SRP13353

JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION
VOL. 35, NO. 2 AMERICAN WATER RESOURCES ASSOCIATION APRIL 1999

AUTOMATED METHODS FOR ESTIMATING BASEFLOW AND GROUND WATER RECHARGE FROM STREAMFLOW RECORDS[1]

J. G. Arnold and P. M. Allen[2]

ABSTRACT: To quantify and model the natural ground water recharge process, six sites located in the midwest and eastern United States where previous water balance observations had been made were compared to computerized techniques to estimate: (1) base flow and (2) ground water recharge. Results from an existing automated digital filter technique for separating baseflow from daily streamflow records were compared to baseflow estimates made in the six water balance studies. Previous validation of automated baseflow separation techniques consisted only of comparisons with manual techniques. In this study, the automated digital filter technique was found to compare well with measured field estimates yielding a monthly coefficient of determination of 0.86. The recharge algorithm developed in this study is an automated derivation of the Rorabaugh hydrograph recession curve displacement method that utilizes daily streamflow. Comparison of annual recharge from field water balance measurements to those computed with the automated recession curve displacement method had coefficients of determination of 0.76 and predictive efficiencies of 71 percent. Monthly estimates showed more variation and are not advocated for use with this method. These techniques appear to be fast, reproducible methods for estimating baseflow and annual recharge and should be useful in regional modeling efforts and as a quick check on mass balance techniques for shallow water table aquifers.
(KEY TERMS: shallow aquifer; base flow filter; hydrograph recession analysis; water balance; ground water recharge.)

INTRODUCTION

Shallow aquifer recharge and discharge characteristics are crucial for efficient development and management of ground water resources, as well as for minimizing pollution risks to the aquifer and connected surface water. Ground water has been shown to make up greater than 90 percent of the streamflow in portions of the Atlantic Coastal Plain (Williams and Pinder, 1990), and up to 50 percent of total flow in Central Texas (Arnold *et. al.,* 1993). Reay *et. al.* (1992) found that neglecting shallow ground water discharge as a nutrient source to streams could lead to misinterpretation of data and error in water quality management strategies. The complex links between recharge mechanisms for shallow ground water and nitrate pollution reported in Pennsylvania (Gerhart, 1986) support these conclusions. The importance of shallow ground water recharge is underscored by recent work by Krulikas and Giese (1995) who state that since Florida is highly dependent on ground water resources, the legislature is considering implementation of tax incentives to owners of high recharge lands. In addition, shallow ground water contributions to streams constitute a critical design variable for reservoirs that must maintain sufficient throughflow to satisfy navigation, water supply, hydroelectric power and recreational uses (McMahon and Mein, 1986).

Ground water recharge to shallow unconfined aquifers is complex and is dependent upon the occurrence, intensity, and duration of precipitation, temperature, humidity, wind velocity, as well as the character and thickness of soil and rock above the water table, the surface topography, vegetation, and land use (Memon, 1995). Ground water recharge shows significant spatial and temporal variability as a consequence of variations in climatic conditions, land use, irrigation and hydrogeological heterogeneity (Sharma, 1989; Osterkamp *et al.,* 1994). Estimates of ground water recharge and discharge can be quantified by two methods: by water balance studies in humid areas, or by monitoring the movement of water through the vadose zone with tensiometers, tracers, and weighing lysimeters in drier climates (Sharma, 1989; Wu *et al.,* 1996; Wood and Sanford, 1995). The actual methods used to estimate recharge depend on

[1]Paper No. 98084 of the *Journal of the American Water Resources Association.* **Discussions are open until December 1, 1999.**
[2]Respectively, Agricultural Engineer, USDA-Agricultural Research Service, 808 East Blackland Road, Temple, Texas 76502; and Professor of Engineering Geology and Hydrology, Department of Geology, Baylor University, P.O.Box 97354, Waco, Texas 76798 (E-Mail/Arnold: arnold@brc.tamus.edu).

the scale and accuracy required. It should be noted that due to the high costs of monitoring water balance, percolation models are being used for water resources assessment in drier climates such as Bauer and Vaccaro (1987) in the Columbia Plateau, Taylor and Howard (1996) in Africa, and Berger (1992) in Nevada. For large areas in subhumid to humid climates, two water balance methods have been used extensively by hydrologists: the baseflow record estimation (Knisel, 1963; Meyboom, 1961; Nathan and McMahon, 1990; Olmsted and Hely, 1962), and the recession curve displacement method (Bevans, 1986; Hoos, 1990; Rorabaugh, 1964). These methods have wide application in ground water characterization because of the abundance of stream flow records upon which they are based.

The baseflow record estimate is a method to estimate the total baseflow under the stream hydrograph. Work by Sloto (1991), Rutledge (1993), and most recently, Arnold *et al.* (1995), have devised methods to automate this procedure. This trend of using numerical algorithms more suited to computer operations has removed some of the more subjective elements from the procedure and therefore enhances the reproduction of values amongst practitioners. While a necessary objective of verifying the actual quick or stormflow versus baseflow in hydrograph separation must await more extensive isotopic, tracer, and chemical studies, such as Chapman and Maxwell (1996), these computerized methods have been shown to be reproducible and comparable to manual separation methods in accuracy (Fritz *et al.*, 1976; Sklash and Farvolden, 1979).

The recession curve displacement technique consists of a set of calculations that estimate total recharge for each streamflow and coupled recession event (Rorabaugh, 1964). This procedure has been recently automated by Rutledge and Daniel (1994). To verify their automated method, the authors compared their estimates of modeled recharge estimates to manual calculations using the same method. Comparison of the computer method to the manual method showed good agreement. The purpose of this paper is to test: (1) an existing digital filter method and (2) to test an automated derivation of the Rorabaugh (1964) technique against actual field estimates of baseflow and recharge (Figure 1). Field based estimates of baseflow and recharge by Schicht and Walton (1961), Olmsted and Hely (1962), Rasmussen and Andreasen (1959), and Meinzer and Steams (1928) using water balance methodologies, should allow direct assessment of the applicability of these computerized techniques to predict areal recharge in large watersheds.

STUDY WATERSHEDS

Basins studied fall within four major ground water regions (Heath, 1984): the Glaciated Central Region, the Atlantic and Gulf Coastal Plain, the Piedmont Blue Ridge, and the Northeast and Superior Uplands (Figure 2, Table 1). The basins chosen to analyze the automated recharge technique were based on four criterion: (1) recharge was independently analyzed for each basin using manual water balance methods, (2) the basins represented a variety of humid ground water regions, and (3) studies utilized actual ground water hydrograph response in estimating recharge, and (4) basins were monitored for one year or more. Table 2 indicates the general level of monitoring utilized in the cited studies. Average conditions at all sites consisted of three years of study, 35 square kilometers per rain gage, one recording stream gage, and 19 square kilometers per ground water well.

HISTORICAL RECHARGE ESTIMATES FROM MEASURED DATA

Recharge to an aquifer was estimated from its relation to other measured components of the hydrologic budget (Schicht and Walton, 1961; Meinzer and Steams, 1928; Olmsted and Hely, 1962; Rasmussen and Andreasen, 1959). Part of precipitation on the basins infiltrates through the soil zone to the water table and becomes ground water. Some of this ground water is subsequently discharged to the streams as baseflow and some is lost to the atmosphere by evapotranspiration. In a given period of time, precipitation reaching the water table (recharge) is balanced by baseflow (ground water discharge to the stream), seepage to deeper aquifer units, and evapotranspiration, plus or minus changes in ground water storage.

$$R = BF + ET + S + St \qquad (1)$$

where R is ground water recharge, BF is ground water discharge (baseflow), ET is evapotranspiration, S is subsurface seepage out of the basin, and St is change in ground water storage.

