations at Klingerstown and near Dalmatia, respectively. Estimates of mean-annual recharge determined by RORA were 15.8 in. from the streamflow record at Klingerstown and 15.6 in. from the streamflow record near Dalmatia.

Table 5. Estimates of mean-monthly and mean-annual recharge and base flow, in inches, for streamflow-gaging stations on East Mahantango Creek, 1968-2001.

Method	Computer program	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
East Mahantango Creek at Klingerstown														
Recharge, in inches														
Rorabaugh Equations	RORA	2.10	1.97	2.55	1.65	1.45	0.64	0.28	0.19	0.60	0.87	1.55	1.95	15.8
Base flow, in inches														
Hydrograph Separation with HYSEP	Local Minimum	1.60	1.41	1.63	1.38	.91	.45	.28	.15	.20	.38	.65	1.26	10.3
	Sliding Interval	1.72	1.61	1.82	1.56	1.05	.58	.31	.19	.25	.52	.81	1.44	11.9
	Fixed Interval	1.69	1.59	1.83	1.54	1.03	.58	.31	.19	.25	.54	.80	1.42	11.8
Hydrograph Separation with PART	PART	1.75	1.68	1.97	1.71	1.17	.60	.35	.19	.25	.57	.87	1.55	12.7
East Mahantango Creek near Dalmatia														
Recharge, in inches														
Rorabaugh Equations	RORA	1.63	2.00	2.91	1.59	1.41	.69	.35	.28	.70	.81	1.62	1.62	15.6
Base flow, in inches														
Hydrograph Separation with HYSEP	Local Minimum	1.10	1.12	1.76	1.66	1.16	.66	.45	.32	.29	.43	.70	1.12	10.8
	Sliding Interval	1.21	1.34	2.00	1.82	1.28	.76	.47	.33	.34	.55	.83	1.33	12.3
	Fixed Interval	1.18	1.34	2.03	1.81	1.27	.78	.48	.33	.34	.55	.84	1.31	12.2
Hydrograph Separation with PART	PART	1.25	1.40	2.10	1.94	1.36	.79	.51	.34	.33	.59	.87	1.43	12.9

Base Flow from Streamflow-Hydrograph Separation

Values of monthly and annual base flow were estimated by streamflow-hydrograph separation using the PART and HYSEP programs (table 5). Mean-annual base flow for East Mahantango Creek at Klingerstown during 1968-2001 was 12.7 in. from the PART program. Estimates from the HYSEP program were 10.3 in. (Local Minimum version), 11.9 in. (Sliding Interval version), and 11.8 in. (Fixed Interval version). Mean-annual base flow for East Mahantango Creek near Dalmatia during 1968-2001 was 12.9 in. from the PART program. Estimates from the HYSEP program were 10.8 in. (Local Minimum version), 12.3 in. (Sliding Interval version), and 12.2 in. (Fixed Interval version).

Comparison of Results

Estimates of recharge and base flow were compared for an 8-year period (1994-2001) and for a 34-year period (1968-2001) (table 2). The short, 8-year period was used because it corresponds to the period of record available for the gravity lysimeters at the Masser Recharge Site. The longer 34-year period was used to take advantage of the additional data from climatic stations and streamflow-gaging stations at the WE-38 experimental watershed.

Climatic conditions during the 8-year period were either about the same or drier than the 34-year period, depending on the criteria used for comparison. Precipitation at meteorological station RB-37 was only slightly greater during 1994-2001 (average of 42.1 in.) than during 1968 to 2001 (average of 41.8 in.); however, streamflow during 1994-2001 was about 11 percent lower at the WE-38 streamflow-gaging station and 7 percent lower at the streamflow-gaging station on East Mahantango Creek near Dalmatia than during 1968-2001. It follows that recharge and base-flow estimates determined from streamflow data might be lower during 1994-2001 than 1968-2001, but methods based on precipitation (daily water-balance) might be similar or slightly greater for 1994-2001. Comparison of results in table 2 shows that this was the case. Estimates of mean-annual recharge based on streamflow data for the WE-38 watershed (Rorabaugh equations and base-flow methods) were 11 to 13 percent less during 1994-2001 than 1968-2001, whereas recharge from the daily water balance increased by about 5 percent during 1968-2001.

Period of Available Lysimeter Record (1994-2001)

Indirect estimates of recharge and base flow were compared to the direct measurement of potential recharge from the lysimeters from 1994 to 2001. Estimates of mean-annual recharge for the 8-year period at the Masser Recharge Site and the WE-38 watershed ranged from 9.9 to 14.0 in. (24-33 percent of precipitation), and estimates of mean-annual base flow ranged from 9.0 to 11.6 in. (21-28 percent of precipitation) (fig. 15 and table 2). Mean-annual recharge was greatest from

