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CONSIDERATIONS FOR USE OF THE RORA PROGRAM TO ESTIMATE GROUND-WATER RECHARGE FROM STREAMFLOW RECORDS

Open-File Report 00-156

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By A.T. Rutledge

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Reston, Virginia
2000

U.S. DEPARTMENT OF THE INTERIOR
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PREFACE

The computer programs described in this report are available for downloading over the Internet from a USGS software depository. The public anonymous FTP site is at ftprvares.er.usgs.gov or 130.11.51.209. The programs are available in two formats: one in the directory /pub/arutledg/sf.programs and the other in /pub/arutledg/sf.programs.pc. Included in each directory are streamflow data files for some of the stations that are used in examples in this report. Each directory includes a “read” file that explains how to get started. The directory also includes specific instructions for executing RORA for some of these stations (file “read.rora”).

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CONVERSION FACTORS AND ABBREVIATIONS

Multiply	By	To obtain
inch (in.)	25.4	millimeter
inch per day (in/d)	25.4	millimeter per day
inch per year (in/yr)	25.4	millimeter per year
foot (ft)	0.3048	meter
square mile (mi^2)	2.590	square kilometer
cubic foot per second (ft^3/s)	0.02832	cubic meter per second

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ABSTRACT

The RORA program can be used to estimate ground-water recharge in a basin from analysis of a streamflow record. The program can be appropriate for use if the ground-water flow system is characterized by diffuse areal recharge to the water table and discharge to a stream.

The use of the program requires an estimate of a recession index, which is the time required for ground-water discharge to recede by one log cycle after recession becomes linear or near-linear on the semilog hydrograph. Although considerable uncertainty is inherent in the recession index, the results of the RORA program may not be sensitive to this variable.

Testing shows that the program can yield consistent estimates under conditions that include leakage to or from deeper aquifers and ground-water evapotranspiration. These tests indicate that RORA estimates the net recharge, which is recharge to the water table minus leakage to a deeper aquifer, or recharge minus ground-water evapotranspiration.

Before the program begins making calculations it designates days that fit a requirement of antecedent recession, and these days are used in calculations. The program user might increase the antecedent-recession requirement above its default value to reduce the influence of errors that are caused by direct-surface runoff, but other errors can result from the reduction in the number of peaks detected.

To obtain an understanding of flow systems, results from the RORA program might be used in conjunction with other methods such as analysis of ground-water levels, estimates of ground-water discharge from other forms of hydrograph separation, and low-flow variables. Relations among variables may be complex for a variety of reasons; for example, there may not be a unique relation between ground-water level and ground-water discharge, ground-water recharge and discharge are not synchronous, and low-flow variables can be related to other factors such as the recession index.

INTRODUCTION

The computer program RORA (Rutledge, 1998) estimates the ground-water recharge in a basin from analysis of a streamflow record. The program is a computerized version of a method of measuring the displacement of the streamflow-recession curve resulting from each recharge event, also known as the Rorabaugh Method. The program was originally developed as part of the Regional Aquifer System Analysis (RASA) of the U.S. Geological Survey (Sun and Weeks, 1991). The particular study includes the Appalachian and Piedmont Physiographic Provinces in the eastern United States, which is referred to as the AP-RASA project (Swain and others, 1991). Although the program was developed for the AP-RASA project, it may have applications in other environments.

The purposes of this report are to demonstrate the sensitivity of program output to the uncertainty of input variables, discuss the effects of various conditions that depart from the original assumptions of the RORA program, and provide information that will facilitate correct use of the program. Although some discussion here relates to the application of the Rorabaugh Method in general, the primary focus is the RORA program.

The program is intended for analyzing a ground-water-flow system that is characterized by diffuse areal recharge to the water table and ground water discharge to a stream. The method is appropriate if all or most ground water in the basin discharges to the stream and if a streamflow-gaging station at the downstream end of the basin measures all or most of this outflow. Regulation and diversion of streamflow should be negligible. Additional discussions of program limitations are included in the sections "Suggested Constraints on Program Use" and "The Use of Ground-Water-Level Data."

The program is completely automated except for the need for a user-specified recession index. The program reads a data file of daily streamflow and then estimates recharge for the period of interest. The estimates are made quickly for a period of record that can be very long (several years), without the subjectivity inherent in manual methods.

The Rorabaugh Model

The Rorabaugh Model (Rorabaugh, 1964) is based on an ideal flow system in which the aquifer has uniform thickness, hydraulic conductivity, and storage coefficient, and the stream fully penetrates the aquifer (fig. 1). The initial condition set by Rorabaugh (1964) is that the hydraulic head in the aquifer is the same everywhere as the stage of the stream. Recharge is considered to be an instantaneous increase in hydraulic head (h_0) applied uniformly throughout the aquifer while the stream stage remains unchanged. Aside from this recharge to the water table and the subsequent discharge to the stream, there are no other gains or losses of water to or from the system. The resulting ground-water discharge to the stream (q) is described by Rorabaugh's (1964) equation 1:

$$q = 2T\frac{h_0}{a}\;{}_{m=1,3,5...}^{\infty}\; e^{-m^2\pi^2 Tt/(4a^2 S)} \qquad (1)$$

where q is ground-water discharge per unit of stream length (one side), T is transmissivity, h_0 is instantaneous water-table rise, a is distance from the stream to the hydrologic divide, t is time elapsed after the instantaneous water-table rise, and S is the storage coefficient.

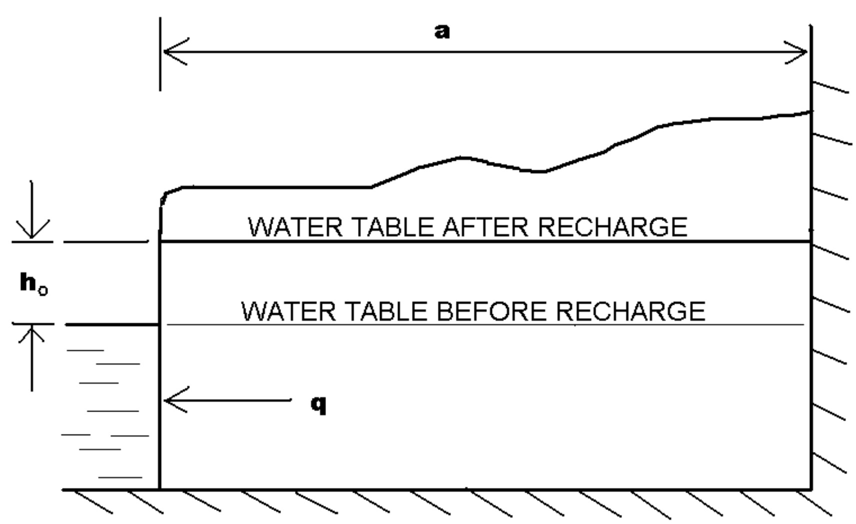


Figure 1. Definition sketch for Rorabaugh's equation (from Rorabaugh, 1964).

The use of equation 1 requires knowledge of four independent variables (T, h_0, a, and S) that may not be easily obtained. The following equation was developed (Rutledge, 1997, eq. 7):

$$Q = \frac{1.866 A R_i}{K} \times \sum_{m=1,3,5...}^{\infty} e^{-0.933 m^2 \pi^2 t/(4K)} \, , \qquad (2)$$

where Q is the total ground-water discharge in the basin; A is the drainage area of the basin; R_i is the instantaneous recharge in units of length; and K is the recession index in units of time. The recession index is a measure of the time required for the ground-water discharge to recede by one log cycle when the recession becomes linear (or nearly linear) on a semilog hydrograph. After an appreciable recharge event, a certain time interval must elapse before this linear recession can be observed. This is referred to as critical time, which can be determined from the following equation (modified from Bevans, 1986, eq. 8):

$$t_c = 0.2144K \; . \qquad (3)$$

As indicated by Rorabaugh (1964, p. 434), the principle of superposition can be applied to generate a hydrograph of ground-water discharge that results from a series of recharge events. The synthetic hydrograph of ground-water discharge to a stream (fig. 2) is generated from the flow model PULSE (Rutledge, 1997) on the basis of model-input data that will be described further. (See “Experimental Design for Testing RORA.”)