Ground water runoff, or baseflow, and ground water evapotranspiration were determined from the mean ground water stage-runoff rating curves. These were prepared by plotting mean weekly ground water stages from monitored wells in the basin against streamflow on corresponding dates when streamflow consisted entirely of ground water runoff. Separate rating curves were prepared for late fall through early spring, and late spring through early

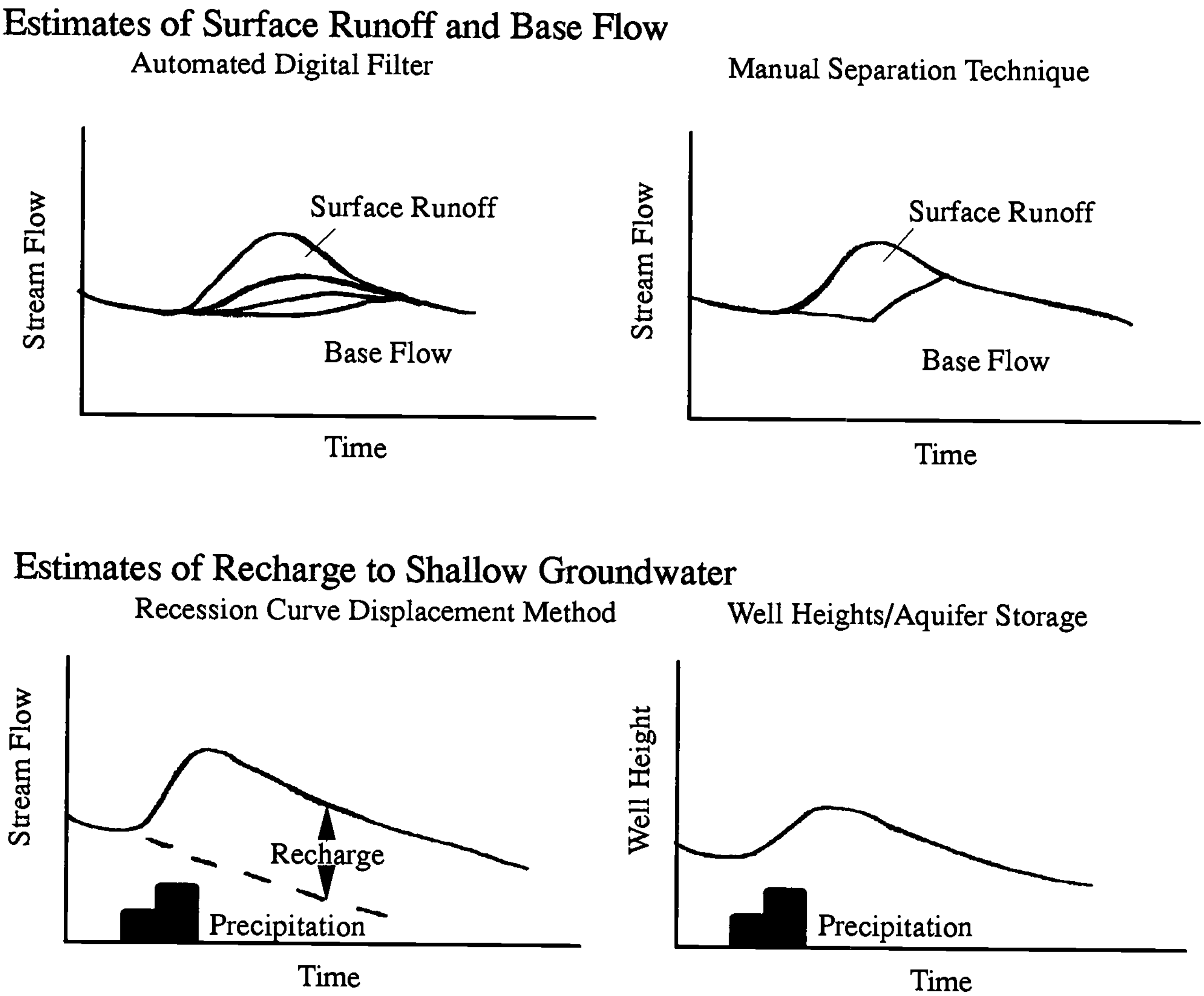

Figure 1. Schematic Diagram of Methods to Estimate Baseflow and Ground Water Recharge.

fall. The difference in the ground water runoff between the two curves was taken as the approximate ground water evapotranspiration. The curves were also used to evaluate the separation of the total flow hydrographs into direct runoff and ground water runoff. Well heights were used to infer baseflow or ground water runoff from the basins using the ground water stage runoff rating curve. In the basins studied, the relationship between the well height and inferred ground water runoff was quite good.

Evapotranspiration was solved from the water budget equation assuming no significant change in soil moisture during the year. Subsurface seepage was estimated for the three Illinois basins from the Darcy equation:

$$Q = TIL \qquad (2)$$

where Q is the underflow, T is the coefficient of transmissivity, I is the hydraulic gradient of the water table, and L is the width of the cross section of the deposits. Seepage was considered negligible in calculations for all the basins studied and deleted from the equation. The change in ground water storage was estimated from the change in mean ground water stage from observation wells and the estimated gravity yield of the wells.

$$St = H^* (S_y) \qquad (3)$$

where H is mean change in ground water stage, and S_y is specific yield of the deposits. Specific yield was estimated from the ratio of the annual integration of the winter baseflow recession curve to the average water table response inferred from laboratory tests on grain size and porosity, or a similar indirect method. In all cases the rates were compatible with local estimates from the literature as cited by the authors. This is similar to methods used by Fairchild *et al.* (1990) in their assessment.

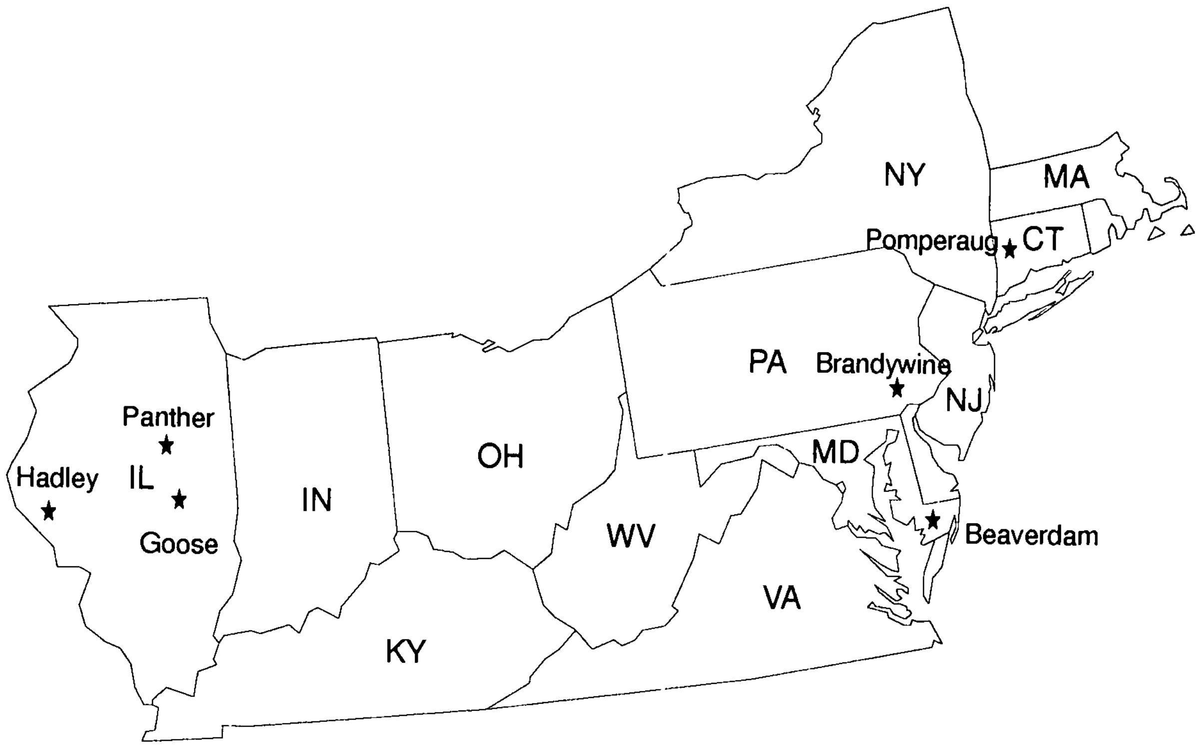

Figure 2. Locations of the Study Watersheds.