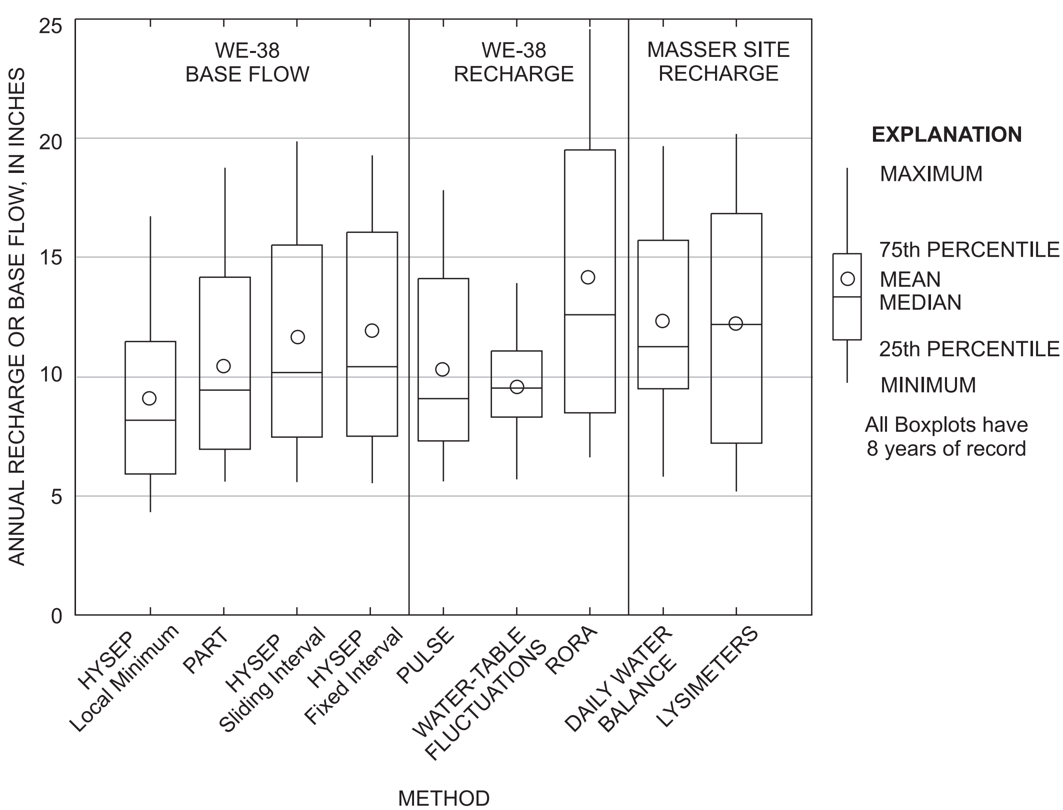

Figure 15. Estimates of annual recharge and base flow, 1994-2001.

the RORA program and least from the WTF method (fig. 15). The variability of annual recharge also was greatest for the RORA program and least for the WTF method.

The mean differences in annual recharge or base flow between any two methods during 1994-2001 are shown in table 6. Methods that compare closely have small absolute values of mean difference. The mean difference compares the differences of the annual estimates of recharge or base flow as:

$$\bar{D} = 1/n\left[\sum_{i=1}^{n}(r_1 - r_2)_i\right] \qquad (6)$$

where:

$\bar{D}$ is the mean difference, in inches;
n is number of years of record;
r_1 is the annual recharge estimate from method 1 for year i, in inches; and
r_2 is the annual recharge estimate from method 2 for year i, in inches.

On the basis of mean difference, the water-balance method and unsaturated-zone drainage from lysimeters compared most closely (mean difference of 0.07 in.). This result was unexpected because of the inherent error in water-balance models and because simulations were made without any attempt to calibrate the model to the lysimeter measurements

Table 6. Mean difference, in inches, between estimates of annual recharge or base flow by all methods, 1994-2001.

[Gray shading indicates that mean recharge or base flow for the two groups is significantly different on the basis of a paired-t-test at the 95-percent confidence level. Negative values indicate that the value from the method along the top column is greater than for the method from the corresponding row.]

		Mean difference, in inches, between estimates of annual recharge or base flow								
		BASE-FLOW METHODS				RECHARGE METHODS				
	METHOD	HYSEP Sliding Interval	HYSEP Fixed Interval	HYSEP Local Minimum	PART	Rorabaugh equations (PULSE)	Rorabaugh equations (RORA)	Unsaturated-zone drainage (mean of 7 lysimeters)	Water-table fluctuations (weighted average from 10 upland wells)	Water balance (HELP3 model)
BASE-FLOW METHODS	HYSEP Sliding Interval	0								
	HYSEP Fixed Interval	.12	0							
	HYSEP Local Minimum	-2.5	-2.6	0						
	PART	-.78	-.91	1.7	0					
RECHARGE METHODS	Rorabaugh equations (PULSE)	-.92	-1.1	1.5	-.14	0				
	Rorabaugh equations (RORA)	2.6	2.5	5.0	3.4	3.5	0			
	Unsaturated-zone drainage (mean of 7 lysimeters)	.76	.63	3.2	1.5	1.7	-1.8	0		
	Water-table fluctuations (weighted average from 10 upland wells)	-1.8	-1.9	.66	-1.0	-.87	-4.4	-2.6	0	
	Water balance (HELP3 model)	.83	.71	3.3	1.6	1.8	-1.7	.07	2.6	0

by adjusting HELP3 model-input parameters. The Fixed-Interval and Sliding-Interval versions of HYSEP showed the closest overall similarity of annual base flow with a mean difference of 0.12 in. The poorest overall correspondence on an annual basis was between estimates by the RORA program and the Local-Minimum version of HYSEP, with a mean difference of 5.0 in.

Differences between methods also were tested statistically by comparing annual estimates of recharge or base flow from 1994-2001 using a paired-t-test (Helsel and Hirsch, 1992, p. 147). Prior to conducting the paired-t-test, a Kolmogorov-Smirnov Test indicated the assumption that the paired differences were normally distributed could not be rejected for any two methods. The statistical tests showed that mean recharge or base flow was significantly different at the 95-percent confidence level for 16 of the 36 possible pairs of methods (table 6). All base-flow methods differed significantly from each other except for two of the HYSEP versions (Fixed Interval and Sliding Interval). The Local-Minimum version of the HYSEP method was the most different of the base-flow methods. It was significantly different than six other methods, with mean differences that were generally greater than for other base-flow methods (table 6). Of the recharge methods, results from RORA differed significantly from the most (six) other methods, and unsaturated-zone drainage from the gravity lysimeters differed from the fewest (zero) other methods.

Annual variations in base flow and recharge from 1994 to 2001 are shown for the different methods in figure 16. The mean-annual unsaturated-zone drainage from seven lysimeters at the Masser Recharge Site is shown in gray to allow it to be readily compared to other methods. Estimates of annual base flow ranged from 4.3 to 19.9 in.; annual recharge estimates ranged from 5.2 to 24.6 in. All methods gave small estimates for dry years with below normal precipitation (1995, 1997, 1999, and 2001) and larger estimates for wet years.