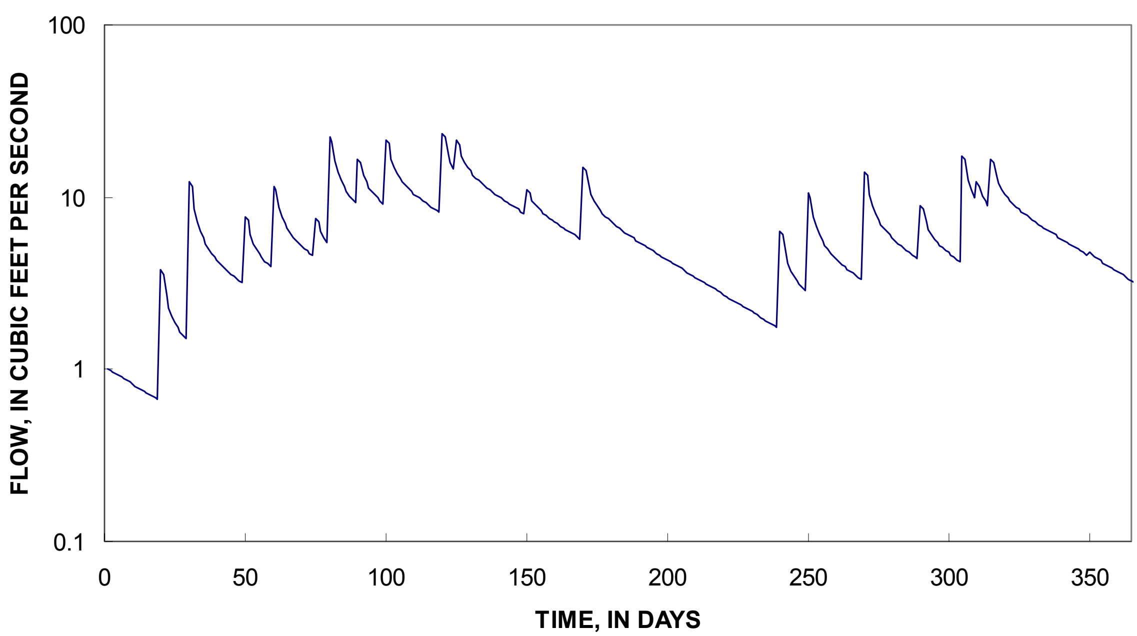


Figure 2. Hydrograph of ground-water discharge generated by the flow model PULSE using hypothetical model-input data. (Model-input recession index is 100 days per log cycle.).

An adaptation of the Rorabaugh Model developed by Daniel (1976) allows for a gradual component of recharge in addition to the instantaneous component:

$$q = \left(\frac{h_0 T}{a}\right)\left(\frac{Ca^2 S}{h_0 T}\right)\left[1 + 2\sum_{m=1,3,5...}^{\infty}\left(\frac{h_0 T}{Ca^2 S} - \frac{4}{\pi^2 m^2}\right) \times e^{-m^2\pi^2 Tt/(4a^2 S)}\right] , \qquad (4)$$

where C is a gradual gain or loss, $C=dh/dt$. This equation was also modified so that independent variables include recharge, drainage area, and the recession index (Rutledge, 1997, eq. 10):

$$Q = R_g A + 2R_g A \times \sum_{m=1,3,5...}^{\infty}\left[\frac{(0.933R_i)}{R_g K} - \frac{4}{\pi^2 m^2}\right] \times e^{-0.933 m^2 \pi^2 t/(4K)} , \qquad (5)$$

where R_g is gradual recharge rate, in units of length per time.

The utility of this equation, as described by Daniel (1976), is to simulate the effects of ground-water evapotranspiration (specified as a negative gradual recharge), which might occur after the instantaneous recharge. The formulation also can be used to simulate the effect of gradual recharge (Rutledge, 1997, p. 6-8).

The RORA Program

A few aspects of the RORA program that are relevant to discussion in this report are described here. This report does not include a thorough description of the algorithm of RORA. The reader is referred to the documentation report for details (Rutledge, 1998, p. 17-26).

The RORA program differs from the PULSE program in that RORA is an inverse method for estimating recharge. The input data (flow) is used to estimate recharge, unlike the PULSE program which simulates flow from user-designated recharge. RORA is based on the assumption that the hydrograph of ground-water discharge can be described by use of Rorabaugh's instantaneous-recharge model (equation 1) and superposition. This inverse method makes use of the following: After an instantaneous recharge event, if the resulting ground-water discharge (Q) at critical time were known, the recharge could be approximated using this equation (modified from Rutledge, 1998, eq. 7):

$$R \cong \frac{2QK}{2.3026} . \qquad (6)$$

This inverse method for estimating recharge can be demonstrated using a hydrograph of ground-water discharge for one recharge event that is preceded by zero flow (fig. 3). The hydrograph was generated using PULSE, designating a recession index = 100 d, drainage area = 10 mi^2, and recharge = 1.0 in. From equation 3, critical time is 21.44 days. Because the program makes calculations on the basis of the hour and because recharge is designated to occur on the first hour of day 10, the flow at critical time after recharge should be roughly equal to the mean flow on day 32. That amount is 3.03499 ft^3/s, from an output file created by PULSE. Recharge is calculated using the following equation, which includes unit conversions:

$$R = 0.8686\left(\frac{3.03499\,ft^3}{s}\right)(100d)\left(\frac{86400s}{d}\right)\left(\frac{area}{10 \bullet 5280^2\,ft^2}\right)\left(\frac{12in}{ft}\right) . \qquad (7)$$

The result of this calculation is 0.98 in. Small differences between the recharge designated in the flow model and the recharge calculated by the inverse method will result because equation 6 is an approximation and because of errors resulting from time increments used by the programs.

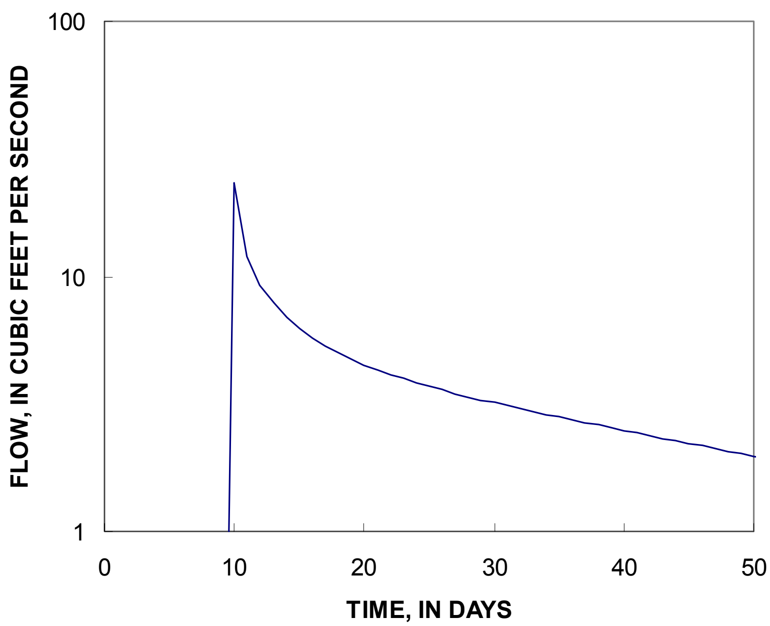


Figure 3. Hydrograph of ground-water discharge generated by the flow model PULSE using hypothetical model-input data. (Recession index = 100 days per log cycle, drainage area = 10 square miles, initial ground-water discharge = zero, recharge simulated = 1 inch on day 10.)

The example described above includes zero flow prior to the recharge event of interest. The RORA program also can make calculations if ground water is discharging to a stream as a result of previous recharge events. This is accomplished by defining a "baseline" ground-water discharge resulting from previous recharge. This baseline is described mathematically within the program but it can be illustrated as the dotted line in figure 4. In this example the baseline is linear, but the program allows for nonlinear recession (Rutledge, 1998, page 23).

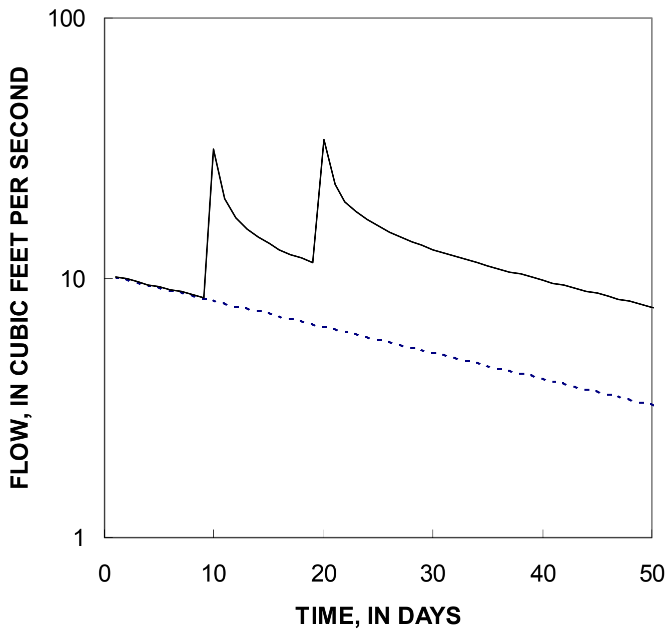


Figure 4. Hydrograph of ground-water discharge generated by the flow model PULSE using hypothetical model-input data. (Recession index = 100 days per log cycle, drainage area = 10 square miles, initial ground-water discharge = 10 cubic feet per second, simulated recharge = 1 inch on day 10 and day 20.)