METHODS

Baseflow Separation

Numerous analytical methods have been developed to separate baseflow from total streamflow (McCuen, 1989). Although most procedures are based on physical reasoning, elements of all separation techniques are subjective. The digital filter technique (Nathan and McMahon, 1990) used in this study was originally used in signal analysis and processing (Lyne and Hollick, 1979). Although the technique has no true physical basis, it is objective and reproducible. The equation of the filter is:

$$q_t = \beta q_{t-1} + (1 + \beta) / 2^* (Q_t - Q_{t-1}) \quad (4)$$

where q_t is the filtered surface runoff (quick response) at the t time step (one day), Q is the original streamflow, and β is the filter parameter (0.925). The value of 0.925 was determined by Nathan and McMahon (1990) and Arnold *et al.* (1995) to give realistic results when compared to manual separation techniques. Baseflow, b_t, is calculated with the equation

$$b_t = Q_t - q_t \quad (5)$$

The filter can be passed over the streamflow data three times (forward, backward, and forward), depending on the user's selected estimates of baseflow from pilot studies of streamflow data. In general, each pass will result in less baseflow as a percentage of total flow. Arnold *et al.* (1995) compared the digital filter results with results from manual separation techniques and with the PART model (Rutledge, 1993; Rutledge and Daniel, 1994) for 11 watersheds in Pennsylvania, Maryland, Georgia, and Virginia (White and Sloto, 1990).

Annual baseflow from one pass of the filter were on average within 11 percent (plus or minus) of baseflow estimated by manual techniques and the PART model. A recent study by Mau and Winter, (1997) found that this filter method agreed reasonably well with graphical (manual) partitioning if the appropriate filter parameter is used.

Ground Water Recharge

Several methods have been developed to estimate ground water recharge from stream flow records. One popular method is the recession curve displacement method which is commonly referred to as the Rorabaugh method (Rorabaugh, 1964). This method estimates total recharge for each stream flow peak, is theoretically based, and includes ground water variables. The disadvantage is the time required to calculate recharge for each peak.

TABLE 1. Characteristics of Study Watersheds.

Basin	Panther Creek Illinois	Goose Creek Illinois	Hadley Creek Illinois	Pomperaug Creek, Connecticut	Beaverdam Creek, Maryland	Brandywine Creek, Pennsylvania
Heath Groundwater Regions (1984)	Glaciated Central Region	Glaciated Central Region	Glaciated Central Region	Northeast and Superior Uplands	Atlantic Coastal Plain	Piedmont Blue Ridge
Maximum Relief (m)	30.5	18.3	120	300	23	274
Topography	gently undulating uplands	level uplands	rugged uplands	rounded hills, wide flat valleys	plain, low relief, gentle slopes	rounded hills, wide flat flood plain
Land Use	80% cultivated 20% pasture woodland, farm lots	86% cultivated 14% pasture woodland, farm lots	40% cultivated 60% woodland and farm lots	66% cultivated 34% woodlands minor ponds,	60% cultivated 40% trees brush, minor ponds	51% cultivated 21% woodlands 28% roads, streams miscellaneous
Soil/Aquifer	silt loams over glacial till; 31 m to bedrock	silty clay loam and silt loam over glacial till; 53 m to bedrock	silt loams and loess or glacial till; 7-15 m to bedrock	glacial till and outwash; 5-10 m to bedrock	lowlands well drained sand; uplands silt, clay, sandy silt	thin to thick regolith
Bedrock	shale	shale	shale	metamorphic schist, gneiss	sedimentary sand, silt, clay	minor limestone; crystalline metamorphic and igneous
Average Depth to Water Table (m)	2.1	2.4	6.1	1-10	3-6	1-10
Mean Annual T (degrees C)	11	12	13	9	13	12
Mean Annual Precipitation (cm)	85.3	94	91.4	123.9	107.5	112
Basin Area (sq. 246 km)	246	122	188	89	19.5	743.3

TABLE 2. Instrumentation on Study Watersheds.

Basin	Panther Creek	Goose Creek	Hadley Creek	Pomperaug Creek	Beaverdam Creek	Brandywine Creek
Years Study	8	3	2	1	1	
Rain Gages	9 (27 sq. Km/gage)	6 (20.3 sq. Km/gage)	11 (17 sq. Km/gage)	4 (22 sq. Km/gage)	12 (1.6 sq. Km/gage)	6 (124 sq. Km/gage)
Stream Gages	1	1	1	1	1	1
Ground Water	5-16	3	5-21	29	25	16
Wells	49-15 sq. Km/well	40.6 sq. Km/well	38-9 sq. Km/well	3.1 sq. Km/well	0.8 sq. Km/well	46.4 sq. Km

Potential ground water recharge was shown to equal approximately one-half of the total volume that recharged the system at a "critical time" after the peak (Rorabaugh, 1964; Glover, 1964). The recession curve displacement method uses this approximation and the principle of superposition to estimate total recharge with the equation:

$$R = \frac{2(b_2 - b_1)k}{2.3026} \quad (6)$$

where R is volume of recharge, b_1 is ground water discharge at critical time after the peak on the previous recession curve, b_2 is ground water discharge at critical time after peak on the current recession curve, and k is the recession index. Critical time can be approximated by the following equation (Rorabaugh, 1964):

$$T_c = \frac{0.2\ \alpha^2 S}{TR} \quad (7)$$

where T_c is critical time, a is the average distance from the stream to the ground water divide, S is the storage coefficient, and TR is transmissivity. Bevans (1986) and Rutledge and Daniel (1994) describe and illustrate the method in detail. The method was automated in a program called RORA by Rutledge (1993).

The method developed in this study is a modification of the recession curve displacement method. The method presented here consists of the following steps:

Step 1. Run one pass (forward) of the digital baseflow filter across the daily stream flow.

Step 2. Find the first point where the baseflow curve rejoins the total stream flow curve (Point A in Figure 3) and compute the recession constant

$$\alpha = ln\ (q_N / q_A) / N \quad (8)$$

where q_N and q_A stream flow at points N and A, respectively. To accurately estimate α, the recession period (N) must be at least ten days.

Step 3. Find the next point where the baseflow curve rejoins the total streamflow curve (Point B_1 in Figure 3).

Step 4. Extrapolate the recession curve from point A to point B_2.

$$q_{B2} = \frac{q_A}{e^{(nd^* \alpha)}} \quad (9)$$

where q_{B2} is stream flow at point B_2, and nd is the number of days from points A and B.

Step 5. Compute ground water recharge for the period between points A and B using the equation

$$R = (q_A - q_{B2})^* \ nd \quad (10a)$$

or

$$R = 0.0372 * (q_A - q_{B2})^* \ nd/da \quad (10b)$$

Equation (10a) assumes stream flow q in cfs and recharge R in cfs-d. Equation (10b) assumes q in cfs, da is drainage area in square miles, and R in inches.

Step 6. Repeat steps 1-5 for each baseflow recession period.

RESULTS AND DISCUSSION

Baseflow

The digital filter was run for all six watersheds and the ratio of baseflow to total flow is shown in Table 3. With the exception of the 1952-1953 period for the Brandywine Watershed, all measured estimates fell between one pass and two passes of filtered baseflow. Monthly measured and filtered (one pass) time series of baseflow are shown in Figure 4 for all six watersheds. Statistics of the monthly comparisons (one pass of the filter) are given in Table 4. R^2 values ranged from 0.62 to 0.98 and slopes ranged from 0.91 to 1.75. An R^2 and slope of one, and an intercept of zero, indicate perfect agreement. Combining all months of all watersheds resulted in an R^2 of 0.86 and slope of 1.07 (Figure 3) showing that the digital filter can give reasonable estimates of monthly baseflow in comparison to measured estimates. This allows rapid estimates of ground water discharge to streams over the period of record. In this study, baseflow and recharge values determined from field measurements of the water balance are referred to as measured estimates.