Seasonal variations in mean-monthly base flow and recharge from 1994-2001 are shown for different methods in figure 17. Estimates of mean-monthly base flow ranged from 0.16 to 2.49 in., and estimates of mean-monthly recharge ranged from 0.06 in. (from lysimeters) to 3.10 in. All methods show the same general seasonal pattern in recharge or base flow—lowest in the summer and early autumn and greatest during winter and early spring. Because the seasonal distribution of precipitation is fairly even, seasonal variations in recharge are caused mainly by variations in the consumptive use of water through evapotranspiration.

Seasonal patterns in base flow are shown and estimates are compared among themselves and to the mean-monthly unsaturated-zone drainage from seven lysimeters in figure 17A. Mean-monthly base flow estimated from the Local-Minimum version of HYSEP was less than base flow from the other methods for all months. Base flow from the HYSEP Fixed Interval version, HYSEP Sliding Interval version, and PART compared closely during all months except January. Base-flow estimates were generally slightly less than values of unsaturated-zone drainage from September through March and greater during April through August. This probably reflects the slight lag in timing between recharge and ground-water discharge. Infiltration recorded at the lysimeters from September through January takes some time to reach the water table. Some of this water goes to satisfy deficiencies of soil moisture; thus, base flow is less than infiltration during these months. Base flow from April through August exceeds infiltration measured at the lysimeters because the base flow is contributed partly from ground-water recharge in previous months.

Seasonal trends for four different recharge methods are compared among themselves and to the mean-monthly unsaturated-zone drainage from seven lysimeters in figure 17B. Mean-monthly recharge followed the same seasonal trends as base flow; however, there was considerably greater variability among estimates of recharge. The daily water balance provided estimates of annual recharge corresponding closely to the unsaturated-zone drainage from lysimeters (fig. 16B), but on a monthly basis, correspondence to lysimeter measurements was not as good. Monthly recharge estimates differed from lysimeter results most greatly during January and February, probably because of difficulties in simulating the effects of frozen ground and snowpack. HELP3 (water-balance method) simulated 12.3 in. of annual recharge and 3 in. of direct annual runoff for 1994-2001. Nearly all the direct runoff was simulated during winter months January–March. However, direct runoff has not been observed at the site, so the water-balance model may be overestimating runoff (and underestimating recharge) during winter months.

Recharge estimates from RORA followed the seasonal pattern of lysimeter percolate closely, but estimated more recharge than other methods during January and February. Recharge from water-table fluctuations showed the least seasonal variability and tended to estimate less recharge than the lysimeters. Variability among the recharge methods was greatest during months of greatest recharge (December through April).

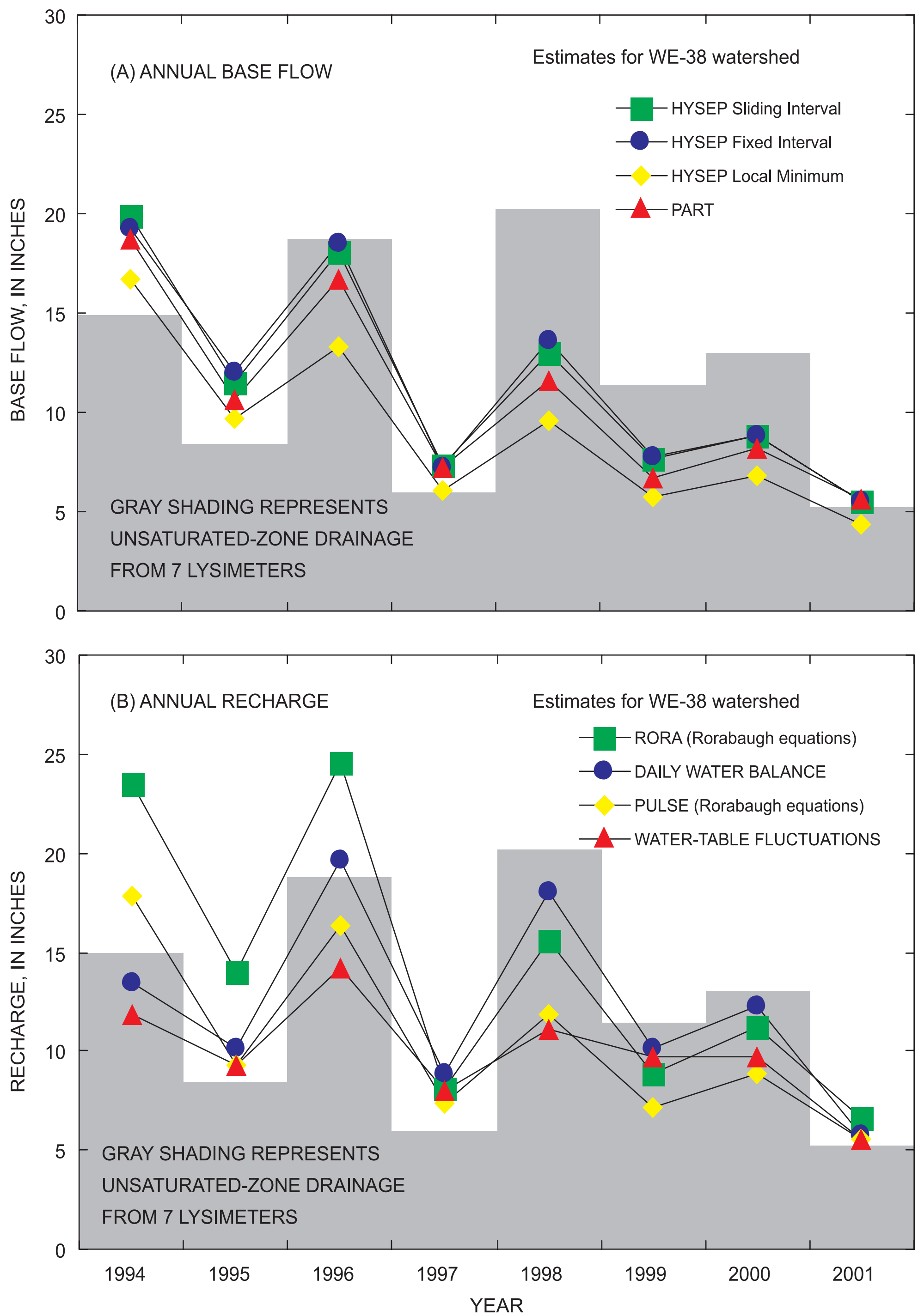

Figure 16. Annual (A) base flow and (B) recharge estimates for WE-38 watershed and lysimeter percolate at the Masser Recharge Site, 1994-2001.

