
Comparison of recharge estimates at a small watershed in east-central Pennsylvania, USA

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Abstract The common recommendation that recharge should be estimated from multiple methods is sound, but the inherent differences of the methods make it difficult to assess the accuracy of differing results. In this study, four methods for estimating groundwater recharge and two methods for estimating base flow (as a proxy for recharge) are compared at two hydrologic research sites in east-central Pennsylvania, USA. Results from the multiple methods all provided reasonable estimates of groundwater recharge that differed considerably. The estimates of mean annual recharge for the period 1994–2001 ranged from 22.9 to 35.7 cm—about 45% of the mean of all estimates. For individual years, recharge estimates from the multiple methods ranged from 30 to 42% of the mean value during the dry years and 64 to 76% of the mean value during wet years. Comparison of multiple methods was found to be useful for determining the range of plausible recharge rates and highlighting the uncertainty of the estimates.

Keywords Groundwater recharge · Base flow ·
Fractured rocks · USA

Introduction

Groundwater recharge is nearly impossible to measure directly, so 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 frequently is estimated by an analysis of streamflow records, groundwater levels, or water balance. In some cases, base flow has been used as an approximation of recharge.

A common recommendation is that recharge should be estimated by the use of multiple methods and the results compared (Nimmo et al. 2003; Healy and Cooke 2002; Scanlon et al. 2002). This is a prudent approach, though good-quality data usually are not available to make estimates from multiple methods. However, in east-central Pennsylvania, USA, there are two hydrologic research sites, operated by the US Department of Agriculture, Agricultural Research Service (ARS), as part of their Pasture Systems and Watershed Management Research Unit Research Watershed, where long-term monitoring of climate, groundwater, surface water, and the unsaturated zone allows comparison of multiple methods for estimating groundwater recharge with available data.

This paper compares results from four methods for estimating groundwater recharge and two methods for estimating base flow by hydrograph separation and discusses their application and limitations. The methods and results reported here are summarized from Risser et al. (2005).

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 7.3-km² sub-watershed of East Mahantango Creek that drains a 420-km² rural, agricultural watershed in the unglaciated part of the Valley and Ridge Physiographic Province. The Masser Recharge Site is a 0.8-ha plot in an upland setting about 1.2 km west of the WE-38 watershed. Although the Masser Recharge Site is not within the WE-38 watershed, the physical and hydrologic characteristics of the site are representative of conditions found in parts of the WE-38 watershed (Table 1). A summary of site conditions and the groundwater system of the WE-38 watershed is contained in Urban (1977) and Gburek et al. (1999). The Masser

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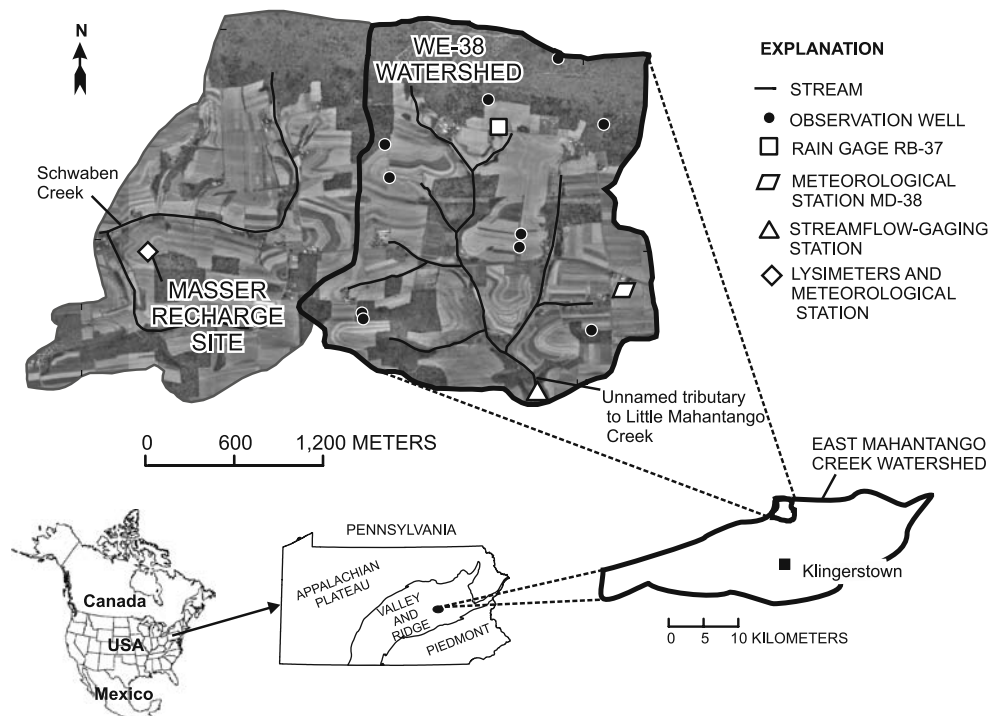


Fig. 1 Location of Masser Recharge Site and WE-38 watershed in east-central Pennsylvania, USA

Recharge Site is described in detail in Gburek and Folmar (1999b) and Stout et al. (1998).

The climate of the study area is classified as humid continental. Average monthly temperature ranges from -4°C in January to 22°C in July. Annual precipitation averages about 107 cm and is distributed fairly evenly throughout the year. On average, annual potential evapotranspiration is about 66 cm (Waltman et al. 1997), so annual precipitation exceeds potential evapotranspiration by about 41 cm. Groundwater moves predominantly within secondary openings in folded and fractured shales, siltstones, and sandstones of the Trimmers Rock Formation of Devonian age and the Catskill Formation of Devonian and Mississippian age. This complex water-table aquifer

exists within a shallow layered framework in which fracture density decreases with depth and the most conductive layers are at depths of less than about 22 m below land surface. Bedrock is overlain by shallow soils, mostly residual silty loams, which are permeable and well-drained causing little or no direct surface runoff to be produced during storms.