The program also can make calculations if another recharge event occurs before the flow at critical time can be observed (fig. 4). This is accomplished by making use of the following observation about flow-model discharge prior to critical time: The discharge resulting from the event of interest will be approximately proportional to the reciprocal of the square root of time since the recharge event (Rorabaugh, 1964, equation 4). For each recharge event, the ground-water discharge resulting from the event can thus be described (up to critical time) by the following equation (modified from Rutledge, 1998, equation 8):

$$Q \cong \frac{C_e}{\sqrt{t}} \ , \qquad (8)$$

where C_e is some constant for the event. This equation is considered to represent the ground-water discharge on days following the event of interest. The algorithm uses the flow on these days, subtracting the flow at the baseline, to determine the ground-water discharge resulting from the event of interest. The program then calculates C_e for each of these days by a rearrangement of equation 8. The average value of C_e for the event of interest is then combined with t = critical time, to calculate the ground-water discharge that would have occurred at that time in the absence of other recharge events, using equation 8. Then recharge resulting from the event of interest is calculated using equation 6. This hydrograph of ground-water discharge (fig. 4) was analyzed using the RORA program. The amounts calculated by RORA are 0.969 inch for the first event and 1.004 inch for the second event (recharge designated in the flow model is 1.0 inch for both events). Differences occur because equations 6 and 8 are approximations.

The procedure described above for defining ground-water discharge after the event of interest is performed using days in the streamflow record that fit a requirement of antecedent recession. Flow on these days is considered to represent ground-water discharge to the stream. The program determines this requirement by solving the following empirical equation for the time of surface runoff (from Linsley and others, 1982) and rounding to the next larger integer:

$$N = A^{0.2}, \qquad (9)$$

where N is the time in days and A is the drainage area in square miles.

A period of ground-water discharge is one day that fits this requirement or a series of consecutive days that fit the requirement. The program uses equation 9 (rounded upward) to determine the default value of the requirement of antecedent recession. The program user can modify this variable (see later section in this report). The program defines a peak as the largest streamflow between two periods of ground-water discharge. Calculations are performed based upon the assumption that peaks represent the time of recharge events. This report includes discussion of uncertainties related to the time of recharge. Periods of ground-water-flow recession and peaks designated by RORA are shown for an example streamflow hydrograph (figure 5).

The above description of the method would apply to the very first recharge event. The documentation report includes discussion of baseline determination for other recharge events.

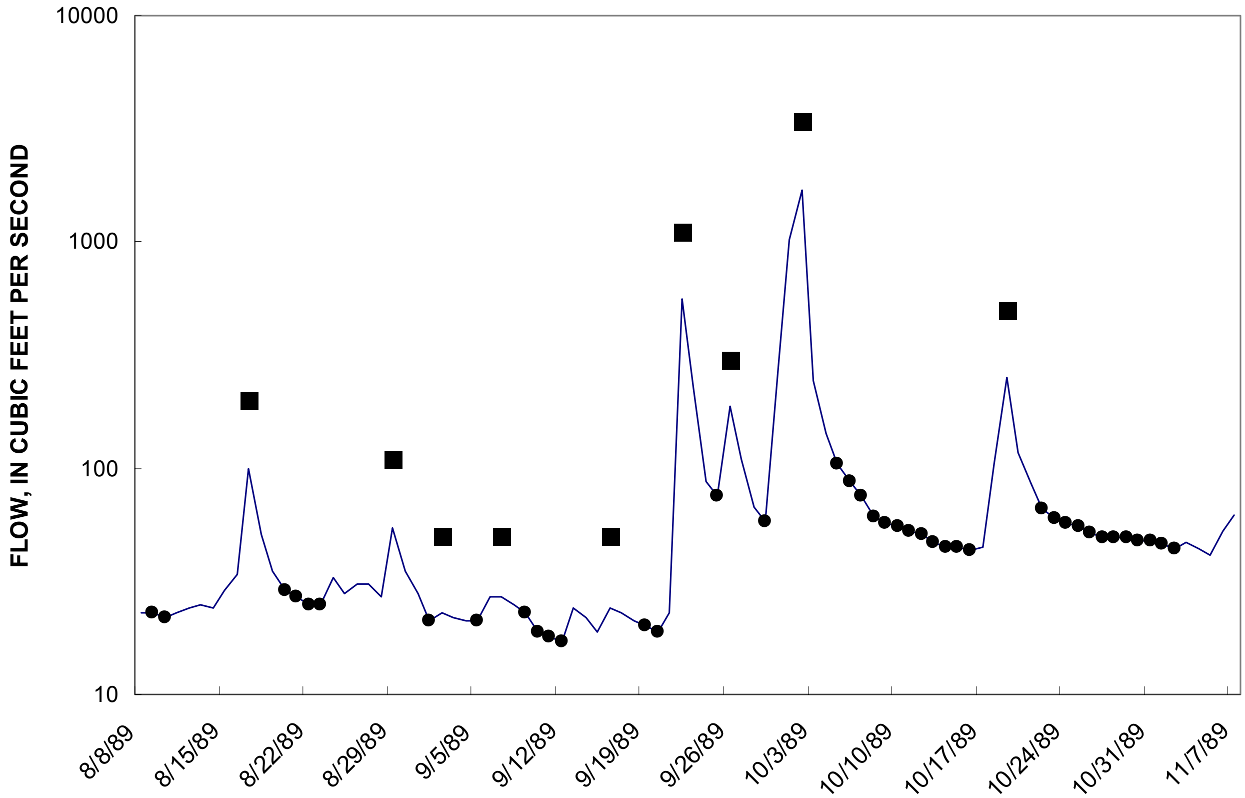


Figure 5. Streamflow on days that fit the requirement of antecedent recession (circular markers) and designation of peaks by RORA (square markers) (Streamflow-gaging station is Indian Creek near Laboratory, North Carolina).

Suggested Constraints on Program Use

In addition to constraints mentioned earlier as to the type of flow system for which the RORA program is intended, additional constraints may be warranted. For example, the use of the program for analysis of streamflow records from very small basins may give unreliable results because small flow rates are subject to errors that may be considerable in proportion to the total; in addition, underflow may be proportionally large relative to the reported streamflow. Certain model limitations also may be associated with large drainage area. Given a storm event that affects two basins of significantly different size, the period after the storm during which the hydrograph is dominated by surface runoff will be longer for the larger basin, and the opportunity to quantify ground-water discharge from the streamflow data will be reduced. Because the Rorabaugh Model is based upon a conceptualization of the system as one process, additional problems develop from large areas because storm systems are not uniform, and large areas tend to blend multiple hydrogeologic settings. The method is intended for application to a flow system in which ground water discharges to a stream, so any change in flow direction resulting from the bank-storage effect will cause interference. This effect may increase as drainage area increases. Although some constraints may be associated with drainage area, no absolute limits can be considered universal. The author recommends that drainage area be greater than 1 mi^2 and less than 500 mi^2, but the program user should use judgment depending on hydrologic setting.

The use of the model may not be appropriate in basins with small relief. The program uses equation 9 (rounded upward) to determine the requirement of antecedent recession, which designates those parts of the record that represent ground-water discharge. In extremely flat areas, the time period of surface runoff may not be estimated using this equation. The program allows the user to increase the requirement of antecedent recession above its default value, but this practice may cause other errors because of the reduction in number of peaks detected. (See the section on “Requirement of Antecedent Recession.”)

The program is based on the assumption that recharge occurs in the form of discrete events that are roughly concurrent with peaks in streamflow (Rutledge, 1998, p. 3). This report includes discussion of methods that might be used to evaluate this assumption. (See the section on “Use of Ground-Water-Level Data.”)

In addition to physical characteristics of a basin that indicate the use of RORA is not appropriate, the shape of the streamflow hydrograph also might be an indicator. If the Rorabaugh Model describes the ground-water discharge to the stream, then the shape of the semilog streamflow hydrograph should be similar to that in figure 2. In figure 6, for example, the hydrographs of two streams show peaks in flow and subsequent periods of recession that are roughly similar to those in figure 2, but the hydrograph for a third stream does not show such features. The drainage area of this station (A) is very large (7,880 mi^2) and includes part of a major wetland (Okefenokee Swamp). These features indicate questionable model applicability for flow measured at this station. The shape of the streamflow hydrograph is only one indicator of model applicability. Even if a hydrograph has a "favorable" shape, one cannot guarantee that the model applies.