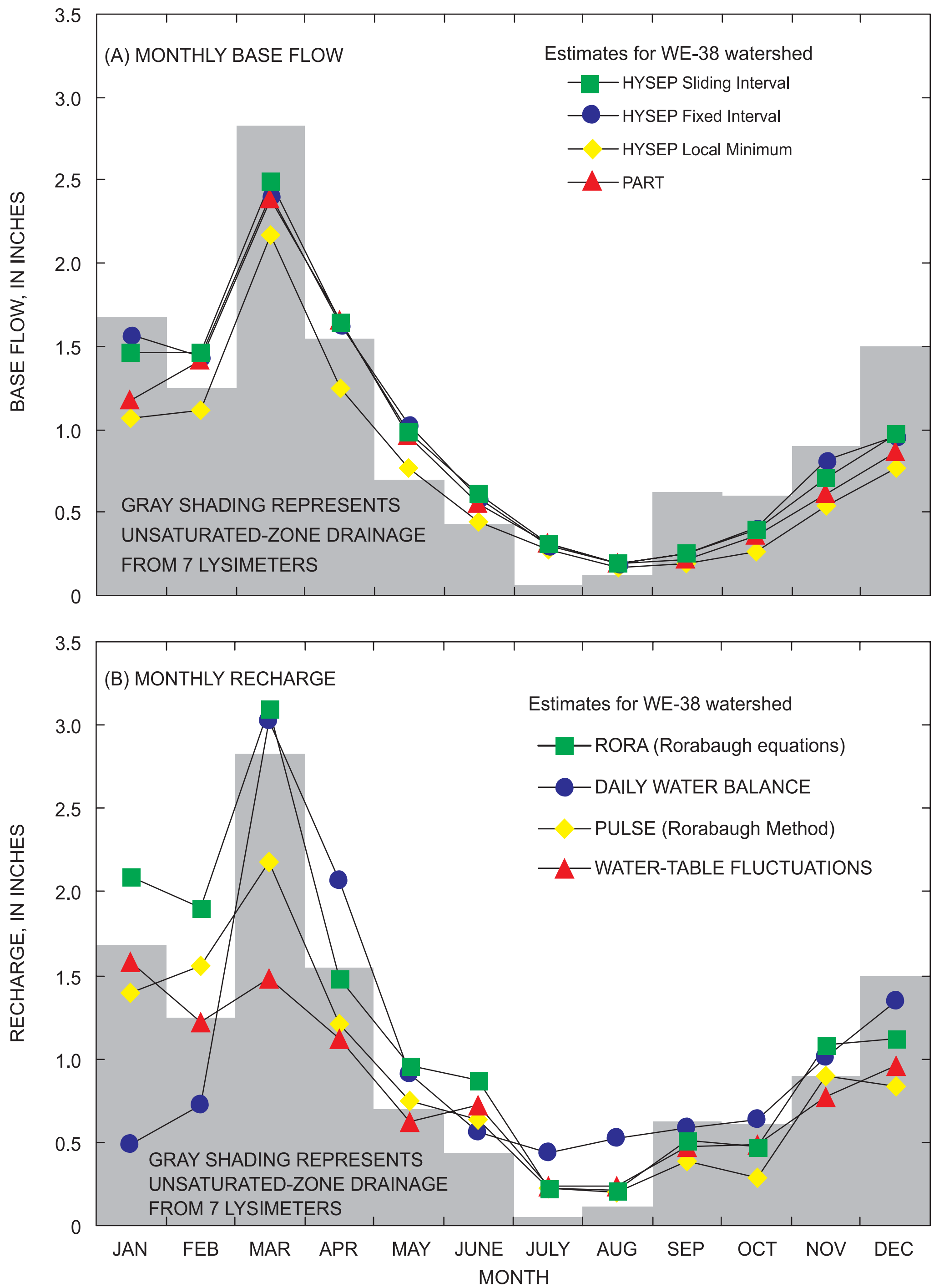

Figure 17. Mean-monthly (A) base flow and (B) recharge estimates for the WE-38 watershed and lysimeter percolate at the Masser Recharge Site, 1994-2001.

Period of Available Streamflow and Climate Records (1968-2001)

Recharge and base-flow estimates during 1968-2001 for the WE-38 watershed are compared in table 2 and figure 18. Estimates of mean-annual recharge or base flow ranged from about 10.2 in. by the Local-Minimum version of the HYSEP method to 15.8 in. by RORA (fig. 18 and table 2). Differences in mean-annual recharge or base flow were shown to be statistically significant between any two methods, except the HYSEP Fixed-Interval/Sliding-Interval pair and the PART/Water-Balance pair, according to results from a paired-t-test at the 95-percent confidence level. Although fewer methods were compared for the 1968-2001 period than for the 1994-2001 period, the results were consistent with the 1994-2001 period, except for the water-balance method, which was shown to differ significantly from RORA and the Sliding-Interval and Fixed-Interval versions of HYSEP during 1968-2001, but not during 1994-2001. This probably is because the water-balance point estimates of recharge for the Masser Recharge Site were used for the 1994-2001 comparisons and the areal-weighted estimates for the WE-38 watershed were used for 1968-2001. The similar results for the longer period of available data (1968-2001) indicate that valid conclusions probably can be drawn for methods that only were available for the shorter time period (1994-2001).