Available data

In the WE-38 watershed, ARS has collected meteorological and streamflow data since 1968 and groundwater data since 1973. At the Masser Recharge Site, unsaturated-zone drainage has been collected by the use of 28 zero-

Table 1 General characteristics of the Masser Recharge Site and WE-38 watershed in east-central Pennsylvania, USA

Site characteristics	Masser recharge site	WE-38 watershed
Area (km^2)	7.3	0.008
Topographic setting	Near top of a knoll with slopes of about 2%. Altitude ranges from 261–267 m	Headwater basin with variable slopes ranging from less than 2 to 80%. Altitude ranges from about 230 to 490 m
Mean annual precipitation 1994–2001	0.99 m from rain gage at site	1.07 m from rain gage RB-37 (location shown in Fig. 1)
Soils and overburden	Highly weathered overburden from 0 to 1.5 m thick with silty loam and stony silty loam soils	Highly weathered overburden from 0 to 2.4 m thick with silty loam and stony silty loam soils covering about 75% of the watershed
Land cover	Mowed grass	Mostly cropland and pasture with mature forest on ridge to the north. Major land cover percentages—crops 47%, forest 39%, grass or pasture 10%, developed 4%
Bedrock geology	Fine grained sandstone with interbedded sandstone conglomerate, siltstone, and shale of the Catskill Formation	Shale, siltstone, and sandstone of the Catskill Formation and mostly shale of the Trimmers Rock Formation near the outlet of the watershed
Depth to groundwater	~5–15 m	Near streams water table can be at land surface seasonally and is as much as 25 m below land surface beneath uplands

tension monolith lysimeters (16 monitored continuously) since 1994. Data from seven of the 61-cm diameter lysimeters were used for this study. The seven lysimeters collect and monitor percolate at 1 m below a grass-covered field plot. The lysimeters are situated in two adjacent rows within an area of about 15 m².

In this study, estimates of recharge and base flow are compared by various methods for the WE-38 watershed and nearby Masser Recharge Site for the 8-year period (1994–2001) coinciding with the operation of the lysimeters at the Masser Recharge Site. Daily precipitation data used in this study were from rain gage RB-37 in the WE-38 watershed (Fig. 1) and at the Masser Recharge Site. Daily temperature data were used from measurements collected at meteorological station MD-38 in the WE-38 watershed (Fig. 1) and at the Masser Recharge Site. Daily streamflow data were used from a gaging station at the outlet of the WE-38 watershed. Daily groundwater levels were used from 10 wells in the WE-38 watershed. The wells were constructed with 6-m lengths of 15-cm diameter casing and were completed as open holes below the casing to depths of 17–61 m below land surface.

Application of methods

Recharge for this study was computed on an annual basis by four methods:

Unsaturated-zone drainage measured from zero-tension monolith lysimeters (Lerner et al. 1990)

Daily water balance by use of the hydrologic evaluation of landfill performance (HELP3) model (Schroeder et al. 1994)

Water-table fluctuations (WTF) in wells (Healy and Cooke 2002)

Rorabaugh equations by the use of computer programs RORA (Rutledge 1998) and PULSE (Rutledge 1997)

Base flow was estimated by two computerized methods of hydrograph separation:

PART (Rutledge 1998)

HYSEP (Pettyjohn and Henning 1979; Sloto and Crouse 1996).

Unsaturated-zone drainage, collected by lysimeters at the Masser Recharge Site, provides a direct measurement of downward water flux, which is a dataset that is rarely available. The other recharge and base-flow methods were chosen for analysis because they are straightforward in their application and are widely used by practicing hydrologists in the humid eastern United States. Although base flow is not recharge, it is sometimes used as an approximation of recharge when underflow, evapotranspiration from riparian vegetation, and other transfers of groundwater from the watershed are thought to be minimal.

The methods used in this study have inherent differences that need to be considered when comparing their results (Table 2). The most basic difference is that recharge methods are designed to quantify the amount of water added to the water table, whereas base-flow methods quantify that part of the streamflow hydrograph attributed to groundwater discharge. Thus, except for the water-table fluctuation method, each method provides an estimate, not of recharge, but of either *potential* recharge (percolation below the root zone that should reach the water table in the future) or *net* recharge defined by Rutledge (2000) as recharge minus groundwater evapotranspiration or leakage to a deeper aquifer. Other inherent differences are that some methods provide estimates at a point location and others provide a spatially averaged value; all are indirect estimates in that none directly measure the flux of water across the water table. In addition, estimates of recharge and base flow are derived by the use of differing data sources (e.g., meteorological data, groundwater levels, or streamflow); thus, any errors in those datasets are likely to be incorporated into the results depending on the datasets required by the method.

In this study, methods for estimating recharge and base flow were applied at the Masser Recharge Site and WE-38 watershed for 1994–2001. Note that, although six basic methodologies were applied, two versions of the Rorabaugh equations and base-flow separation were tested, providing eight differing estimates of recharge or base flow (Table 2). Recharge was estimated at the Masser Site by the gravity lysimeters and water-budget methods and at the WE-38 watershed by all methods except gravity lysimeters. Recharge estimates at the Masser Recharge Site should be comparable to estimates from WE-38 watershed because of its close proximity and similarity of topographic setting, soils, geology, land cover, and climate. The Masser Recharge Site is most representative of pasture and grassed areas on interfluvies within the WE-38 watershed.

Unsaturated-zone drainage

Unsaturated-zone drainage was used to estimate recharge from direct measurements of percolate collected in seven zero-tension monolith lysimeters at the Masser Recharge Site during 1994–2001. The seven lysimeters chosen for analysis all had relatively continuous records of percolate collected at a depth of 1 m below a grass plot. Other lysimeters at the site were either constructed differently or had significant periods of missing record.