Recharge

Only Goose, Panther, and Pomperaug basins had estimates of monthly ground water recharge. Recharge of 3.89 inches was measured at the Hadley Creek Watershed for 1956. Table 5 shows measured and predicted annual recharge for these four basins.

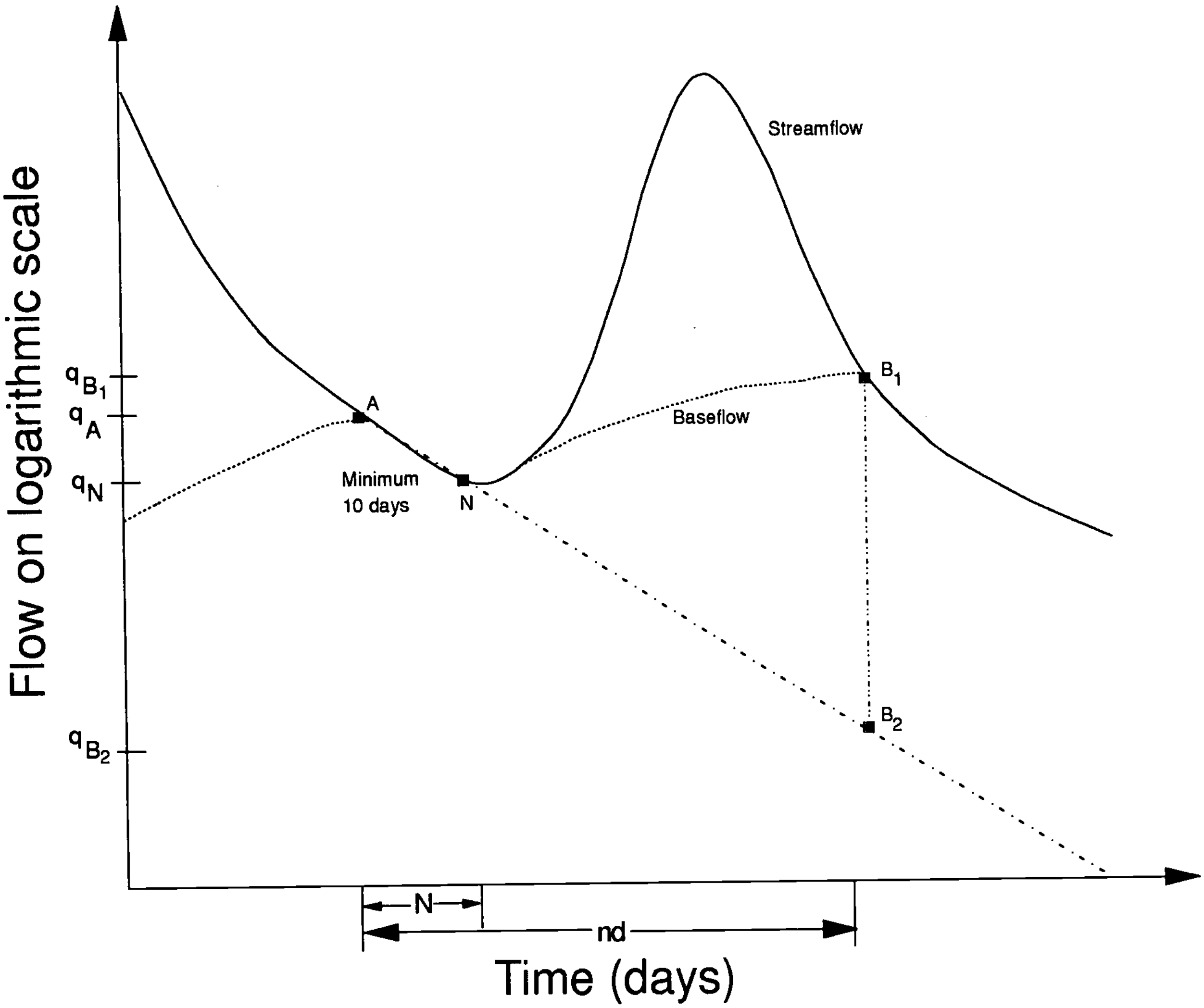

Figure 3. Technique for Estimating Recharge from Daily Streamflow.

TABLE 3. Baseflow as a Fraction of Total Streamflow for Measured One, Two, and Three Passes With the Digital Filter.

	Measured	Pass 1	Pass 2	Pass 3
Goose, Illinois, 1955-1958	0.49	0.59	0.40	0.30
Panther, Illinois 1951-1952, 1956	0.46	0.54	0.37	0.29
Hadley, Illinois April 1956-September 1958	0.15	0.23	0.12	0.09
Brandywine, Pennsylvania 1928-1931	0.70	0.74	0.64	0.58
Brandywine, Pennsylvania 1952-1953	0.65	0.75	0.64	0.58
Pomperaug, Connecticut August 1913-December 1916	0.42	0.69	0.55	0.47
Beaverdam, Maryland April 1950-March 1952	0.72	0.74	0.64	0.58