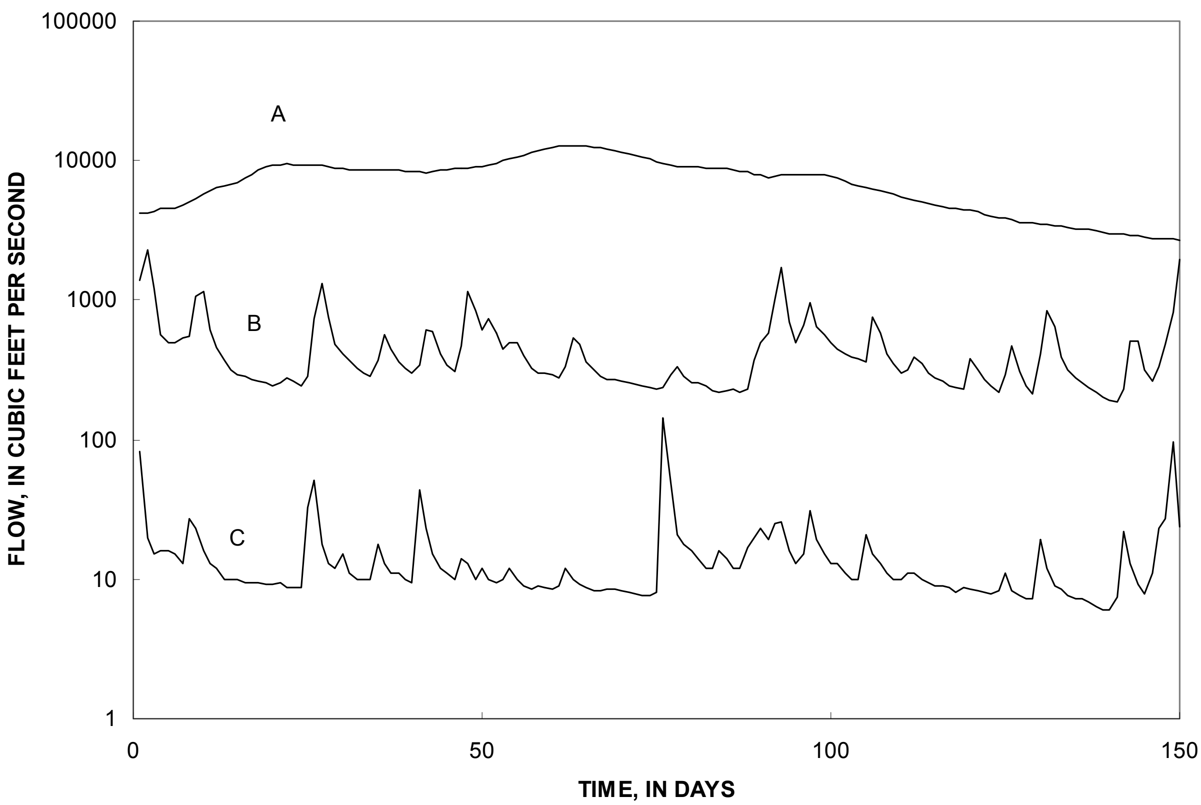


Figure 6. Streamflow hydrographs for three stations, for the first 150 days of 1990: (A) Suwannee River near Branford Florida; (B) Nottoway River near Rawlings, Virginia; and (C) Holiday Creek near Andersonville, Virginia.

EXPERIMENTAL DESIGN FOR TESTING RORA

Forward models can be used to evaluate the applicability and sensitivity of inverse models for use in estimating hydrologic values or properties. For the purposes of this report, the forward model PULSE (Rutledge, 1997) was used to generate synthetic hydrographs of ground-water discharge on the basis of assumed recharge data sets. The applicability of RORA to estimate recharge under prescribed conditions and the sensitivity of the recharge estimates to various assumptions then can be evaluated.

The testing of RORA by means of PULSE input data can be very simple, as in the analysis of the example hydrograph in figure 2. Results from this analysis are shown in table 1. The hydrograph is based on the instantaneous-recharge model described above, with specified recharge on the 12th hour of the days designated. Because RORA is based on the assumption that this model describes the entire hydrograph, the comparison between the two sets of values is very close (table 1). The hydrograph is model generated; but when an actual streamflow hydrograph is analyzed, extrapolation errors will occur at the beginning and ending of the period analyzed if streamflow peaked near the beginning or the ending of the period analyzed. RORA can ignore the very last peak in such a period. Most hydrographs illustrated in this report start and end with a clear period of recession, and most include a very small recharge event near the end of the period shown. The comparison between flow-model-designated recharge and results from RORA is shown on the basis of each recharge event (table 1). When actual streamflow records are analyzed, the results from RORA should be reported or used only at a large time scale. (See “Time Scale for Reporting Results.”)

The test described above and illustrated in figure 2 and table 1 is very straightforward. This report also includes testing of (1) uncertainty in the recession index, (2) modification in the time of recharge, (3) gradual recharge, (4) ground-water evapotranspiration, (5) modification of the requirement of antecedent recession, and (6) estimation of recharge for streamflow hydrographs using PULSE and RORA separately.

This report makes use of inferences that can be drawn from analysis of actual streamflow records. For example, stations analyzed previously in the AP-RASA project (Rutledge and Mesko, 1996) are used to test program sensitivity to variation in the recession index and the requirement of antecedent recession. Comparison between results of the program and results of manual methods are used to evaluate the correct time scale for reporting results.

Table 1. Instantaneous recharge amounts used to generate the hydrograph of ground-water discharge in figure 2 by use of the PULSE model, and recharge estimates calculated by the RORA program from analysis of that synthetic record of ground-water discharge

Day of year	Flow-model recharge (inches)	Recharge estimated by RORA (inches)
20	.20	.203
30	.70	.711
50	.30	.297
60	.50	.504
75	.20	.200
80	1.10	1.114
90	.50	.505
100	.80	.793
120	1.00	1.006
125	.50	.495
150	.20	.186
170	.60	.605
240	.30	.303
250	.50	.506
270	.70	.703
290	.30	.296
305	.85	.861
310	.20	.203
315	.53	.532
350	.02	----
Total	10.00	10.02

EVALUATION OF THE PROGRAM

The purposes of this section are to demonstrate sensitivity of the output of the RORA program to uncertainty in variables, to discuss the effects of various conditions that depart from the original assumptions, and to provide information that will facilitate correct use of the program. Some of the following relates to the application of the Rorabaugh Model in general.

Recession Index

The use of the Rorabaugh Method requires the designation of a recession index. When this variable is determined from streamflow data, the data analyzed should come from parts of the year when ground-water evapotranspiration (GWET) is small because GWET can affect the rate of recession. This section includes discussion of methods for calculating the recession index and the reasons for uncertainty in this variable. Although uncertainty in the recession index is considerable, the effect on the estimate of recharge may be very small. (See last paragraph in this section.)

One method for calculating the recession index is to locate a part of the streamflow record with continuous recession, find a segment that begins a sufficient amount of time after recharge so that it will exhibit near linearity on the semilog hydrograph, determine the slope of the segment, and express the result in days per log cycle. The synthetic data set of ground-water discharge (fig. 2) can be used to demonstrate why the segment must begin a sufficient amount of time after the last recharge event. Various segments were selected from the long period of recession that follows the recharge event on day 170. The following are the measured slopes of segments. The recession index specified in PULSE input is 100 days per log cycle. The slope of each segment was determined by means of the RECESS program (Rutledge, 1998):

Days after recharge	Slope in days per log cycle
5-10	54.8
11-15	79.1
16-20	91.5
21-25	95.3
26-30	99.2

The substantial difference between the first two and the last three segments shows that a period of recession must be of considerable duration after the last significant recharge event in order to accurately define the recession index. In addition, the measured recession index can differ from one period of recession to another. Therefore, the suggested procedure is to locate several segments throughout the period of record, obtain estimates of the recession index for each, and then use the median value for execution of RORA. A large period of streamflow record is usually required for adequate sampling of the recession index because long periods of continuous recession may be sparsely distributed in the record. For example, in the AP-RASA study, recession analysis included the selection of only 5-10 segments per decade of streamflow record (Rutledge and Mesko, 1996, table 2).

Certain limitations are associated with the method described above. In some circumstances, the segments of continuous recession will not be of sufficient duration to quantify the index. This effect will be magnified if the actual (unknown) recession index is large. This limitation can be demonstrated using the model-input data set that is used to generate the hydrograph in figure 2. Although one recession index is indicated in figure 2, the PULSE model can be executed a number of times, each time specifying a different "known" recession index. After each execution, each synthetic data set of ground-water discharge over time can be analyzed by use of the RECESS program. To demonstrate, one could select a segment that begins 21 days after and ends 30 days after the recharge event on day 170. For this particular synthetic hydrograph, a segment farther along the extended period of recession would more reliably indicate the true recession index. The segment used here, however, might be more representative of the kind of segments that are available from actual streamflow data. With each application of RECESS, the observed recession index is noted:

Flow-model recession index	Observed recession index
50	50.1
100	97.4
150	137.9
200	174.5
250	202.8

The results of this experiment indicate that the method of using continuous recession segments will break down if the actual recession index is extremely large (greater than about 100 days per log cycle in this example). Alternatively, this kind of experiment may indicate that as long as the observed recession index is small, then it may be considered reliable.