Zero-tension lysimeters are a method of estimating potential recharge by directly measuring the vertical flow of water through a large, undisturbed section of the unsaturated zone at a depth below most root systems (Lerner et al. 1990). 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 potential volume of recharge that could reach the water table, although not necessarily the timing of its arrival. The advantage of zero-tension lysimeters is

Table 2 Summary of methods used for estimating recharge at the Masser Recharge Site and WE-38 watershed

Method	Computer program or instrumentation	Quantity estimated	Scale of estimate	Required data	Relative cost or effort required	Method applied at site	
						WE-38 watershed	Masser recharge site
Unsaturated-zone drainage Daily water balance	Zero-tension lysimeters HELP3 Model	Recharge (potential) Recharge (potential)	Point Point or areal	Measured percolate Meteorological data, soil properties, and vegetation type	High Medium	X X	X X
Water-table fluctuation Rorabaugh equations	Observation wells RORA program PULSE program	Recharge (net) Recharge (net)	Point or areal Areal	Groundwater levels in wells Streamflow	Medium Medium	X X X	X X X
Base flow from HYSEP	HYSEP program: local minimum version HYSEP program: fixed interval version	Base flow Base flow	Areal Areal	Streamflow	Low	X	X
Base flow from PART	PART program	Base flow	Areal	Streamflow	Low	X	X

that they are one of the few methods that provide an estimate of recharge potential 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 et al. 1990).

The mean percolate from the seven zero-tension lysimeters for the 8-year period was 31.1 cm (Table 3), although it varied by individual lysimeter from about 27–35 cm, indicating either the inherent spatial variability of the soils within the small (~15 m²) plot or the differences caused by lysimeter installation.

Water-balance equation

Estimates of recharge from a daily water balance were computed by use of the computer program hydrologic evaluation of landfill performance (HELP3) (Schroeder et al. 1994). HELP3 was developed by the US Army Waterways Experiment Station to compute the water balance of landfills. It 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. Overland flow and subsurface runoff are accounted for in the model, but two-dimensional flow is not explicitly simulated. Recharge estimates from HELP3 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 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 et al. 2003). The HELP3 model was applied at the Masser Recharge Site to estimate recharge at the lysimeter installation (point location) and at the WE-38 watershed to provide spatially variable (areal) estimates in an approach similar to that described by Jyrkama et al. (2002). When used to estimate areal estimates for a watershed, HELP3 has drawbacks over the more advanced rainfall-runoff models, which are designed to be calibrated at various spatial and temporal scales to streamflow hydrographs. The advantage of the HELP3 model is in ease of use and fewer data requirements compared to rainfall-runoff models.

Point estimate at Masser Recharge Site

Recharge was estimated from HELP3 at the Masser Recharge Site during 1994–2001 using input data for 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 US Department of Agriculture (Richardson and Wright 1984). The total

Table 3 Estimates of annual recharge for Masser Recharge Site and WE-38 watershed for 1994-2001

Year	Precipitation (cm)	Base flow or recharge, in cm					RORA	PULSE	Unsaturated-zone drainage	Water-table fluctuations	Water budget (WE-38 watershed)	Mean	SD	Range as % of mean
		Base flow HYSEP local minimum	Base flow HYSEP fixed interval	Base flow PART										
1994	125.2	42.5	49.0	47.7	59.5	45.3	37.9	30.1	33.2	43.1	9.4	68		
1995	98.1	24.5	30.5	27.1	35.5	23.7	21.4	23.5	27.9	26.8	4.6	53		
1996	140.1	33.8	47.0	42.5	62.4	41.6	47.6	36.1	45.6	44.6	8.7	64		
1997	86.9	15.4	18.5	18.4	20.6	18.8	15.2	20.4	20.1	18.4	2.1	30		
1998	120.4	24.2	34.6	29.4	39.5	30.1	51.2	28.1	51.7	36.1	10.5	76		
1999	104.0	14.6	19.6	17.0	22.5	18.3	28.9	24.8	23.7	21.2	4.7	68		
2000	108.8	17.3	22.4	20.8	28.5	22.5	33.0	24.7	30.1	24.9	5.2	63		
2001	72.1	10.9	14.1	14.2	16.8	14.2	13.2	14.2	14.2	14.0	1.6	42		
Mean	106.9	22.9	29.5	27.1	35.7	26.8	31.1	25.2	30.8	28.6	4.0	45		
SD	21.8	10.7	13.2	12.3	17.4	11.3	14.2	6.5	12.6	12.3				
Range as % of mean	646	138	119	123	128	116	123	87	122	119				

SD standard deviation

depth of the soil profile simulated with HELP3 corresponds to the 1-m depth of the lysimeters, and the soil properties were obtained directly or computed from properties measured at the Masser Recharge Site (Stout et al. 1998) or listed in the Northumberland County soil survey (Eckenrode 1985). The data values used for simulation are summarized in Risser et al. (2005).

Estimates of annual recharge during 1994-2001 from the water-balance equation at the Masser Recharge Site were highly correlated to estimates from the zero-tension lysimeters ($r^2=0.99$) and mean recharge for the 8-year period was 31.2 cm—nearly identical to the mean percolate from the lysimeters (31.1 cm). The close agreement 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 by adjusting HELP3 model-input parameters.

Areal estimate at WE-38 watershed

Because of the good agreement between estimates of recharge between HELP3 and the zero-tension lysimeters at the Masser Recharge Site, the HELP3 program was used to estimate recharge for the entire WE-38 watershed by using a geographic information system (GIS) to divide the watershed on the basis of similar land cover, hydrologic soil group, and slope into 26 landscape units. The properties used in the HELP3 program for each landscape unit are given in Risser et al. (2005). 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. For the 8-year period 1994-2001, mean annual recharge was 30.8 cm for the watershed as a whole (Table 3) and recharge ranged from 26.4 to 34.0 cm across the 26 landscape units.