Effect of Watershed Scale

Estimates of recharge and base flow in this report have been compared at two small sites. Estimates from the Masser Recharge Site are for a single upland location, and estimates from the small WE-38 watershed represent an average for a 2.8-mi^2 drainage area. Because recharge can vary spatially, estimates of recharge derived from watersheds of different size may not agree. Similarly, the conditions required for base flow to be a good surrogate for recharge (for example, negligible underflow and evapotranspiration from ground water) can be affected by the size of the watershed upstream of the streamflow-gaging station where base flow is determined. Thus, results from RORA and methods of hydrograph-separation for base flow were compared for nested watersheds at three scales from the streamflow record at WE-38 (2.8 mi^2), East Mahantango Creek at Klingerstown (45 mi^2), and East Mahantango Creek near Dalmatia (162 mi^2).

Recharge from RORA

The premise of the Rorabaugh equations, that recharge events occur concurrently with peaks in streamflow, might not be correct for watersheds larger than the 2.8-mi^2 WE-38 watershed. To test the effect of watershed scale on estimates of recharge from the recession-curve displacement approach of RORA, the program was applied to streamflow record collected from three watershed scales during 1968 to 2001. Comparison of hydrographs from streamflow-gaging stations for 1998 at WE-38 and East Mahantango Creek near Dalmatia (smallest and largest watersheds) indicates a close correspondence in timing and magnitude of streamflow peaks (fig. 19), which support the application of RORA across this range in watershed scales.

Results from RORA indicate that this change in watershed scale did not appear to significantly affect the estimate of mean annual recharge (fig. 20). Recharge rates computed from the three streamflow records ranged from 15.6 to 15.8 in/yr (75 to 79 percent of streamflow), which is within the 5-percent error inherent in the streamflow record.

Base Flow from Streamflow-Hydrograph Separation

The effect of watershed scale on estimates of base flow by use of the hydrograph-separation programs HYSEP and PART was evaluated by comparing results from streamflow-gaging stations at WE-38 (2.8 mi^2), Klingerstown (45 mi^2) and near Dalmatia (162 mi^2) during 1968-2001. The increase in watershed size caused a slight increase in the estimate of mean-annual base flow computed by the use of PART and the Local-Minimum version of the HYSEP method as watershed size increased (fig. 20). Base flow computed from PART increased from 12.3 in/yr at the WE-38 gage to 12.9 in/yr at the Dalmatia streamflow-gaging station (61 to 63 percent of streamflow); recharge computed from the HYSEP Local-Minimum method increased from 10.2 in/yr at the WE-38 streamflow-gaging station to 10.8 in/yr at the Dalmatia streamflow-gaging station (50 to 53 percent of streamflow). These increases could be caused by an increase in the contribution of ground-water discharge to streamflow, but the increase is within the 5-percent error inherent in the streamflow record. If not caused by measurement error, the increase could be the result of ground water that passed beneath the small 2.8-mi^2 basin or the result of less evapotranspiration from ground water in the larger basin where drainage density is smaller.

An increase in watershed size caused a noticeable decrease in the estimate of mean-annual base flow computed by use of the Fixed-Interval and Sliding-Interval versions of the HYSEP method at the 45-mi^2 watershed scale (blue symbols) (fig. 20). The base-flow rate decreased from about 13.1 in/yr at the WE-38 streamflow-gaging station to 11.8 in/yr at the Klingerstown streamflow-gaging station (65 to 57 percent of streamflow). This decrease was not caused by watershed hydrology but was the result of the interval (2N*) used in the hydrograph-separation technique changing from 3 days to 5 days. Both methods can be viewed as accomplishing the base-flow separation by moving a bar one-interval wide upward until it intersects the trace of the streamflow hydrograph. The longer the interval length, the less amount of flow is separated as the base-flow component, because a wider bar is unable to be moved upward beneath storm peaks on the hydrograph as far as a narrower bar. The interval changes from 3 days to 5 days at a watershed area of 32 mi^2, to 7 days at 240 mi^2, and to 9 days at about 1,000 mi^2. The effect of changing the interval from 3 to 5 days can be seen

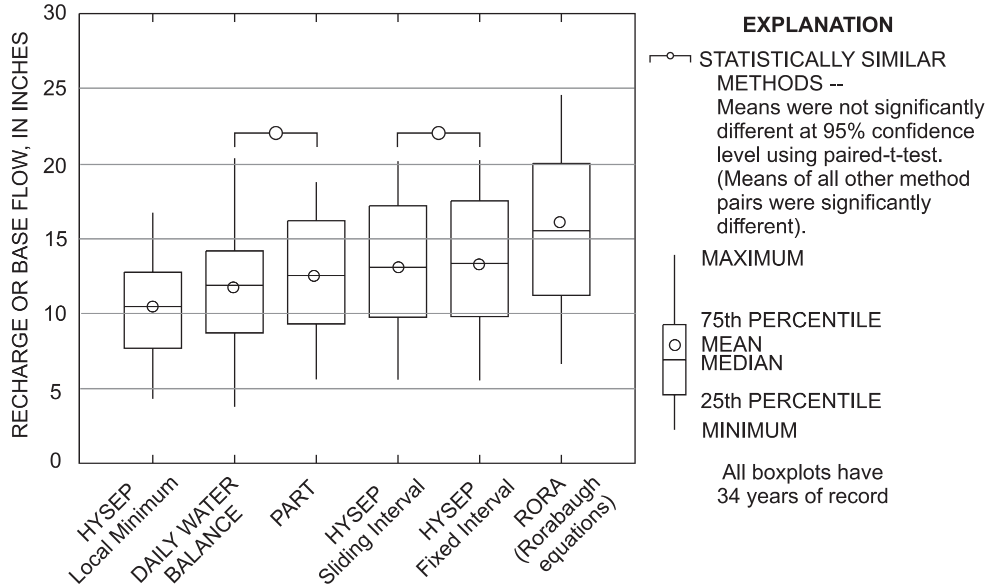

Figure 18. Results of comparing estimates of annual recharge and base flow at the WE-38 watershed, 1968-2001.