An alternative method for obtaining the recession index is the general connection of minimums over a long period of recession that is interrupted by numerous storm events. This method might be used if periods of continuous recession are few or nonexistent (which can be the case if the streamflow record is short), but it can result in an estimate that is anomalously large if recharge occurs during any of the storm events. This method, and its potential shortcomings, can be demonstrated using a hydrograph generated by the PULSE model that shows the effects of alternating periods of large and small recharge rates (fig. 7). During the periods of small recharge, there is a general decline in flow. The estimate of the recession index obtained by connecting the minimums can be incorrect and can vary from one of these periods to another because of differences in the rate of recharge. Although the recession index specified in the PULSE model is 100 days, the two examples of connecting the minimums yield estimates of 190 days and 140 days (fig. 7).

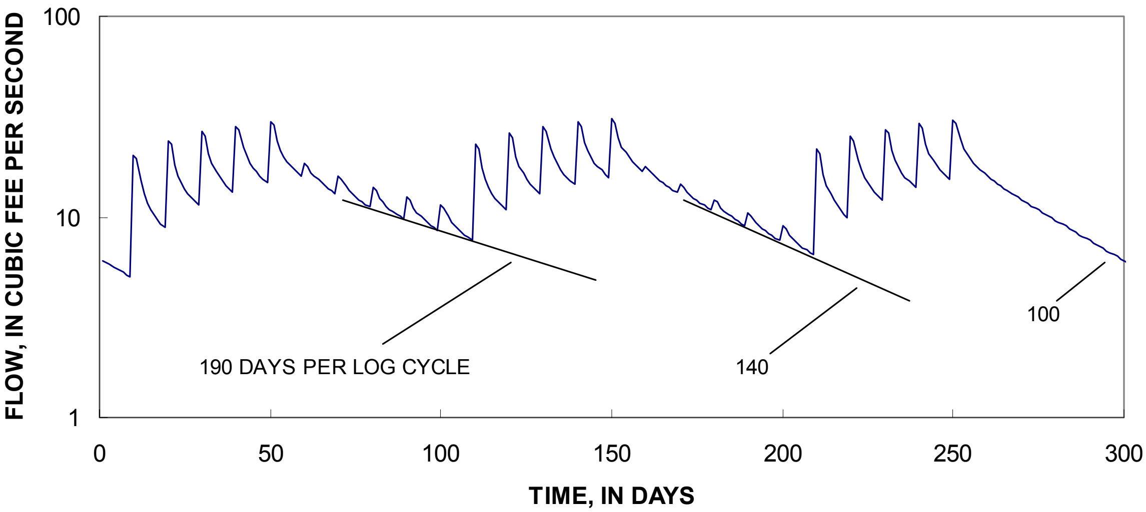


Figure 7. Hydrograph of ground-water discharge generated by the PULSE model using hypothetical model-input data, showing estimated base-flow recession curves generated by connecting the minimums over periods of general decline in flow. (Model-input recession index is 100 days per log cycle. The recharge per event is 1 inch from day 10 to 50, day 110 to 150, and day 210 to 250. The recharge per event is 0.2 inch from day 60 to day 100 and 0.1 inch from day 160 to day 200.)

If sufficient streamflow data are not available for determining the recession index, indirect methods may be considered. For example, this equation, derived from Rorabaugh and Simons (1966, p. 12) might be used:

$$K = \frac{0.933a^2S}{T} \quad , \qquad (10)$$

where K is recession index, a is distance from the stream to the hydrologic divide, S is storage coefficient, and T is transmissivity. This equation might result in a wide variety of estimates. For example, if the uncertainty in each variable a, S, and T were 30 percent above and below a median value, then the range of possible values of the recession index would be about an order of magnitude. Another indirect method is to obtain estimates from analysis of data sets from other basins in the area. Regionalized estimates of the recession index may be useful in some applications.

In the simulations described to this point, the ground-water-discharge hydrograph becomes linear on the semilog hydrograph after some time has elapsed since the last recharge event. The heterogeneity of natural flow systems will cause departures from this ideal case. The effect of heterogeneity can be demonstrated by considering a 10-mi^2 basin that is made up of three subbasins. One subbasin, which constitutes most of the total area, is 8 mi^2, and the aquifer characteristics in this subbasin result in a recession index equal to 100 days. The two other subbasins each measure 1 mi^2. The aquifer characteristics cause the recession index to be 50 days in one and 2,000 days in the other. This conceptual model might result from the variation in geologic materials in the basin. The effect of this heterogeneity is simulated by executing PULSE three times, each with the same recharge (table 1) but with different drainage area and recession index (as specified above). Then, the three hydrographs of ground water discharge are added to give the total basin ground-water discharge. The resulting hydrograph (fig. 8) shows the effect of this heterogeneity, as evident from the slight curvature in the recession curve even during long periods without recharge.

To compare with earlier analysis, the RECESS program was used, selecting the segment that spans from 21 to 30 days after the recharge event on day 170 (fig. 8). The recession index is calculated to be 97 days per log cycle. Another segment spanning from day 51 to 60 indicates a recession index of 108 days per log cycle. It is evident that if recession were to continue for a much longer time period than shown, the measured recession index would continue to increase. The synthetic data set was analyzed using the RORA program, with various values specified for the recession index:

Recession Index (days per log cycle)	Recharge (inches)
97	9.5
108	9.5
500	12.3

In this experiment, the recession index observed under “average flow” conditions represents the prevailing hydraulic conditions in the basin, whereas the recession index observed under extreme low-flow conditions does not. The aquifer characteristics in a very small part of the basin may dominate recession characteristics in conditions of extreme low flow. Similar low-flow conditions might result from stream segments going dry, causing an increase in the average distance from the divide to the stream (a in eq. 10), or from small, unknown regulation or diversion of flow.

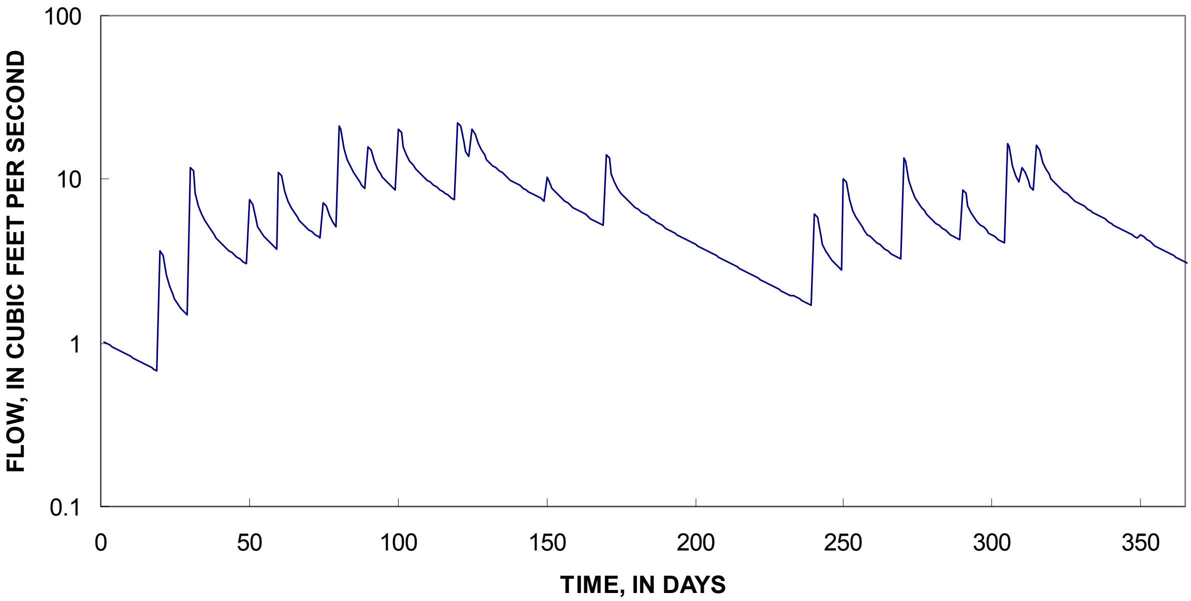


Figure 8. Hydrograph of ground-water discharge for a hypothetical basin consisting of three subbasins, that is generated by executing the PULSE model three times (One basin measures 8 square miles and the recession index is 100 days per log cycle. The other two subbasins each measure 1 square mile. In one of these the recession index is 50 days per log cycle and in the other, 2,000 days per log cycle.).

Although considerable uncertainty is inherent in the recession index, further analysis of streamflow data that were used in the AP-RASA project indicates that the estimate of recharge is not particularly sensitive to this variable. This project included the estimation of the median recession index for each station from periods of continuous recession (using RECESS), followed by the use of RORA to estimate recharge designating this median recession index as input to that program. Most values of the recession index in this analysis are between 50 and 120 days. This sensitivity test shows that if the recession index is decreased by 50 percent the recharge estimate will increase by generally 4-9 percent (fig. 9). If the recession index is increased by 50 percent the recharge estimate will decrease by generally 2-4 percent. Even when the recession index is increased by 10 times, most estimates of recharge change by less than 10 percent. Most of these changes are less than 1 in/yr.