The HELP3-derived recharge estimates for the WE-38 watershed are similar to other estimates (Table 3), but the

sum of mean annual recharge and direct runoff from the HELP3 water balance does not correspond very closely to measured streamflow from the WE-38 watershed. During 1968-2001, the HELP3 program simulated an average of 29.7 cm/yr of recharge and 7.7 cm/year of direct runoff, making the sum of simulated recharge plus runoff equal to 37.4 cm/year. Streamflow at the WE-38 gaging station averaged 51.1 cm/year during the same period. Although some of the discrepancy could be caused by error in streamflow measurements at the gaging station, evapotranspiration may be overestimated in the HELP3 water balance. McGuire et al. (2002) suggest from oxygen-18 evidence that residence times of shallow, lateral flow paths comprising stream water are less than for recharge to the water table. Lateral flow, which was not included in water-balance simulations, could have caused some of the discrepancy between the water balance results and measured streamflow.

Water-table fluctuations

Water-table fluctuations (WTF) in wells were used to estimate annual recharge for the watershed by analyzing hydrographs from 10 wells in upland settings (Fig. 1) for 1994-2001. 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 as:

$$R = \Delta h \cdot S_y, \quad (1)$$

where R is recharge (cm), Δh is change in water-table altitude (cm), and S_y is specific yield (dimensionless).

In this study, the rise in water level ' Δh ' 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. The average specific yield of the watershed, S_y , was estimated empirically from the watershed-wide

water-table decline measured during periods of streamflow recession (Olmsted and Hely 1962, p. A-16) as:

$$S_y = S/\Delta h, \quad (2)$$

where S is streamflow volume during a recession period consisting of only groundwater discharge, expressed as depth of water over the watershed area. S was measured at the streamflow-gaging station and Δh was computed as the area-weighted average water-level decline measured in observation wells in the WE-38 watershed. Application of Eq. (2) for 11 periods of streamflow recession during months when evapotranspiration of groundwater was expected to be minimal gave an average S_y of 0.013 for the watershed. This compares to other estimates of S_y ranging from 0.001 to 0.01 determined from calibration of a groundwater flow model in WE-38 watershed (Gburek et al. 1999) and of about 0.01 estimated from water-table rises and lysimeter percolate measured at the Masser Recharge Site (Gburek and Folmar 1999b). Mean annual recharge computed by the WTF method for the WE-38 watershed for 1994-2001 was 25.2 cm (Table 3). The mean value for the watershed was determined from equation 1 using an area-weighted average annual water-table rise from the 10 upland wells of 19.4 m and S_y of 0.013.

To estimate spatial variability in recharge by this method, mean annual recharge during 1994-2001 was computed for 10 individual upland wells (mid-slope or headwater settings) by use of Eq. (1) from the estimates of mean annual Δh at each well, which ranged from 6.6 m to 112 m, and from estimates of apparent S_y determined at each well. 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 Eq. (1). The apparent specific yield was determined by applying Eq. (2) for the water-level decline at each well instead of for the watershed average. Apparent specific yields for the individual wells ranged from 0.0035 to 0.035. The apparent specific yields for each well were multiplied by the water-level rise to compute annual recharge for the WE-38 watershed during 1994-2001. Estimates of mean-annual recharge computed from the individual upland wells ranged from 19.3 to 39.1 cm.

The variability in estimates of Δh and S_y among wells illustrates the practical difficulties in application of the method in fractured-rock aquifers. The variability of Δh 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. The variability in S_y illustrates the possibility of extreme variability of this parameter in a fractured-bedrock aquifer. Because S_y is so small at this site, small absolute differences in estimates of S_y can cause large relative differences in estimated recharge.

Rorabaugh equations with RORA and PULSE

Recharge was estimated by analysis of streamflow records using two approaches—the computer programs RORA

(Rutledge 1998) and PULSE (Rutledge 1997). RORA provides estimates of groundwater recharge from the displacement of the streamflow-recession curve using equations developed by Rorabaugh (1964) and Glover (1964). PULSE uses the same equations with an equation from Daniel (1976) to compute the groundwater discharge to a stream following an instantaneous pulse of recharge to the water table. Although groundwater 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 groundwater-discharge hydrograph that is a good match to recession periods of measured 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 use streamflow data to estimate groundwater recharge, but they are not “hydrograph-separation” techniques. They are based on a one-dimensional analytical model of groundwater discharge to a fully penetrating stream in an idealized, homogenous aquifer with uniform recharge. 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.

Annual recharge estimates were made with the RORA and PULSE programs using streamflow data from the WE-38 streamflow-gaging station and a recession index of 26.9 days. The recession index (K) was determined from streamflow records by use of the RECESS program (Rutledge 1998). Twenty recession segments were selected during the months of September through May to exclude periods of significant evapotranspiration from groundwater.

Mean annual recharge for 1994-2001 was 35.7 cm from the RORA program and 26.8 cm from the PULSE program (Table 3). RORA gives the highest estimate of mean annual recharge of all methods, which differs significantly from that of PULSE. Estimates from PULSE might be expected to be less than RORA, especially in summer, because recharge is computed by fitting the model to streamflow recessions, which are affected by groundwater evapotranspiration in summer. However, the greatest differences between RORA and PULSE are during winter months when evapotranspiration is small and the closest agreement between the methods would be expected. This discrepancy makes the accuracy of recharge estimates from RORA difficult to evaluate.