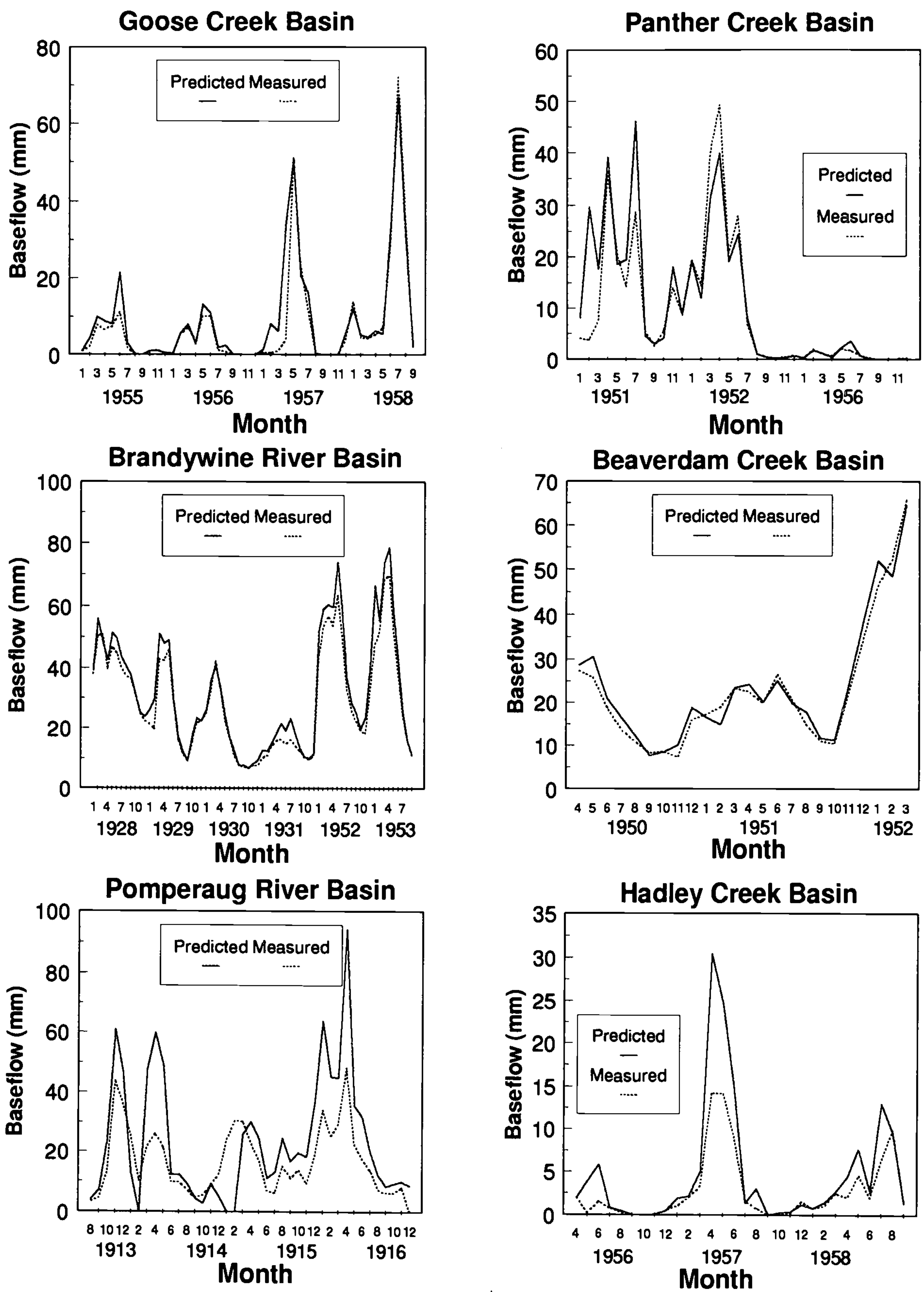

Figure 4. Monthly Time Series of Measured and Estimated Baseflow for All Six Watersheds.

TABLE 4. Monthly Statistics of Measured vs. Filtered Baseflow for One Filter Pass.

	R^2	Slope	Intercept	Number of Points (months)	Total Baseflow (inches) Measured	Filtered
Goose, Illinois, 1955-1958	0.87	0.93	2.04	45	7.76	9.26
Panther, Illinois April 1956-September 1958	0.80	0.91	1.97	36	9.55	10.70
Hadley, Illinois April 1956-September 1958	0.91	1.75	-0.16	30	2.80	4.74
Brandywine, Pennsylvania 1928-1931	0.97	1.04	1.21	48	23.70	25.88
Brandywine, Pennsylvania 1952-1953	0.98	1.13	0.06	21	40.66	46.16
Pomperaug, Connecticut August 1913-December 1916	0.62	1.46	-0.95	41	16.81	23.68
Beaverdam, Maryland April 1950-March 1952	0.97	0.98	1.39	24	22.71	23.68

The percentage by which the result of the automated recharge technique exceeds that of the manual method is also shown in Table 5.

TABLE 5. Annual Differences in Measured and Estimated Ground Water Recharge.

Basin	Year	Measured (mm)	Automated Recession Curve Displacement Method (mm)	Percent Difference
Goose	1955	162.6	87.9	-45.9
	1956	90.68	56.9	-37.3
	1957	264.16	231.7	-12.3
	1958	303.1	231.7	-23.6
Panther	1951	212.9	297.2	+39.6
	1952	203.9	174.5	-14.4
	1956	22.1	11.94	-45
Hadley	1956	98.8	121.92	+23.4
Pomperaug	1913	253.2	150.11	-40.7
	1914	232.7	298.5	+28.3
	1915	438.9	398.6	-11.5
	1916	280.2	236.9	-15.4

The average difference between the measured recharge and predicted is 28 percent. The maximum annual difference is 46 percent for the Goose watershed in 1955, the minimum difference is 11.5 percent for the Pomperaug watershed in 1915. For the two watersheds with four years of field data, Goose and Pomperaug, the average difference for the four years was 26 percent and 11 percent respectively. For the 12 years of record, including all the basins, the automated model underpredicts the cumulative measured recharge by 10.7 percent.

Another model evaluation criterion was used here after Loaque and Freeze (1985), which is the coefficient of efficiency (Nash and Suttcliffe, 1970):

$$EF = \frac{\sum_{i=1}^{n}\left(Q_{ip}-Q_m\right)^2-\sum\left(Q_{ip}-Q_i\right)^2}{\sum\left(Q_{ip}-Q_m\right)^2} \quad (11)$$

where Q_{ip} is the predicted summary variable for the event I, Q_i is the observed summary variable for the event I, Q_m is the mean value of the observed summary variable for n events, and n is the number of events. When $Q_{ip} = Q_i$ then EF = 1. If EF is negative, the model's predicted value is less representative than simply using the arithmetic mean of the data set. The calculated EF for the entire data set (n = 12) is 0.71.

The automated technique appears to be in the range of other field and water balance techniques for estimating recharge. Rushton and Ward (1979) concluded that uncertainties of plus or minus 15 percent should be expected with the soil water balance approach to estimating recharge. Winter (1981) also discussed various errors inherent in measurement and computation of the various components of the water balance, indicating that long term averages had less error than short term values. Winter (1981) suggests errors in annual estimates of precipitation, streamflow, and evaporation ranged from 2-15 percent whereas monthly rates could range from 2-30 percent. This premise was subsequently questioned by more recent work by Essery (1992) who suggested that even long term measurements could be subject to recurring errors of a similar magnitude. In actual field evaluations, Sami and Hughes (1996) compared recharge estimates in a fractured sedimentary aquifer in South Africa from a chloride mass balance to an integrated surface- subsurface model. Their results showed mean annual recharge for the chloride balance to be 4.5 mm. compared to 5.8 mm from the model with mean annual rainfall of 460 mm. This is a difference of about 22 percent.

There are several possible sources for the discrepancy noted between the automated method and field values. The first lies in the assumptions of the Rorabaugh technique used in the recharge estimates: (1) that the potentiometric surface is horizontal prior to the recharge event; (2) that the aquifer is finite with parallel boundaries and is fully penetrating at the discharge boundary, and (3) departures from these assumptions in the current study areas as shown in Table 1. Second, the assumptions upon which the recharge amounts are predicted by both the field based techniques as well as the automated techniques rely upon the hydrograph separation methods and estimates of the annual precipitation falling on the basin. The results shown in Figure 5, and Tables 2 and 4, indicate that these may be the largest sources of errors in comparison of the two methods. The low rain gage density of all the basins studied for the field water balances, coupled with the predicted R^2 values