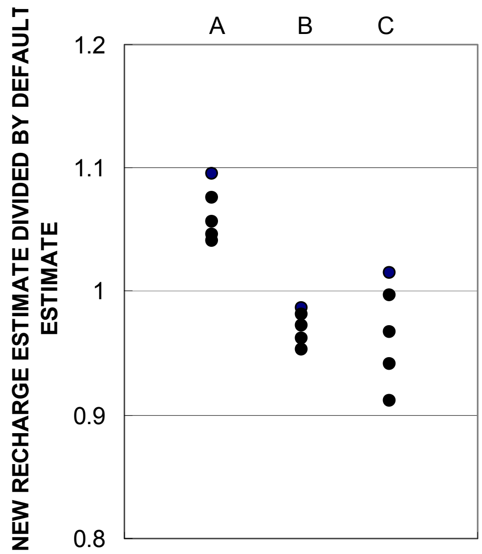


Figure 9. Change in the estimate of recharge from program RORA that results from changing the recession index to (A) 0.5 times default value, (B) 1.5 times default value, and (C) 10.0 times default value. (Source: all streamflow stations in the AP-RASA project with complete record for 1961-90: Rutledge and Mesko, 1996, table 3. Sample size = 89. The default recession index for each station is tabulated on table 2 of that report. All recharge estimates are the mean for the time period 1961-90. Each set of five markers represents the 10th, 25th, 50th, 75th, and 90th percentile, in ascending order.)

Time of Recharge

The RORA program is formulated with the assumption of recharge at the time of peaks in streamflow. The estimate of recharge is subject to uncertainty because the precise time of recharge is unknown. One way of evaluating this uncertainty is to consider calculations for the hydrograph illustrated in figure 2. The RORA program considers recharge events to coincide with the time specified in the PULSE flow model because streamflow peaks at the time specified for recharge. In this hydrograph, recharge (and, thus, peaks in flow) occurs on day 20, 30, 50, 60, and so on (table 1). Uncertainty in the estimate of recharge that will result from uncertainty in the time of recharge can be evaluated by editing the data generated from PULSE and placing a large flow (100 ft^3/s) on the day before each recharge event (day 19, 29, 49, 59, and so on). Then, RORA is executed to analyze this edited data set, and an estimate of recharge is obtained that will differ from that for the unedited data set. This procedure will, in effect, trick the program into considering the recharge to occur one day before the time of recharge designated in the flow-model-input data set. A similar experiment can be done to trick the program in the opposite way. Results indicate sensitivity to the time of recharge (the modeled recharge is 10 in.):

	Large flow on day before recharge event	Large flow on day after recharge event
Recharge estimated by RORA, in inches	10.64	9.56

Although RORA is based on instantaneous recharge, the gradual nature of recharge during a storm event may have a minor effect on estimates. This effect can be shown by means of output from PULSE for a 1.0-in. recharge event, designating recharge to be instantaneous (fig. 10A) and gradual (fig. 10B). The instantaneous event is set for day 10, and the gradual event is set as a constant rate from day 8 to day 12. When the synthetic data set is analyzed with RORA, the results show a difference: 0.988 in. for A and 0.942 in. for B. Most of this difference occurs because RORA considers the time of recharge to be day 10 in A and day 11 in B. To isolate the effect of gradual recharge, one might consider that, at day 10 in both hydrographs, a peak flow is caused by direct runoff. Another test was performed (not illustrated) in which a large flow (100 ft^3/s) was placed at day 10. That results in a more favorable comparison: 0.988 in. for A and 1.001 in. for B.

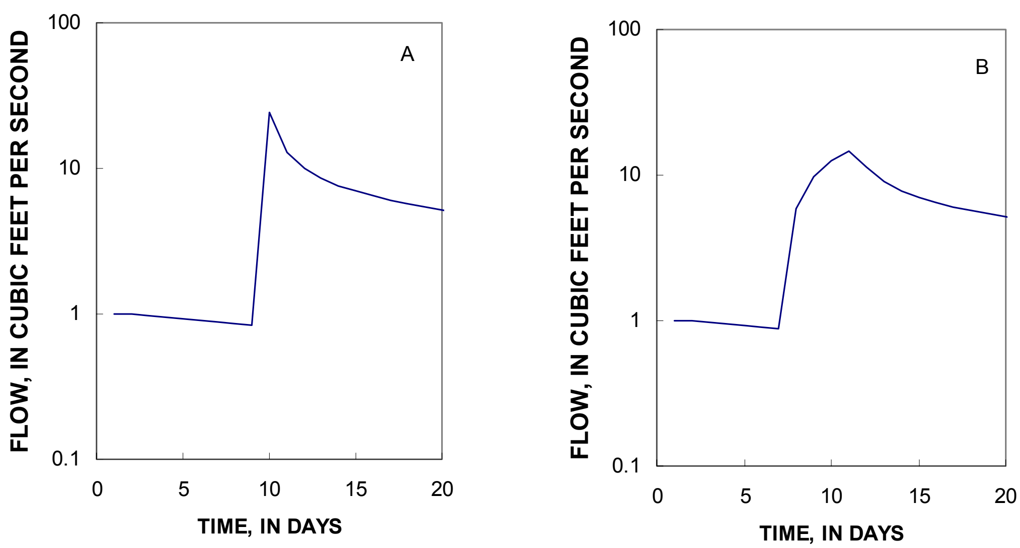


Figure 10. Two hydrographs of ground-water discharge generated by the flow model PULSE using hypothetical model-input data, one applying recharge instantaneously and the other gradually. (In each case, the total recharge simulated using PULSE is 1.0 inch. In case A this is applied at day 10. In case B this is applied gradually from day 8 to day 12.).

Effects of Leakage

Some ground-water flow systems that are driven by discrete recharge pulses to the water table also might include some leakage to or from deeper aquifers. The effect of this leakage can be evaluated by generating a hydrograph of ground-water discharge using the PULSE model, with model input that is identical to that used to generate figure 2 (total instantaneous recharge = 10 in.) but that also includes a smaller gradual component that is constant. The gradual component is specified to begin on day 1 and continue through the entire year at a constant rate of 0.00274 in/d, resulting in a total gradual recharge of 1 in/yr. This experiment is repeated with a negative gradual recharge of the same amount. Three hydrographs are shown in figure 11: one without the gradual component and two with the gradual recharge.

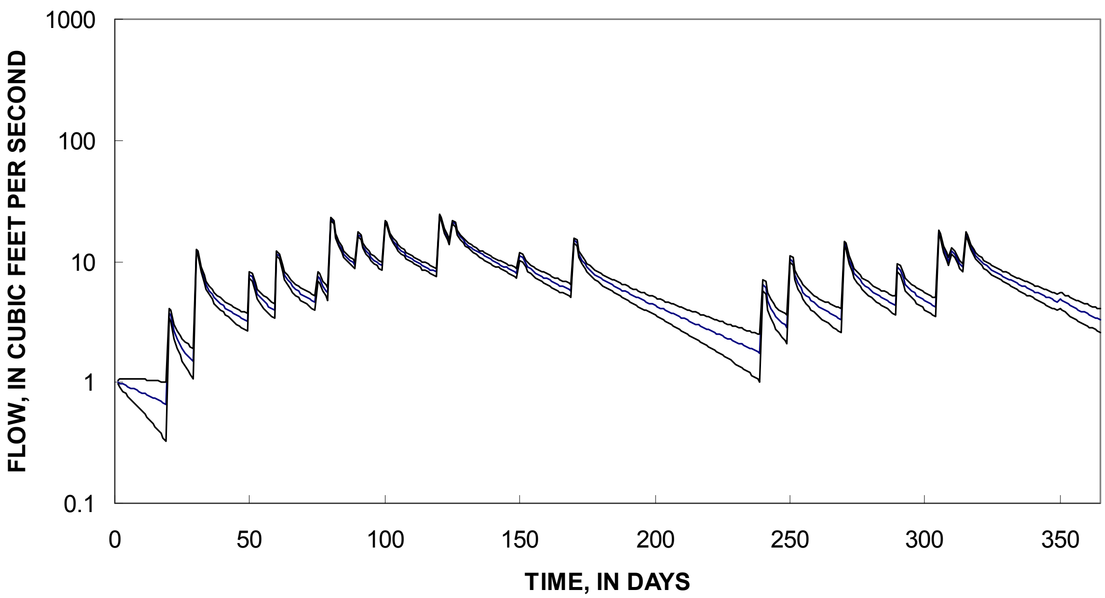


Figure 11. Hydrographs of ground-water discharge generated by the flow model PULSE using hypothetical model-input data. (The middle hydrograph is identical to the hydrograph in fig. 2. That hydrograph is caused by a series of instantaneous recharge events: total = 10 inches. The other two hydrographs are generated by the same series, but they also include a small gradual recharge: +1 inch per year for one and –1 inch per year for the other. Model-input recession index is 100 days per log cycle.)