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 groundwater discharge from areal precipitation to the aquifer. 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. RORA and PULSE were developed to analyze aquifers characterized by areally diffuse recharge events that are fairly concurrent with peaks in streamflow. Thus, results from the methods may not be reliable for recharge caused by leakage from regional systems, slow melting of snow, and percolation through streambeds (Rutledge 1998, p. 3).

Base flow from streamflow-hydrograph separation

Base flow was estimated from daily values of streamflow recorded at the outlet of the WE-38 watershed by streamflow-hydrograph separation using the PART and HYSEP programs. The PART and HYSEP programs separate 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 et al. (1982):

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

where N is the time after which surface runoff ceases (days); and A is the watershed area (mi^2).

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, where $2N^*$ is the nearest odd integer (between 3 and 11) to twice the value of N . 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. 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. In this study, the results from the sliding-interval version are not presented because they were nearly identical to results from the fixed-interval version.

Application of PART and HYSEP was straightforward, requiring no user input other than the drainage area. Mean annual base flow at the WE-38 streamflow-gaging station during 1994–2001 was 27.1 cm from the PART program. Estimates from the HYSEP program were 22.9 cm (local-minimum version) and 29.5 cm (fixed-interval version).

When used as a proxy for recharge, base flow has sometimes been referred to as “effective recharge” (Daniel 1996), “base recharge” (Szilagyi et al. 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 groundwater discharge, and that groundwater discharge is approximately equal to recharge. Implicit is the assumption that groundwater losses from the gaged watershed caused by underflow, groundwater evapotranspiration, and exports of groundwater are minimal. If these conditions are met, base flow may provide a reasonable estimate of recharge for long time periods (1 year or more).

In the WE-38 watershed, water use is minimal and findings by Gburek and Folmar (1999a) suggest that subsurface flow systems are self-contained at the first- or second-order streams, a scale smaller than the 7.3 km^2 area upstream of the gaged outlet of the watershed. Thus, base flow measured at the outlet should be a reasonable estimate of recharge minus any losses from evapotranspiration of groundwater. Still, the 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.

Comparison of methods

Correlations among estimates of annual recharge or base flow during 1994–2001 from the eight methods (all estimates except from the daily water balance equation at the Masser Recharge Site) are shown with scatter plots in Fig. 2. Results from the daily water-balance method at the Masser Recharge Site compared closely to results from the zero-tension lysimeters at the site; thus, application of the method was extended to the WE-38 watershed and those results are compared to the other methods.

Visual examination of trends along with Pearson correlation coefficients indicate that results from methods based on streamflow data—HYSEP local-minimum version, HYSEP fixed-interval version, PART, RORA, and PULSE—are all highly correlated with r^2 values of at least 0.96. Estimates of recharge from the zero-tension lysimeters, water-table fluctuations, and water-balance equation are less closely correlated than methods based on streamflow data, probably because they are more independent estimates based on differing underlying datasets. A notable exception is the high correlation (0.96) between annual recharge estimates from the zero-tension lysimeters at the Masser Recharge Site and the water-balance equation at the WE-38 watershed. Both methods estimate potential recharge passing beneath the root zone, which may explain the similarity of those results.

Differences between methods were tested statistically by comparing annual estimates of recharge or base flow using a paired t -test (Helsel and Hirsch 1992, p. 147). Prior to conducting the paired t -test, a Kolmogorov-Smirnov Test could not reject the assumption that, for any two methods, the paired differences were normally distributed. The statistical tests showed that mean recharge or base flow was significantly different at the 95% confidence level for 11 of the 28 possible pairs of methods (Table 4). All base-