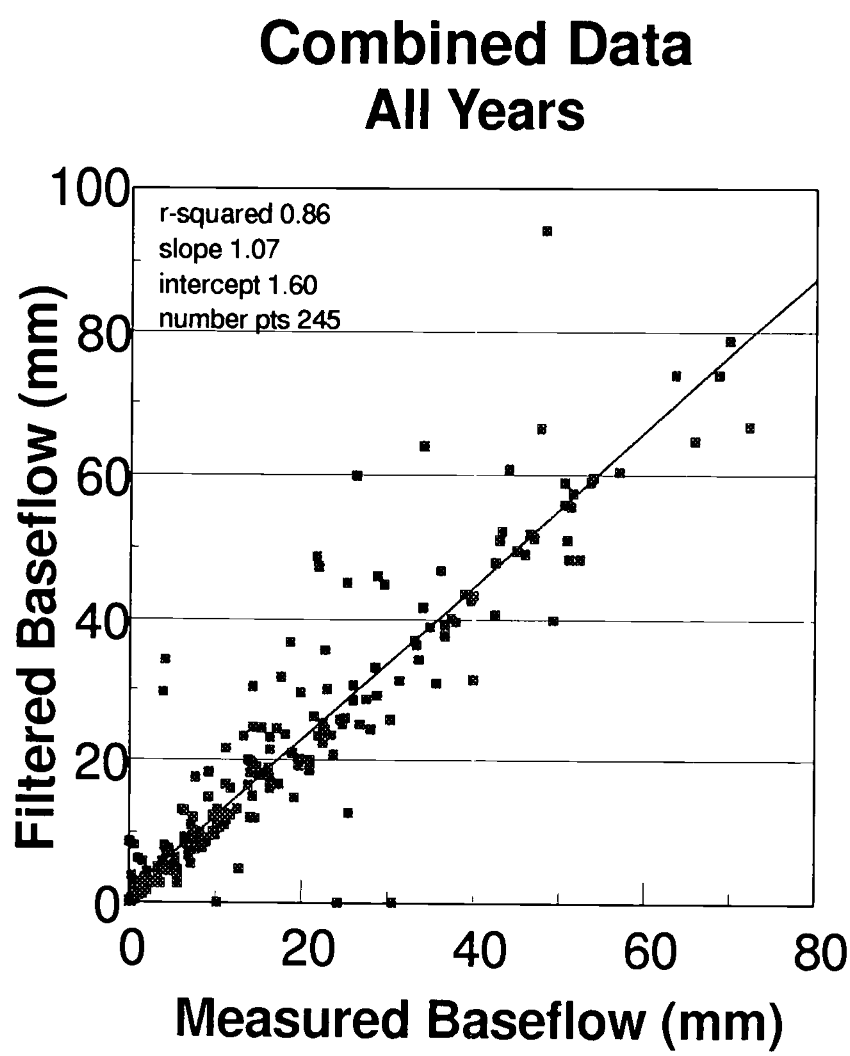

Figure 5. Monthly Measured vs. Estimated (filtered) Baseflow for All Watersheds for All Years of Record.

of 0.86 percent for the automated versus field baseflow separation, illustrates the potential for error. A final source of error could be that the automated method as presented in this paper does not accurately model the manual Rorabaugh method. To test this assumption, the modeled method was run on three years of streamflow data and precipitation for U.S.G.S. Station 03457000 which had been previously analyzed by Hoos (1990) using the manual Rorabaugh method. The results are shown in Table 6. The efficiency (EF) for the modeled recharge method to predict the manual Rorabaugh method is 89 percent.

TABLE 6. Comparison of Recharge by Manual Rorabaugh Method to Automated Method.

	Ground Water Recharge	
Year	Hoos (1990)	Automated Recession Curve Development
1950 (high)	7.6 in.	6.8 in.
1965 (average)	5.2 in.	4.5 in.
1948 (low)	2.6 in.	2.5 in.

While the model is best used to predict longer term annual recharge, monthly estimates were also tried as this information was computed in some of the field studies. It was also thought that some users would want to know how well this approach could estimate monthly values for use in shorter term predictions. For Panther and Goose basins, measured and predicted recharge are shown in Figures 6 and 7, respectively. It is obvious from the monthly time series (Figures 6a and 7a) that some of the months are in error, but general peaks and lows are predicted well. Measured versus predicted R^2 values are 0.56 and 0.71 (Figures 6b and 7b). It was found that it was difficult to determine monthly recharge with the proposed method because the points between the recession curve cross over months. Therefore, monthly separation of recharge becomes problematic.

CONCLUSIONS

This study is an initial attempt to compare automated techniques for baseflow and ground water recharge from daily streamflow hydrographs to measured field estimates. Measured data from six watersheds in the midwest and eastern U.S. were obtained.

Several previous studies have shown that the automated digital filter technique compares well to manual baseflow separation techniques. This study shows the automated digital filter technique also compared well to measured estimates of baseflow from the six watersheds with a monthly R^2 of 0.86 and slope of 1.07. These results demonstrate that the automated digital filter can give reasonable estimates of monthly baseflow in comparison to measured estimates of ground water discharge to streams.

Results obtained with the automated recession curve displacement method were comparable to estimates of recharge from the field based water balance methods. Errors associated with prediction of annual recharge with this automated method seem to be within the range of errors reported in the literature using mass balance techniques. Monthly estimates of recharge using this method are problematic and are not advocated for use at this time except for assessment of general trends in recharge. It appears that this method can give consistent, repeatable results, that are comparable with manual Rorabaugh recharge estimates. When applied in a conscientious manner to flow systems which meet the general Rorabough requirements, this approach should provide a valuable tool for estimating annual ground water recharge over large areas and assist in the calibration of regional ground water models.

LITERATURE CITED

Arnold, J. G., P. M. Allen, and G. Bernhardt, 1993. A Comprehensive Surface Groundwater Flow Model. Journal of Hydrology. 142:47-68.

Arnold, J. G., P. M. Allen, R. Muttiah, and G. Bernhardt, 1995. Automated Baseflow Separation and Recession Analysis Techniques. Groundwater 33:1010-1018.

Bauer, H. H. and J. J. Vaccaro, 1987. Documentation of a Deep Percolation Model for Estimating Groundwater Recharge. U. S. Geological Survey Open File Report 86-536.

Berger, D. L., 1992. Groundwater Recharge Through Active Sand Dunes in Northwestern Nevada. Water Resources Bulletin 28(5):959-965.

Bevans, H. E., 1986. Estimating Stream-Aquifer Interactions in Coal Areas of Eastern Kansas by Using Streamflow Records. *In:* Selected Papers in the Hydrologic Sciences, Seymour Subitzky (Editor). U.S. Geologic Survey Water Supply Paper 2290:51-64.

Chapman, T. G. and A. I. Maxwell, 1996. Baseflow Separation – Comparison of Numerical Methods with Tracer Experiments. 23rd Hydrology and Water Resources Symposium, Hobart Australia, May 21-24, pp. 539-545.

Essery, C. I., 1992. Influence of Season and Balance Period on the Construction of Catchment Water Balances. Journal of Hydrology 130:171-187.

Fairchild, R. W., R. L. Hanson, and R. E. Davis, 1990. Hydrology of the Arbuckle Mountains Area, South Central Oklahoma. Oklahoma Geological Survey, Circular No. 91, Norman, Oklahoma, 112 pp.

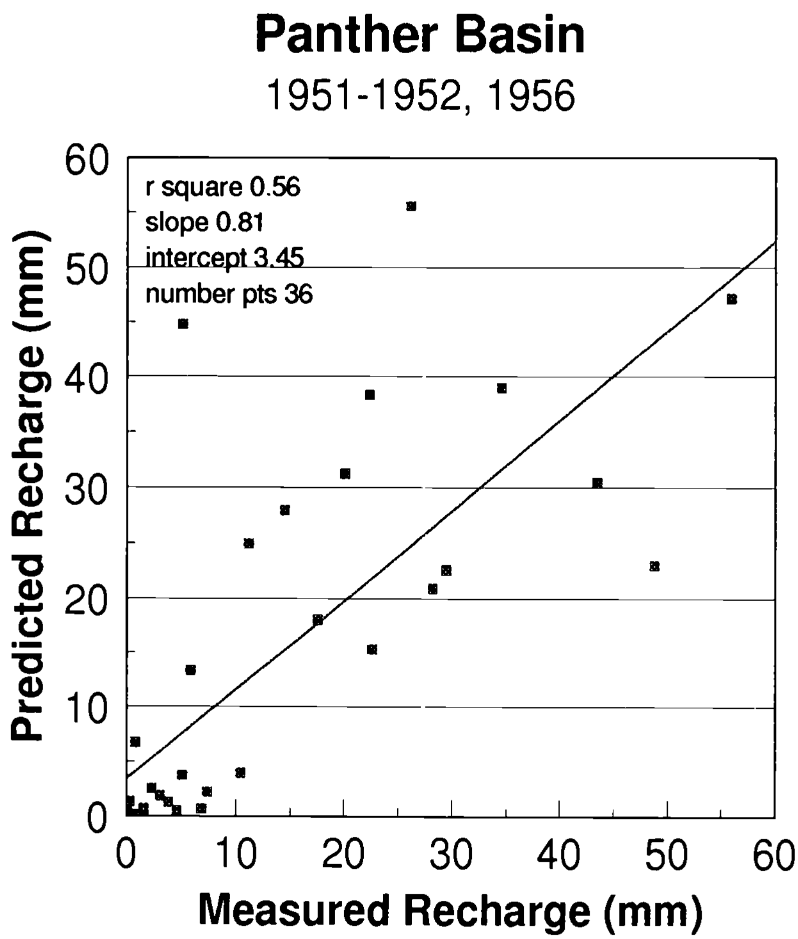

Figure 6a. Monthly Measured vs. Estimated Ground Water Recharge for Panther Basin (I 951, 52 and 56).