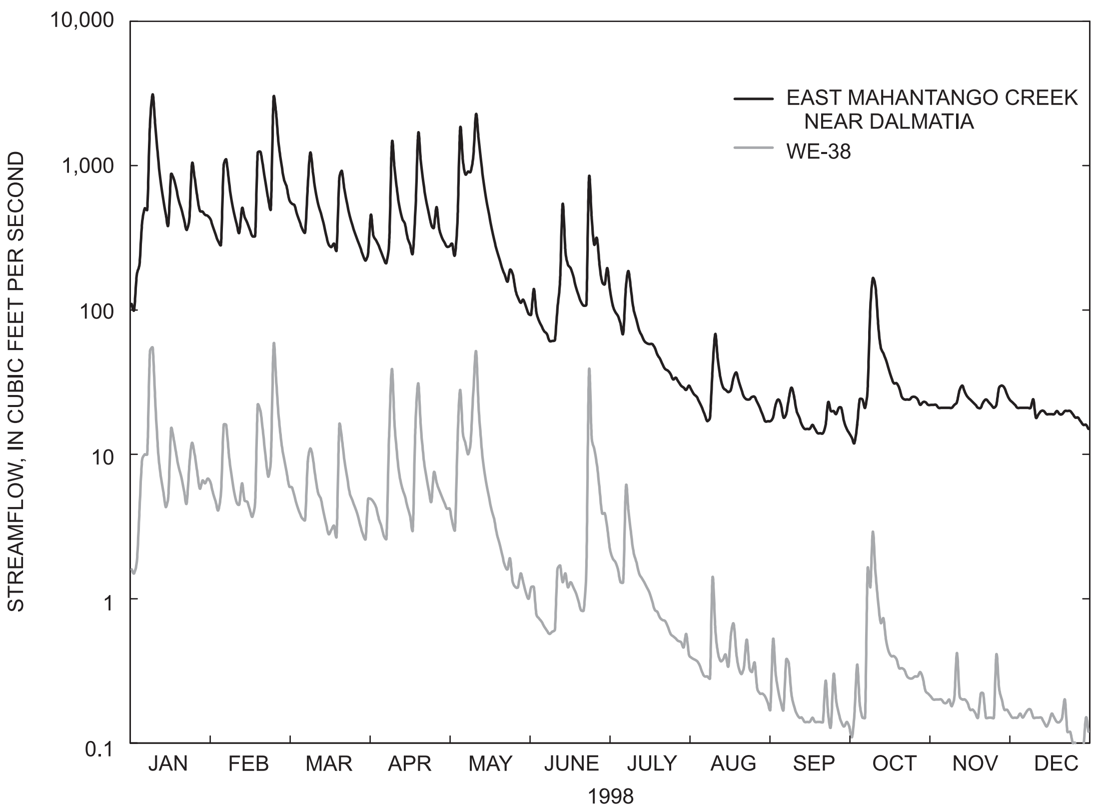

Figure 19. Streamflow hydrographs for watersheds of 2.8 square miles (WE-38) and 162 square miles (East Mahantango Creek near Dalmatia), 1998.

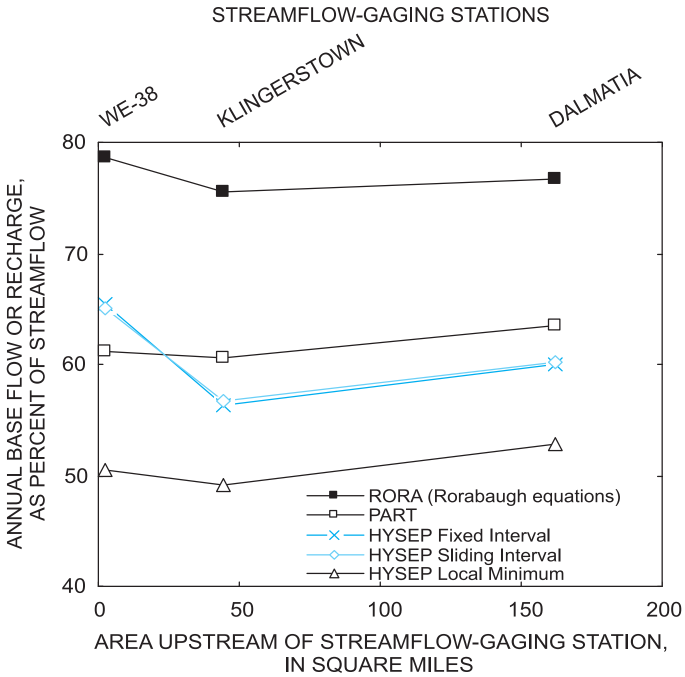

Figure 20. Mean annual recharge and base flow estimated at three watershed scales from the streamflow records at WE-38 (2.8 mi^2), Klingerstown (45 mi^2), and Dalmatia (162 mi^2).

on the hydrographs of base-flow separations by the use of the Fixed-Interval version of the HYSEP method at the WE-38 and Klingerstown streamflow-gaging stations (fig. 21). During the period April-May 1996, the Fixed-Interval version assigned 75 percent of the streamflow at the WE-38 streamflow-gaging station as base flow but only 60 percent of the streamflow at the Klingerstown streamflow-gaging station.

Of the base-flow methods tested, results from the Fixed-Interval and Sliding-Interval versions of HYSEP were statistically similar and both appear to be sensitive to watershed scale. Care should be used when comparing watersheds that cross the thresholds (32, 240, and 1,000 mi^2) where the interval width used in the Fixed-Interval and Sliding-Interval versions of HYSEP changes. For this reason, PART or the Local-Minimum version of HYSEP may be the preferred methods for base-flow estimation of watersheds of differing size.