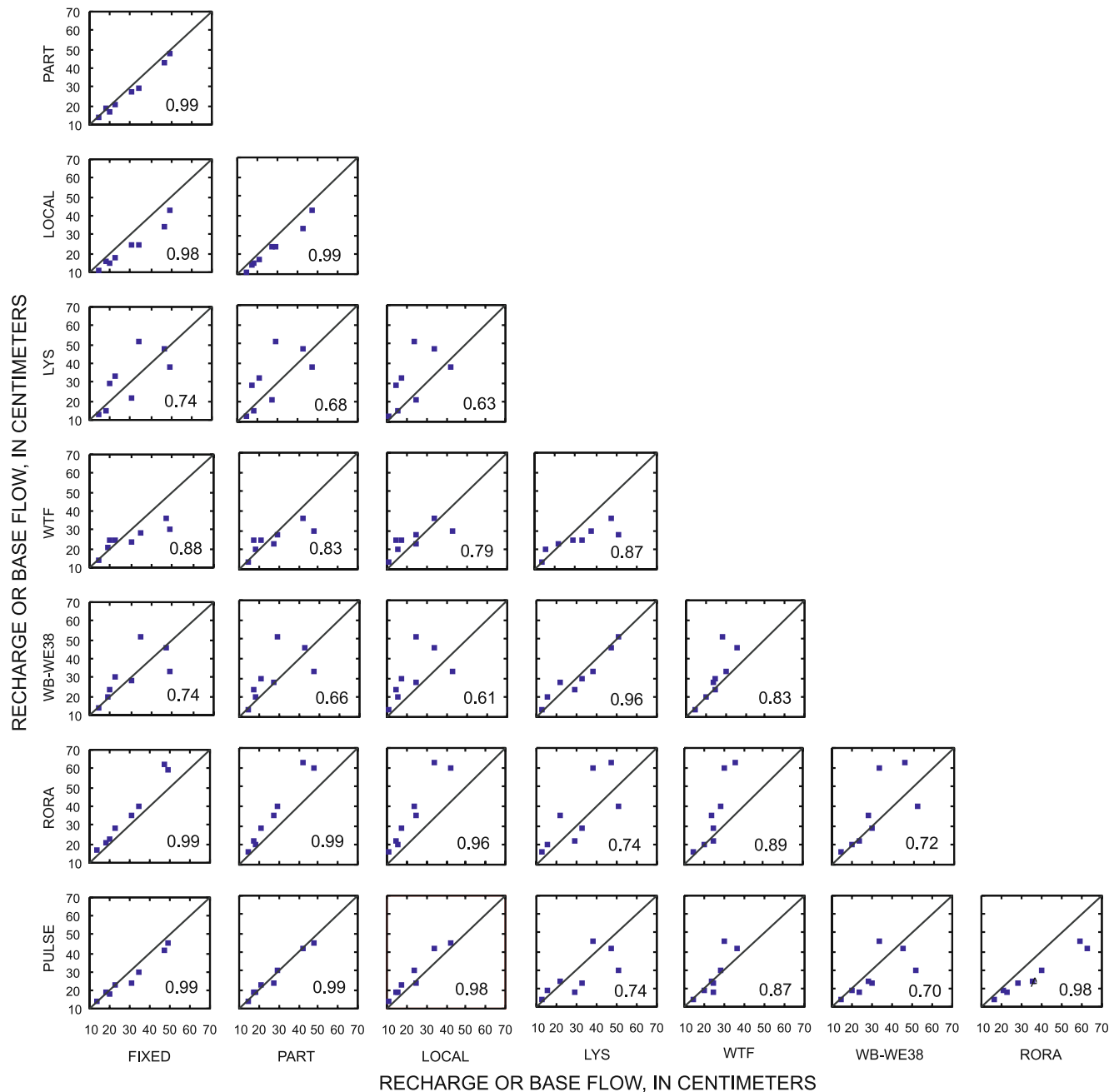


Fig. 2 Scatter plots showing correlations among estimates of annual recharge and base flow for Masser Recharge Site and WE-38 watershed, 1994-2001. Number in the corner of each box is the correlation coefficient (r^2); diagonal line is line of equality. *FIXED* HYSEP fixed-interval version; *PART* Rorabaugh equations with PART program, *LOCAL* HYSEP local minimum version; *LYS* unsaturated-zone drainage from seven zero-tension lysimeters; *WTF* water-table fluctuations from 10 wells; *WB-WE-38*, daily water-budget method at WE-38 watershed; *RORA*, Rorabaugh equations with RORA program

flow methods differed significantly from each other. The local-minimum version of the HYSEP method was the most different of the base-flow methods. It was significantly different than five other methods, with mean differences that generally were greater than for other base-flow methods (Table 4). Of the recharge methods, results from RORA differed significantly from the most (five) other methods, and unsaturated-zone drainage from the zero-tension lysimeters differed from the fewest (zero) other methods. Although the local-minimum version of HYSEP and RORA

were flagged as the most different methods, statistically, it is not possible to say that those results are in error.

Variability of annual estimates

Considerable variability exists in the estimates of annual recharge or base flow among the eight methods during 1994-2001 (Fig. 3 and Table 3). The largest spread of estimates was about 30 cm during each of the wet years (1994, 1996, and 1998); representing 64, 68, and 76% of the

Table 4 Statistical comparison and mean difference, in centimeters, between paired estimates of annual recharge or base flow, 1994-2001

	HYSEP fixed interval	HYSEP local minimum	PART	Rorabaugh equations with PULSE	Rorabaugh equations with RORA	Unsaturated zone drainage	Water-table fluctuation	Daily water balance at WE-38
HYSEP fixed interval		6.6 ^a	2.3 ^a	2.8 ^a	-6.4 ^a	-1.6	4.8	-1.8
HYSEP local minimum	-6.6 ^a		-4.3 ^a	-3.8 ^a	-13 ^a	-8.1	-1.7	-8.4 ^a
PART	-2.3 ^a	4.3 ^a		.36	-8.6 ^a	-3.8	2.5	-4.1
Rorabaugh equations with PULSE	-28 ^a	3.8 ^a	-0.36		-4.1 ^a	-4.3	2.2	-4.6
Rorabaugh equations with RORA	6.4 ^a	13 ^a	8.6 ^a	4.1 ^a		4.6 ^a	11 ^a	4.3
Unsaturated zone drainage	1.6	8.1	3.8	4.3	-4.6		6.6	-1.8
Water-table fluctuation	-4.8	1.7	-2.5	-2.2	-11 ^a	-6.6		-6.6 ^a
Daily water balance at WE-38	1.8	8.4 ^a	4.1	4.6	-4.3	.18	6.6 ^a	

^a Indicates that the mean-recharge or base-flow values for the paired methods are significantly different based on a paired *t*-test at the 95% confidence interval. Mean difference is computed as row value minus column value; thus, negative value indicates that row value is less than the column value

mean of all eight methods, respectively, during those years. Results from the methods compared more closely during dry years (1997 and 2001); variability among estimates was only 5.4 cm in 1997 and 5.9 cm in 2001, representing 30 and 42% of the mean of all eight methods, respectively, for those years.

The percentage of precipitation contributing to recharge each year varied directly in relation to the quantity of annual precipitation. During 1994-2001, mean annual recharge from the eight methods varied from as little as 19% of precipitation during the driest year to about 35% of precipitation during the second wettest year (Fig. 4). This direct relation is the result of more water being available for recharge (precipitation minus evapotranspiration) during wet years. The variability of annual recharge estimates also relates directly to the quantity of precipitation.