The effect of the gradual component on the observed recession index is measured with the RECESS program, using the segment of recession that starts 21 days after and ends 30 days after the recharge event on day 170. Subsequent analysis with RORA, using the observed recession index in each case, yields the following:

Flow-model input recharge			Recession	Recharge calculated
Instantaneous (inches)	Gradual (inches)	Net (inches)	Index (days)	by RORA (inches)
10.0	+1.0	11.0	113	11.047
10.0	0.0	10.0	97	9.998
10.0	-1.0	9.0	82	8.979

These experiments indicate that RORA can give consistent estimates of net recharge if the hydrogeologic system includes a small gradual component of recharge.

In the preceding simulations, the gradual component of recharge is small relative to the instantaneous component. Recharge might be conceptualized as a series of instantaneous events in combination with significant gradual recharge. This conceptualization can be simulated with PULSE, designating a series of instantaneous recharge events that are identical to those in figure 2, and adding (in the same simulation) a considerable amount of gradual recharge. Two tests are run with the same series of instantaneous recharge events but with slightly different gradual recharge as specified below. In both cases, the total recharge is 20 in. (10 in. of instantaneous and 10 in. of gradual). The tabulation includes the estimate calculated by RORA for these two artificial records:

Rate (inch per day)	Time interval (days)	Estimate of recharge from RORA (inches)
0.0540	30-150 and 250-315	21.1
0.0417	20-150 and 240-350	19.3

These tests show that errors can occur if a significant amount of recharge is occurring as a long, gradual process.

Effect of Ground-Water Evapotranspiration

Because the RORA program is based on the assumption that the entire ground-water-discharge hydrograph is described by Rorabaugh's instantaneous-recharge model (eq. 1), the program does not explicity allow for the effects of ground-water evapotranspiration (GWET). Testing of RORA for hydrographs that include the effects of GWET is described in this section.

Hydrographs in figure 12 show results from PULSE when the annual model-input recharge is 15 in., 10 in., and 5 in. These hydrographs might represent wet, average, and dry conditions, respectively. In these simulations, the relative distribution of recharge among peaks is the same. In each frame are two hydrographs that were generated with the identical recharge series. One hydrograph in each frame includes GWET at a constant rate from day 100 to day 240, resulting in a total GWET of 0.4 in. The period of GWET might span spring and most of summer if the hydrograph is for a calendar year. In natural flow systems, the timing of GWET during the year may be affected by temperature, rate of plant growth, and depth to the water table. Earlier work indicates that GWET can cause convexity of streamflow recession (on the semilog hydrograph) during April-June for a stream in Alabama (Daniel, 1976).

The amount of convexity in the semilog streamflow hydrograph that is caused by GWET can vary among hydrographs because of factors other than the rate of GWET. The three hydrographs in figure 12 include the same GWET but different amounts of recharge. The amount of convexity during a period of GWET may depend on the residual ground-water discharge at the beginning of the period, which depends on the amount of recharge prior to the period.

The estimates of total annual recharge that are calculated by RORA for these hydrographs (fig. 12) are as follows. In each case, the recession index was set equal to the recession index in the input data file for program PULSE (100 days).

[All data in inches]

Flow-model input		
Instantaneous recharge	Ground-water Evapotranspiration	Recharge calculated by RORA
15.0	0.00	14.96
15.0	.42	14.56
10.0	.00	9.94
10.0	.42	9.54
5.0	.00	4.92
5.0	.42	4.52

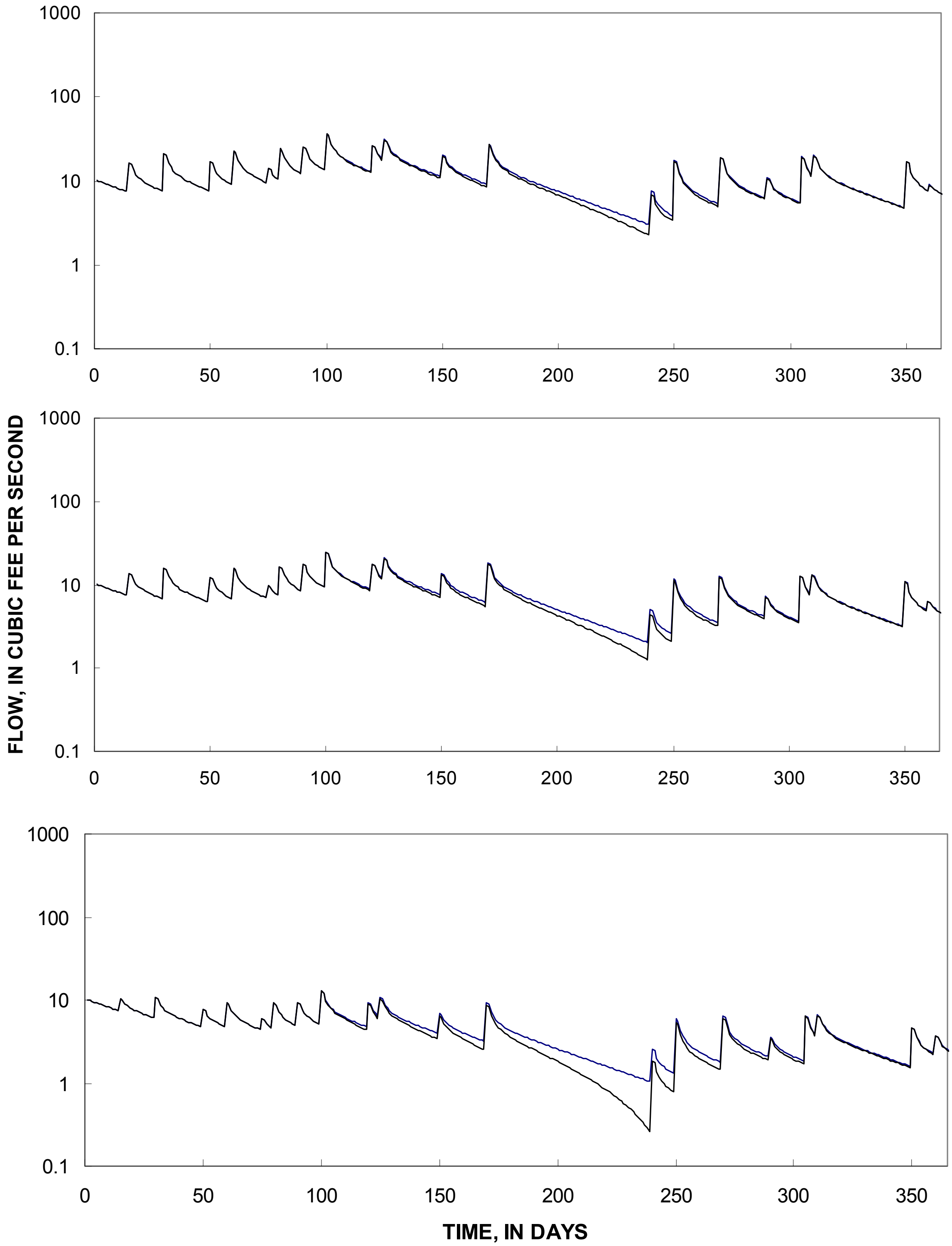


Figure 12. Hydrographs of ground-water discharge generated by the flow model PULSE using hypothetical model-input data. (Recession index is 100 days per log cycle in all simulations. The three frames were generated using three different values for total recharge: 15, 10, and 5 inches from top to bottom. In each frame, there is one hydrograph with and another without ground-water evapotranspiration of 0.42 inch.)

RORA seems to be giving an estimate of net recharge, instead of total recharge, where the net recharge would be equal to recharge minus GWET. Although this result might make sense hydrologically, any estimate of net recharge would be subject to error because RORA calculates recharge given Rorabaugh's instantaneous-recharge model, although GWET tends to be a gradual "negative recharge." An improved understanding of the effects of GWET might result from isolating the process. Two hydrographs shown in figure 13 include a series of five small recharge events during a period of GWET. The GWET spans day 100 to day 200 at a constant rate: 0.003 in/d in figure 13A and 0.005 in/d in figure 13B. The synthetic hydrographs of ground-water discharge were analyzed by the use of RORA. Results indicate a reasonably close comparison between the net recharge (total instantaneous recharge minus total GWET) and the results from RORA:

[All data in inches]

Instantaneous recharge	Ground-water evapotranspiration	Net recharge	Recharge calculated by RORA
0.1	0.3	-0.2	-0.203
0.1	0.5	-0.4	-0.403