Monthly Estimates

Seasonal estimates of recharge from hydrograph-separation of base flow usually are not recommended because of the lag time between recharge and ground-water discharge as base flow. However, for the small 2.8-mi^2 WE-38 watershed the same general seasonal trends were shown by the monthly estimates of both recharge and base flow from 1994 to 2001, indicating that monthly estimates from the base-flow methods may be as good as those derived from recharge methods (fig. 17). This result probably is due to the small size and quick hydrologic response (recession index of only 26.9 days) of the watershed. Therefore, the discrepancy between recharge computed by RORA and base flow from the PART method was compared using streamflow record from the WE-38 gaging station (2.8-mi^2 watershed) and the East Mahantango Creek gaging station near Dalmatia (162 mi^2) (fig. 22). As expected, the comparison indicated a greater discrepancy between the methods as watershed size increased, probably because of the increased lag time between ground-water recharge and discharge for the larger watershed with slower hydrologic response (recession index of 46.6 days).

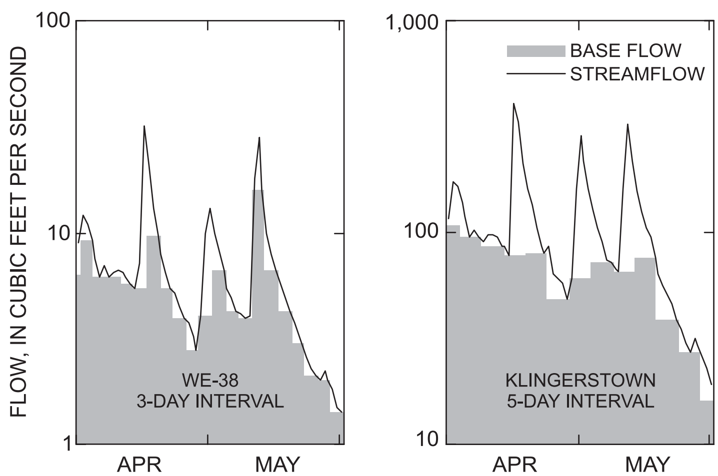

Figure 21. Effect of change in interval from 3 to 5 days on base-flow separation by the HYSEP Fixed-Interval method from streamflow records at WE-38 (2.8 mi^2) and East Mahantango Creek at Klingerstown (45 mi^2), April–May 1996.

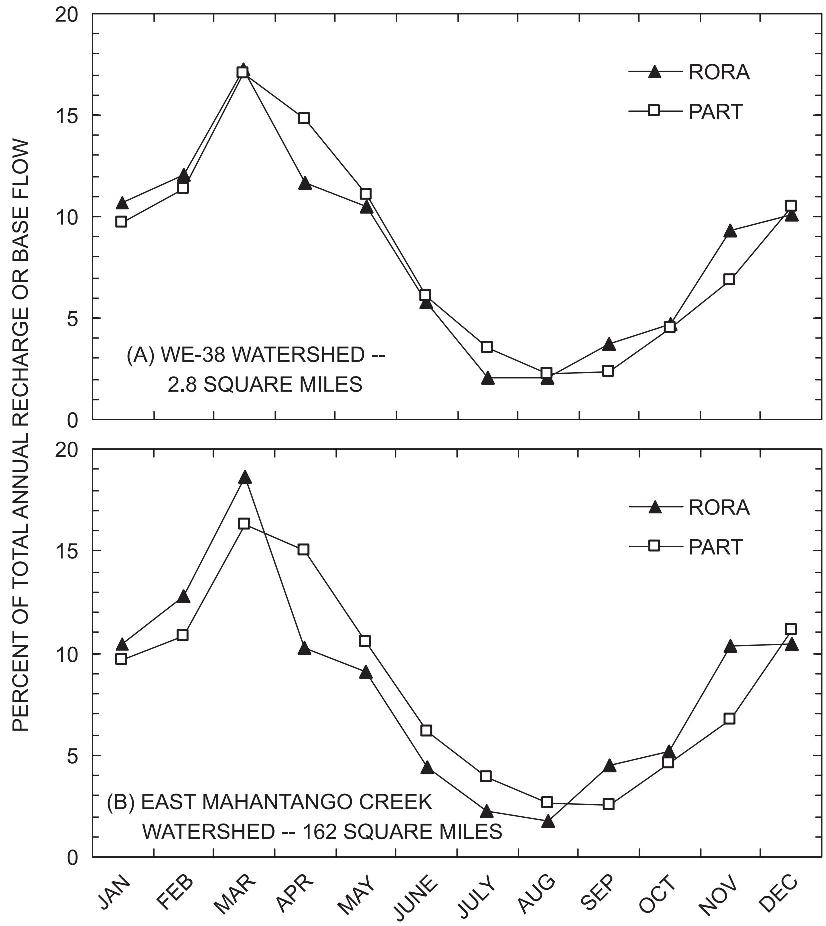

Figure 22. Mean-monthly recharge from RORA and base flow from PART for watershed scales of (A) 2.8 and (B) 162 square miles.

Summary and Conclusions

Ground-water recharge is a fundamental component in the water balance of any watershed. However, because it is nearly impossible to measure directly, numerous methods have been used to estimate recharge, and in some cases, base flow has been used as an approximation of recharge. This report describes the results of a study by the U.S. Geological Survey (USGS), in cooperation with the U.S. Department of Agriculture, Agricultural Research Service (ARS), to compare commonly used methods for estimating ground-water recharge and base flow. The study used ARS data available from 1968 to 2001 at their Masser Recharge Site and WE-38 experimental watershed and from streamflow-gaging stations on East Mahantango Creek, all of which are underlain by fractured bedrock and representative of a humid-continental climate in the northeastern United States. The ARS sites were chosen for study because they provide (1) long-term continuous hydrologic records, (2) measurements of unsaturated-zone drainage from gravity-drainage lysimeters (datasets that rarely are available) and (3) discharge data from the streamflow-gaging stations nested at three scales ranging from 2.8 to 162 mi^2. This study was one of several within the USGS Ground-Water Resources Program designed to provide an improved understanding of methods for estimating recharge in the eastern United States.