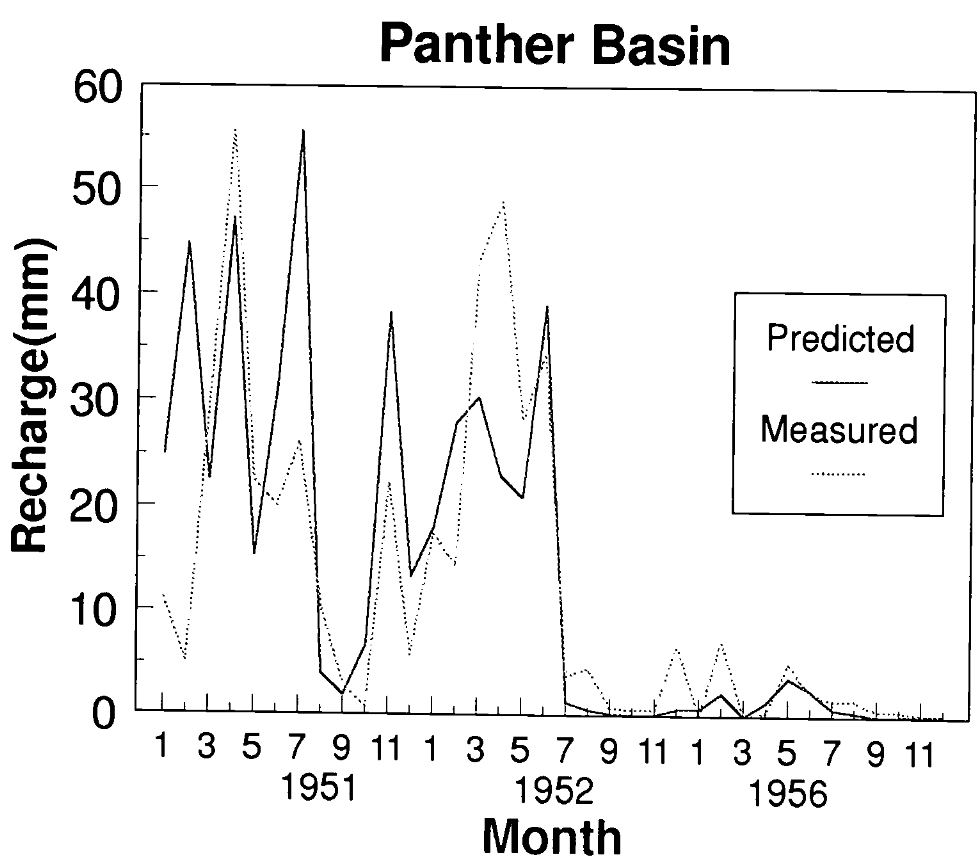

Figure 6b. Time Series of Monthly Measured and Predicted Ground Water Recharge for Panther Basin (1951, 52, and 56).

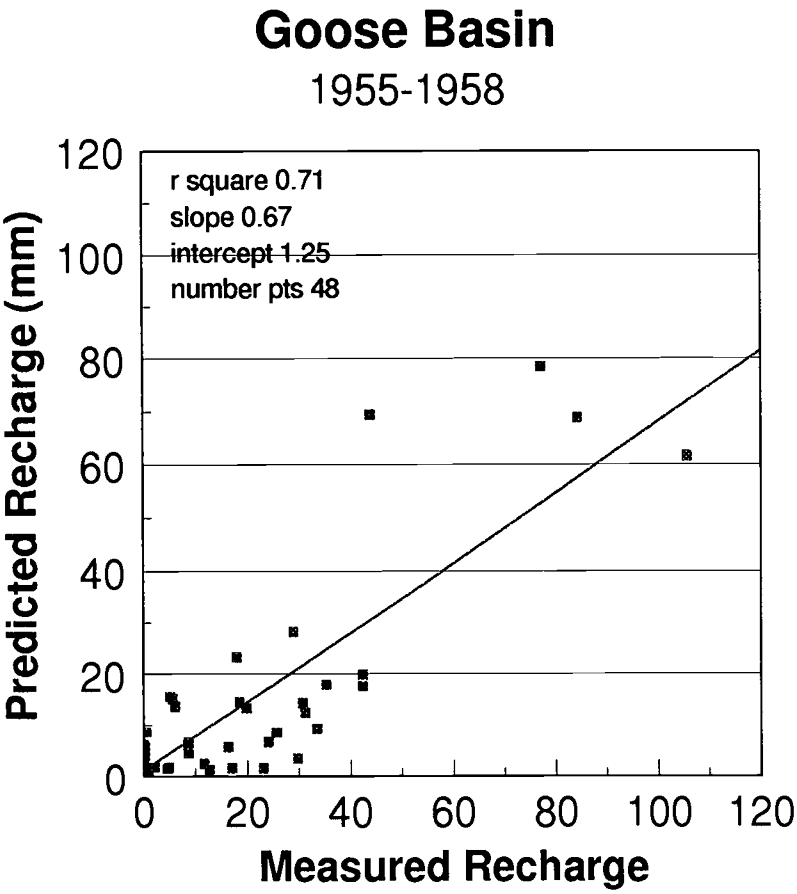

Figure 7a. Monthly Measured vs. Estimated Ground Water Recharge for Goose Basin. (1955-1958).

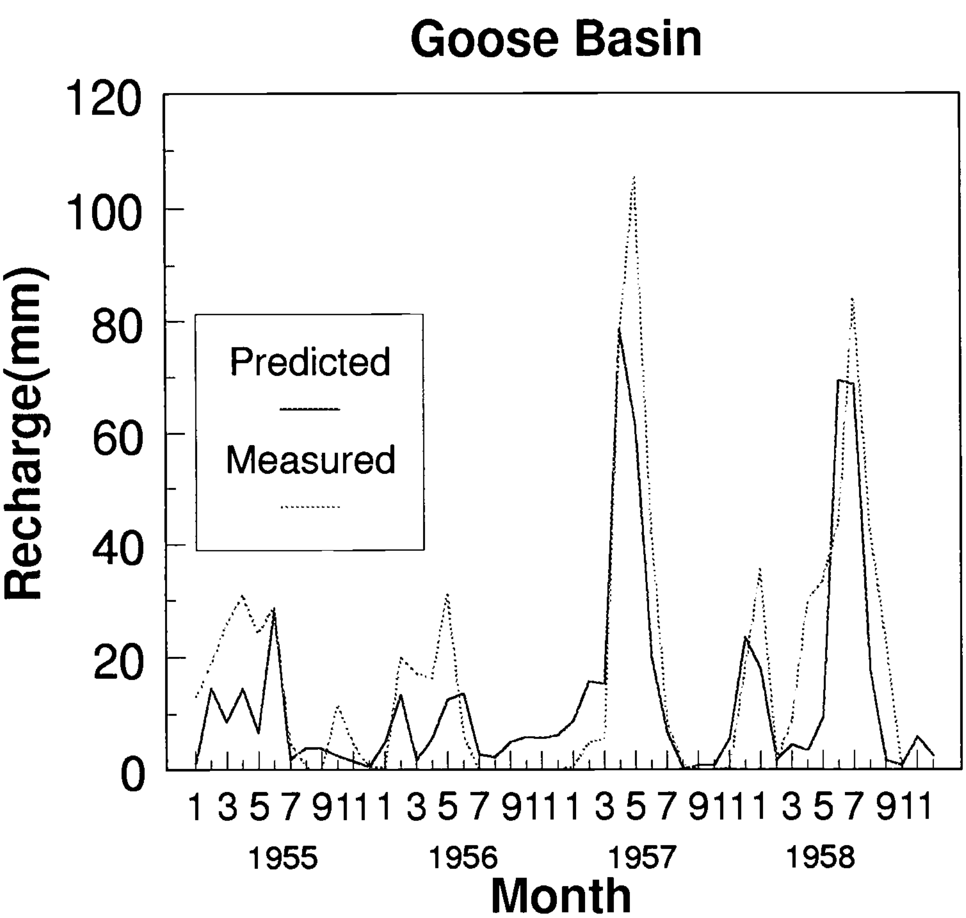

Figure 7b. Time Series of Monthly Measured and Predicted Ground Water Recharge for Goose Basin (1955-1958).