No single method always produced the largest or smallest estimate of annual recharge during 1994-2001 as shown in Fig. 3. The largest estimates were usually from RORA or unsaturated-zone drainage. The smallest estimates were usually from the local-minimum version of HYSEP or the unsaturated-zone drainage. The fact that the unsaturated-zone drainage method gave the largest estimate of recharge for some years and smallest estimate for

other years indicates this method is more responsive to differences in precipitation than most other methods. The large annual variability from the unsaturated-zone drainage is in contrast to the small annual variability of recharge from the WTF method. Conceivably, the highly variable amounts of annual percolate collected in the soil by the lysimeters is lagged in time and damped in magnitude before reaching the water table. McGuire et al. (2002) found that groundwater did have a longer residence time than soil water at the Masser Recharge Site by analysis of seasonal variations of oxygen-18; however, it is also possible that the WTF method underestimates the annual variability in recharge because S_y is assumed to be constant. Heppner and others (2007) indicate that assuming seasonal variability in S_y would allow the WTF method to better estimate the variability in recharge shown by the zero-tension lysimeters.

Variability of long-term estimates

Estimates of mean annual recharge and base flow (as a proxy for recharge) for the 8-year period 1994-2001 for the Masser Recharge Site and the WE-38 watershed

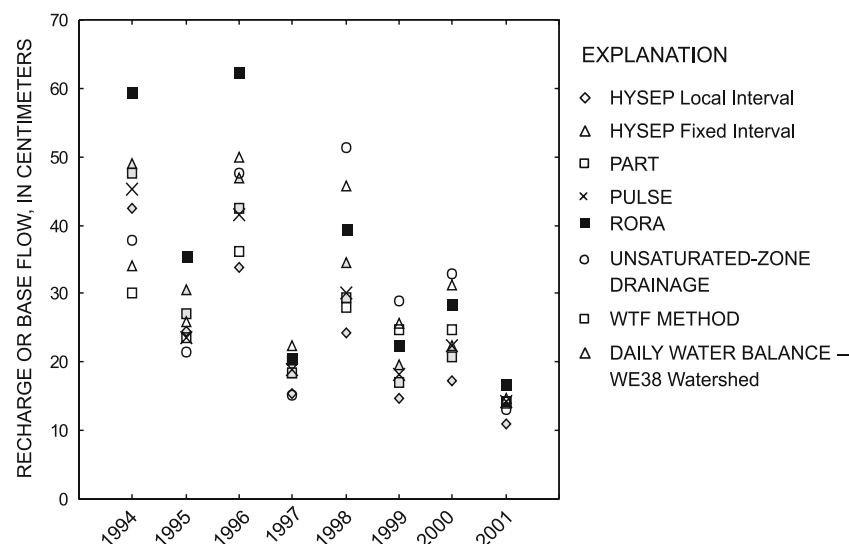


Fig. 3 Variability in estimates of annual recharge and base flow from methods applied at the Masser Recharge Site and WE-38 watershed, 1994-2001

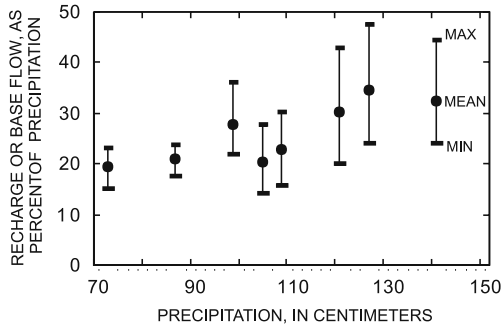


Fig. 4 Relation between annual precipitation and the percentage of precipitation contributing recharge or base flow from methods applied at the Masser Recharge Site and WE-38 watershed, 1994-2001

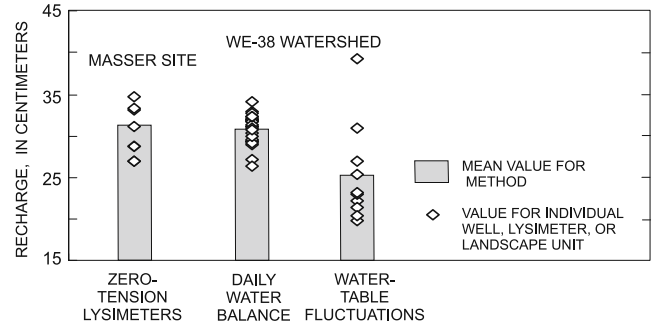


Fig. 6 Spatial variability of mean-annual recharge for 1994-2008 from unsaturated-zone drainage at 7 lysimeters at Masser Recharge Site, water-level fluctuations at 10 wells, and daily water-balance method for 26 landscape units at WE-38 watershed, 1994-2001

ranged, by method, from 22.9 to 35.7 cm (Fig. 5 and Table 3). The smallest estimate was from the local-minimum version of HYSEP, and the largest was from RORA. The range in values (12.8 cm) is about 45% of the mean of all estimates. This range of results might be considered in good agreement for some study areas, but for the small, intensely studied WE-38 watershed, the range seems considerable, given the effort expended to compare multiple methods.

The true value of mean annual recharge during 1994-2001 is unknown, but results from the zero-tension lysimeters, which provide the closest approximation to a direct measurement of recharge possible, indicate mean annual recharge was about 31 cm and ranged spatially among the seven lysimeters from about 27 to 35 cm at the Masser Recharge Site. These results could be viewed as a possible maximum estimate of recharge because of its location on a relatively flat, hilltop setting, with a shallow-rooted grass cover. Results from all the other methods, except for the WTF method, Rorabaugh equations using

RORA, and the local-minimum version of HYSEP, are within the range of recharge from the seven lysimeters; however, results from those three methods cannot be considered outside the realm of possibility. The WTF method gives lower estimates than other methods and produces anomalously small variability in results from year to year (Fig. 3), possibly because S_y is assumed to be constant in time. RORA produces large estimates that deviate from other results most during wet years, so it is possible the method overestimates recharge during wet years; however, the estimates are not so large as to be implausible. The local-minimum version of HYSEP probably underestimates recharge because it does not partition much base flow during storms.