Recharge for this study was estimated on a monthly and annual basis from (1) unsaturated-zone drainage collected in gravity lysimeters, (2) daily water-balance equation, (3) water-table fluctuations in wells, and (4) the equations of Rorabaugh. Base flow was estimated by streamflow-hydrograph separation using the computer programs PART and HYSEP. Estimates of recharge and base flow were compared for a short 8-year period (1994-2001) that coincided with operation of the gravity lysimeters and a longer 34-year period (1968-2001) for which climate and streamflow data were available.

A common recommendation in the literature is that recharge should be estimated from multiple methods and the results compared, but in reality, comparing the results may be difficult because of differences inherent in the methods. In this study, the commonly used methods provided estimates not of recharge, but of some surrogate of recharge (potential recharge, net recharge, or base flow) representing differing segments of the watershed (point estimate or area estimate). For example, the unsaturated-zone drainage collected in gravity lysimeters provided an estimate of the potential recharge at a specific point location that does not compare directly to the net recharge for a watershed estimated from the Rorabaugh equations or base flow from hydrograph separation. Thus, recharge should be compared by multiple methods, but the inherent differences of each method must be given consideration when evaluating results.

Estimates of mean-annual recharge for 1994-2001 in the WE-38 watershed and at the Masser Recharge Site ranged from 9.9 to 14.0 in. (24-33 percent of precipitation), and mean-annual base flow ranged from 9.0 to 11.6 in. (21-28 percent of precipitation). The magnitude and variability of mean-annual recharge estimates was notably smallest with the water-table fluctuation method and greatest from the recession-curve displacement method by use of the RORA program. All methods showed the same general patterns for wet and dry years during the 8-year period, but the mean-annual recharge or base flow was shown to be statistically different between methods for 16 of 36 possible comparisons between methods. The Local-Minimum version of HYSEP and RORA were the most different of the methods—each was statistically different from six other methods.

The same general seasonal trends were shown by the monthly estimates of recharge and base flow for comparisons during 1994-2001; however, there was considerably greater variability among estimates of recharge. The variability among the recharge methods was greatest during months of greatest recharge (December through April). Base-flow estimates tended to generally be less than values of unsaturated-zone drainage from September through March and greater during April through August. This probably reflects the lag in timing between recharge and ground-water discharge. In general, monthly estimates from the base-flow methods were similar to those derived from the recharge methods for the WE-38 watershed. This result probably is due to the small size and fast hydrologic response of the watershed. The discrepancy between recharge and base-flow estimates became greater for the larger 162-mi^2 watershed of East Mahantango Creek, probably because of increased lag time between recharge and ground-water discharge.

Comparison of the results from the different methods of estimating recharge indicated that the mean-annual recharge for the 34-year period 1968 to 2001 at the WE-38 watershed ranged from 11.7 to 15.8 in., and mean-annual base flow ranged from 10.2 to 13.1 in. Recharge and base-flow methods based on streamflow data at the WE-38 streamflow-gaging station gave results that were about 11-13 percent smaller for the 8-year period because streamflow was less by a similar amount. Recharge computed from the water-budget method increased slightly for the 8-year period because that method is based on precipitation record (not streamflow), which was slightly greater in 1994 to 2001 than in 1968 to 2001. This illustrates the sensitivity of results to the underlying hydrologic datasets used by the methods.

Some observations and general conclusions from the comparison of methods used in this study are listed below.

- **Comparison of methods is recommended.**—To bracket the largest range of plausible recharge, comparison of recharge from RORA with base flow from the Local-Minimum version of the HYSEP method is recommended. These methods consistently provided the greatest and smallest estimates respectively of long-term annual recharge and base flow at this study site. Another useful approach, in concept, is to compare results from two methods—one that estimates potential recharge entering the ground-water system and one that estimates base flow leaving the system. Thus, comparison of potential recharge from the water-balance equation with base flow from one of the hydrograph-separation methods (PART or Local Minimum version of HYSEP) is recommended.
- **Watershed size affected base-flow estimates for some methods.**—The increase in watershed size caused a noticeable decrease in the estimate of mean-annual base flow computed by the use of the Fixed-Interval and Sliding-Interval versions of the HYSEP hydrograph-separation method between the 2.8-mi^2 WE-38 watershed and the 45-mi^2 watershed upstream of the Klingerstown streamflow-gaging station. The base flow decreased from 13.1 in/yr at the WE-38 station to 11.8 in/yr at the Klingerstown station (65 to 57 percent of streamflow). This decrease was not caused by watershed hydrology but mostly was the result of the change in "interval" used in the hydrograph-separation algorithm from 3 days to 5 days. It appears the HYSEP Fixed-Interval and Sliding-Interval results are artificially lessened when watershed size increases at thresholds of about 32, 240, and 1,000 mi^2. Thus, if watersheds of various sizes are being compared, it may be advantageous to use PART or the Local-Minimum version of HYSEP because they did not seem to be artificially affected by watershed scale.
- **Long-term base-flow estimates are comparable to recharge estimates.**—For determining mean-annual recharge, base-flow estimates are comparable to recharge estimates from most methods. Excluding estimates from RORA, recharge for the 8-year period 1994 to 2001 at the Masser Recharge Site and the WE-38 watershed ranged from 9.9 to 12.3 in., compared to estimates of 9.0 to 11.6 in. from base-flow methods. Mean-annual recharge estimated by the use of RORA

was 14.0 in. It nearly always provided the greatest estimate of annual recharge among the methods compared in this study.

- **Water-level fluctuations in wells should be used with caution in low-storage fractured-rock aquifers.**—Because of the variability of water-level response in observation wells in fractured rock and the sensitivity of recharge to small errors in estimating specific yield in low-storage aquifers, estimates of recharge from multiple observation wells should be used if possible. If all other factors are equal, wells in upland settings will be the best candidates for use in estimating ground-water recharge by the WTF method.

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