Fritz, P., J. A. Cherry, K. V. Weyer, and M. G. Sklash, 1976. Runoff Analysis Using Environmental Isotopes and Major Ions. *In:* Interpretation of Environmental Isotopes and Hydrogeochemical Data in Groundwater Hydrology. IAEA, pp. 111-130.

Gerhart, J. M., 1986. Groundwater Recharge and Its Effects on Nitrate Concentration Beneath a Manured Field Site in Pennsylvania. Groundwater 24(4):483-489.

Glover, R. E., 1964, The Pattern of Freshwater Flow in a Coastal Aquifer, Washington, D.C. U.S. Geological Survey Water Supply Paper, 1613-C.

Heath, R. C., 1984. Groundwater Regions of the United States. U.S. Geological Survey Water Supply Paper 2242, 78 pp.

Hoos, A. B., 1990. Recharge Rates and Aquifer Characteristics for Selected Drainage Basins in Middle and East Tennessee. U.S. Geological Survey Water Resources Investigations Report 90-4015, 34 pp.

Knisel, W. G., 1963. Baseflow Recession Analysis for Comparison of Drainage Basins and Geology. J. Geophys. Res. 68(12):3649-3653.

Krulikas, R. K. and G. L. Giese, 1995. Recharge to the Surficial Aquifer System in Lee and Hendry Counties, Florida. U.S. Geological Survey Water Resources Investigations Report 95-4003, pp. 1-21.

Kunkel, G. R., 1962. The Baseflow Duration Curve: A Technique for the Study of Groundwater Discharge from a Drainage Basin. Journal of Geophysical Research 67(4):1543-1554.

Loaque, K. M. and R. A. Freeze, 1985. A Comparison of Rainfall Runoff Modeling Techniques on Small Upland Catchments. Water Resources Research 21(2):229-248.

Lyne, V. and M. Hollick, 1979. Stochastic Time Variable Rainfall Runoff Modeling. *In:* Hydrology and Water Resources Symposium, Berth, Australia, 1979, Proceedings. National Committee on Hydrology and Water Resources of the Institution of Engineers, Australia, pp. 89-92.

Mau, D. P. and T. C. Winter, 1997. Estimating Groundwater Recharge from Streamflow Hydrographs for a Small Mountain Watershed in a Temperate Humid Climate, New Hampshire, USA. Groundwater 35(2):291-304.

McMahon, T. A. and R. G. Mein, 1986. River and Reservoir Yield. Water Resources Publication, Littleton, Colorado, 368 pp.

McCuen, R. H., 1989. Hydrologic Analysis and Design. Prentice Hall, pp. 355-360.

Meinzer, 0. E. and N. D. Steams, 1928. A Study of Groundwater in the Pomperaug Basin, Connecticut, with Special Reference to Intake and Discharge. U. S. Geological Survey Water Supply Paper 597-B.

Memon, B. A., 1995. Quantitative Analysis of Springs. Environmental Geology 26:111-120.

Meyboom, P., 1961. Estimating Groundwater Recharge from Stream Hydrograph. Journal of Geophysical Research. 66(4): 1203-1214.

Nash, J. E. and J. Suttcliffe, 1970. River Flow Forecasting Through Conceptual Models, Part 1 – A Discussion of Principles. J. of Hydrology 10(3):282-290.

Nathan, R. J. and T. A. McMahon, 1990. Evaluation of Automated Techniques for Baseflow and Recession Analysis. Water Resources Research 26(7):1465-1473.

Olmsted, F. H. and A. G. Hely, 1962. Relation Between Groundwater and Surface Water in Brandywine Creek Basin, Pennsylvania. U. S. Geological Survey Professional Paper 417-A, 21 pp.

Osterkamp, W. R., L. J. Lane, and C. S. Savard, 1994. Recharge Estimates Using a Geomorphic/Distributed-Parameter Simulation Approach, Amargosa River Basin. Water Resources Bull. 30(3):493-507.

Rasmussen, W. C. and G. E. Andreasen, 1959. Hydrologic Budget of the Beaverdam Creek Basin, Maryland. U.S. Geological Survey Water Supply Paper 1427, 106 pp.

Reay, W. G., D. L. Gallagher, and G. M. Simmons, Jr., 1992. Groundwater Discharge and Its Impact on Surface Water Quality in a Chesapeake Bay Inlet. Groundwater 28(6):1121-1133.

Rorabaugh, M. I., 1964. Estimating Changes in Bank Storage and Groundwater Contribution to Streamflow. International Association of Scientific Hydrology 63:432-441.

Rushton, K. R. and C. Ward, 1979. The Estimation of Groundwater Recharge. Journal of Hydrology 41:345-361.

Rutledge, A. T., 1993. Computer Programs for Describing the Recession of Groundwater Discharge and for Estimating Mean Groundwater Recharge and Discharge from Streamflow Records. U.S. Geological Survey Water Resources Investigations Report 93-4121, 45 pp.

Rutledge, A. T. and C. C. Daniel, 1994. Testing an Automated Method to Estimate Groundwater Recharge from Streamflow Records. Groundwater 32(2):180-189.

Sami, K. and D. A. Hughes, 1996. A Comparison of Recharge Estimates to a Fractured Sedimentary Aquifer in South Africa from a Chloride Mass Balance and an Integrated Surface-Subsurface Model. Journal of Hydrology 179:111-136.

Schicht, R. J. and W. C. Walton, 1961. Hydrologic Budgets for Three Small Watersheds in Illinois. Illinois State Water Surv. Rep. Invest. 40, 40 pp.

Sharma, M. L., 1989. Groundwater Recharge. A. A. Balkema, Brookfield, Vermont, 323 pp.

Sklash, M. G. and R. N. Farvolden, 1979. The Role of Groundwater in Storm Runoff. Journal of Hydrology 43:45-65.

Sloto, R. A., 1991. A Computer Method for Estimating Groundwater Contribution to Stream Flow Using Hydrograph Separation Techniques. *In:* Proceedings, U. S. Geological Survey National Computer Technology Meeting, B. H. Balthrop and J. E. Terry (Editors), Phoenix, Arizona.

U. S. Geological Survey Water Resources Investigations Report 90-4162. pp. 101-110.

Taylor, R. G. and K. W. F. Howard, 1996. Groundwater Recharge in the Victoria Nile Basin of East Africa: Support for the Soil Moisture Balance Approach Using Stable Isotope Tracers and Flow Modeling. Journal of Hydrology 180:31-53.

White, K. and R. A. Sloto, 1990. Baseflow Frequency Characteristics of Selected Pennsylvania Streams. U.S. Geological Survey Water Resources Investigation Report 90-4160, 66 pp.

Williams, J. B. and J. E. Pinder III, 1990. Groundwater Flow and Runoff in a Coastal Plain Stream. Water Resources Bulletin 26(2):343-352.

Winter, T.C., 1981. Uncertainties in the Estimating of Water Balances in Lakes. Water Resour. Res., 17:82-115.

Wood, W. W. and Sanford, W. E., 1995. Chemical and Isotopic methods for Quantifying Ground-Water Recharge in a Regional Semi-Arid Environment. Groundwater. 33(3):458-468

Wu, Jinquan, Renduo Zhang, and Jinzhong Wang, 1996. Analysis of Rainfall-Recharge Relationships. Journal of Hydrology 177:143-160.