The base-flow separation methods, which are easy to apply, give results ranging from 22.9 to 29.5 cm, slightly less than the range of 25.2 to 35.7 cm for the four recharge methods tested. Because base flow does not account for losses of recharge caused by evapotranspiration of groundwater, it might be reasonable to add an estimate

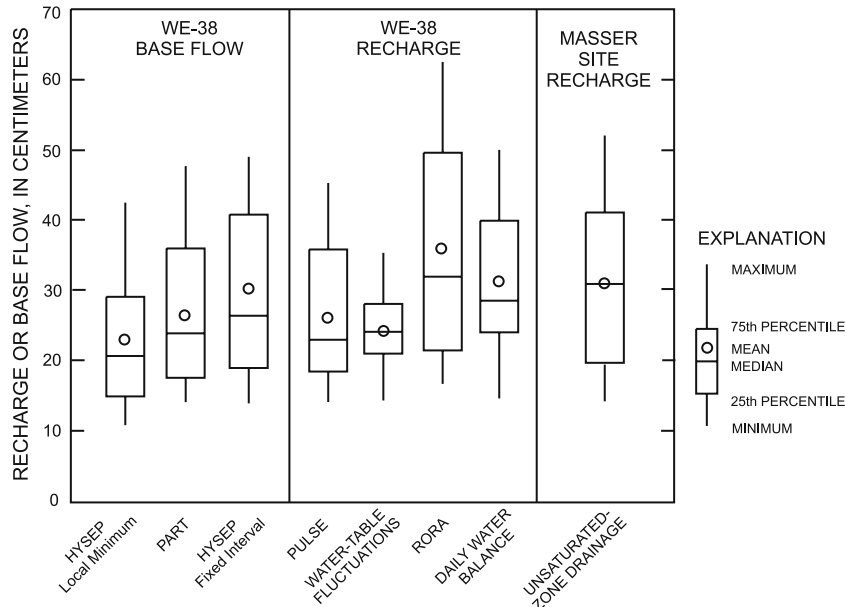


Fig. 5 Comparison of estimates of annual recharge and base flow, by method, for the Masser Recharge Site and WE-38 watershed, 1994-2001

of evapotranspiration from riparian vegetation to base flow as an approximation of groundwater recharge. Assuming that riparian vegetation extracted groundwater from 15 to 30 m on each side of streams within the WE-38 watershed at the rate of potential evapotranspiration, the annual loss would be on the order of 3 to 6 cm. Adding this to the mean annual base-flow estimates for the WE-38 watershed during 1994–2001 gives a range for recharge from 25.9 cm (HYSEP local-minimum version) to 35.5 cm (HYSEP fixed-interval version), which corresponds closely to the range from the recharge methods.

Spatial variability

In addition to temporal variability, methods that estimated recharge at more than one location gave different results, which could be attributed to spatial variability of recharge or errors caused by the instrumentation or methodology. Recharge estimates are plotted in Fig. 6 for unsaturated-zone drainage from 7 zero-tension lysimeters at the Masser Recharge Site, from the WTF method at 10 wells in WE-38 watershed, and from the water-balance equation at 26 landscape units in WE-38 watershed. The mean percolate from the seven zero-tension lysimeters for the 8-year period was 31.1 cm, although it varied by individual lysimeter from about 27 to 35 cm (26% of the mean), indicating either the inherent spatial variability of the soils within the small (approximately 15 m²) plot or the differences caused by lysimeter installation. Zero-tension lysimeters can underestimate recharge if natural lateral movement of percolate is restricted (Wuest 2005) or the impermeable lysimeter bottom causes soil moisture and, hence, evapotranspiration to be greater than in the surrounding soil. Also, disruption of the soil during installation can cause either increased or decreased collection efficiency.

In the WE-38 watershed, spatial variability of recharge computed by water balance method for the 26 landscape units was similar to that exhibited by the Masser Site lysimeters (Fig. 6). One would expect that spatial variability of recharge in the 7.3 km watershed would be greater than the variability within a 15-m lysimeter plot. Yu et al. (2000) simulated a much larger range of subsurface drainage (8–35 cm) at WE-38 watershed during 1984–85 by use of a water-balance model. Most likely, the water-balance equation used in this study underestimates the true spatial variability, but the cause is not known. Spatial variability for the WTF method is greatest of the three methods. Estimates of mean-annual recharge computed from the 10 individual upland wells averaged 25.2 cm and ranged from 19.3 to 39.1 cm (79% of the mean). The large variability is probably caused by the uncertainty in *Sy* and difficulty in accurately estimating the water-level rises caused by recharge.

Conclusions

Application of multiple methods for estimating groundwater recharge at a study area in east-central Pennsylvania, USA, helped to identify the range of plausible

recharge estimates and demonstrate possible bias in some methods. Estimates of mean annual recharge for 1994–2001 from multiple methods ranged from 22.9 to 35.7 cm (45% of the mean of all estimates). For individual years, recharge estimates varied by about 30–42% of the mean value during dry years and by about 64–76% during wet years. This uncertainty was expected because of differences inherent in the assumptions and datasets used in the various methods.

Results are difficult to compare directly because most methods determine some surrogate of actual recharge (potential recharge, net recharge, or base flow) representing differing segments of the watershed (point estimate or areal estimate) and are determined from differing datasets with their own errors (e.g., streamflow and meteorological data). Thus, even when the inherent differences of each method are considered, it may be difficult to build a case for a method (or recharge value) that is clearly the most appropriate unless the other estimates are clearly anomalous. For some purposes, simple determination of long-term base flow, possibly adjusted for the effect of groundwater evapotranspiration, provides a reasonable estimate of recharge that is within the range of variability of recharge methods that are considerably more difficult to apply.

Application of multiple methods served to identify that the maximum value of long-term recharge is from the RORA method, and the minimum is from base flow estimated by the local-minimum version of HYSEP. These easily applied methods could prove to be useful at other sites for bracketing the range of recharge where good streamflow records are available.

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