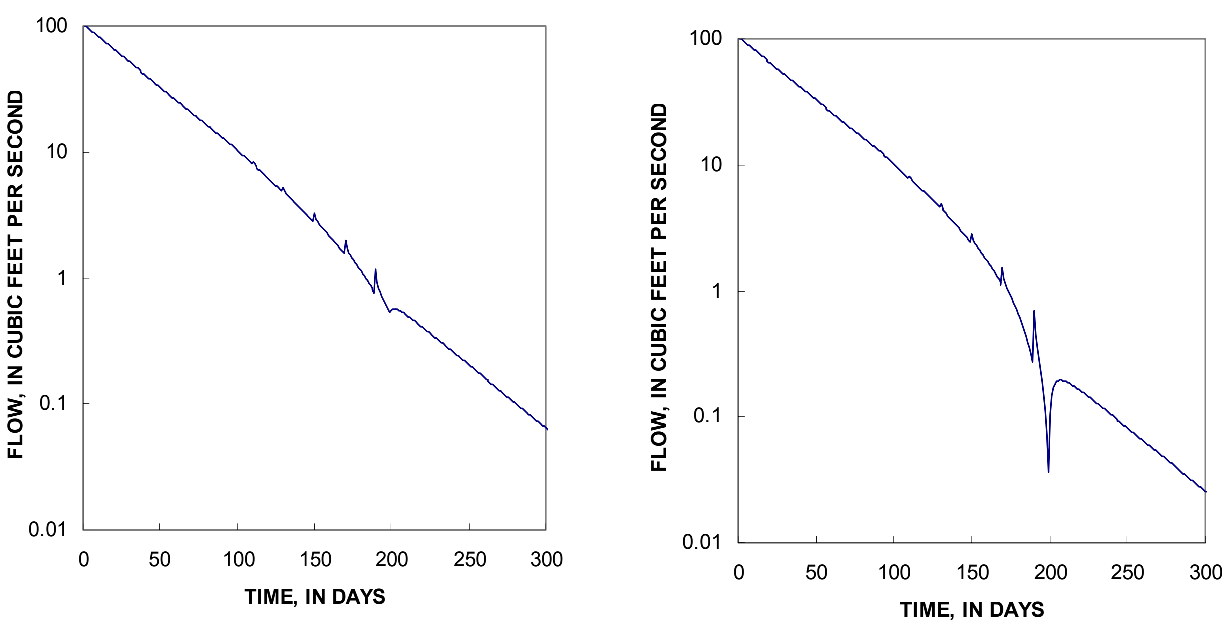


Figure 13. Hydrograph of ground-water discharge generated by the flow model PULSE using hypothetical model-input data, applying ground-water evapotranspiration as one long gradual negative recharge process from day 100 to day 200, and including five small instantaneous recharge events (each is 0.02 inch). Plots are shown for ground-water ET = 0.003 inch per day (A) and 0.005 inch per day (B).

The preceding test shows that RORA may calculate negative recharge during periods of GWET. If the positive recharge is small during a period of GWET, then the negative recharge (GWET) may dominate (fig. 13). This may also be the case for Indian Creek near Troy, Alabama, during spring 1963. The RORA program was used to analyze record from this station, specifying the recession index as 102 days (Daniel, 1976). The program calculated negative recharge in the quarter year April-June 1963, the same quarter year analyzed by Daniel (1976, fig. 3). The estimate of recharge from RORA is -0.27 in. during this quarter. Daniel estimated the rate of GWET at 0.5 centimeters per month, roughly 0.6 in. per quarter. A possible explanation for the difference between Daniel's estimate and the estimate from RORA is that the latter method should be giving total (net) recharge, which would be equal to recharge minus GWET.

Requirement of Antecedent Recession

Before RORA begins making calculations of recharge for each peak, it designates days that fit a requirement of antecedent recession (sometimes referred to as the "time base of surface runoff"). The requirement is equal to equation 9, rounded upward to the next larger integer. The program allows the user to override the default value. It can be increased by 1, 2, or 3 days, but a minor code modification allows for larger changes described here. Although the override option is provided primarily for testing purposes (Rutledge, 1998, page 24), it may provide a way of minimizing errors due to the effect of direct runoff. The fact that a particular day is preceded by N days of recession cannot guarantee this effect is nonexistent.

Sensitivity of estimated recharge to changes in the requirement of antecedent recession was evaluated for the streamflow stations used in the AP-RASA project. The increase in this variable causes a reduction in the number of peaks detected and a change in the estimate of recharge (fig. 14). Because RORA is approximating recharge as a complex series of instantaneous events, the reduction in the number of peaks can induce errors. The errors can be tested by means of a hydrograph generated with PULSE that exhibits complex distribution of recharge over time (fig. 15). The recharge specified in PULSE input data is 11.55 in. Application of RORA to estimate recharge for this hydrograph shows a reduction in the number of peaks detected along with a change in the recharge estimate.

The program user might consider increasing the requirement of antecedent recession by a small amount, such as 1 or 2 days. It is evident, however, that as the requirement is increased, errors caused by the reduction in the number of peaks detected may greatly outweigh all other errors. Equation 9 might be a guide for determining whether RORA can be applied to a particular hydrologic system. If the time of surface runoff is considered to exceed the result of this equation by a large margin – which may be the case in regions of low relief – then the program may not be appropriate for use.

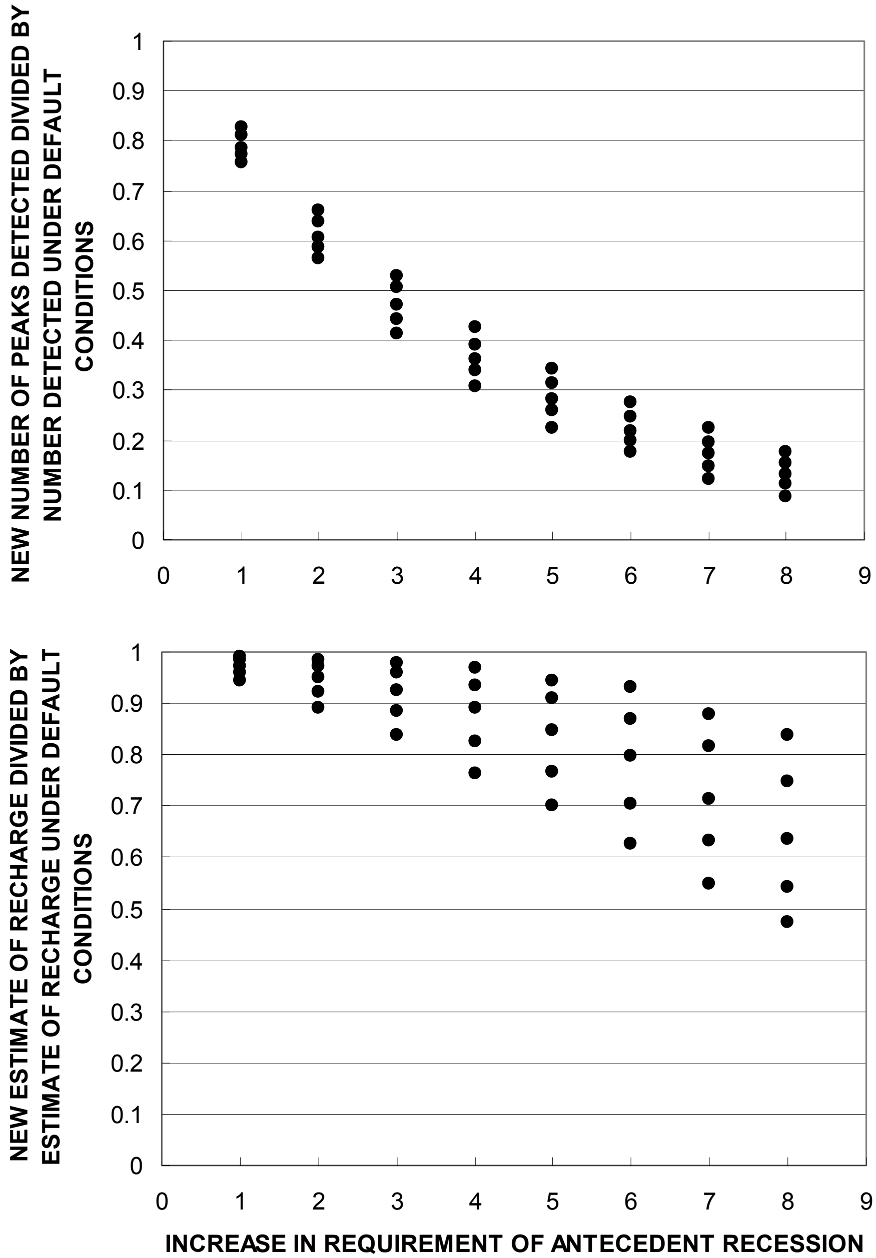


Figure 14. Change in the number of peaks detected and the change in the estimate of recharge from RORA that results from increasing the requirement of antecedent recession above its default value (Source: all streamflow stations in the AP-RASA project with complete records for 1961-90; Rutledge and Mesko, 1996, table 3. Sample size = 89. The recession index for each station is tabulated on table 2 of that report. All recharge estimates are the mean for the time period 1961-90. Each set of 5 dots represents the 10th, 25th, 50th, 75th, and 90th percentile, in ascending order.)

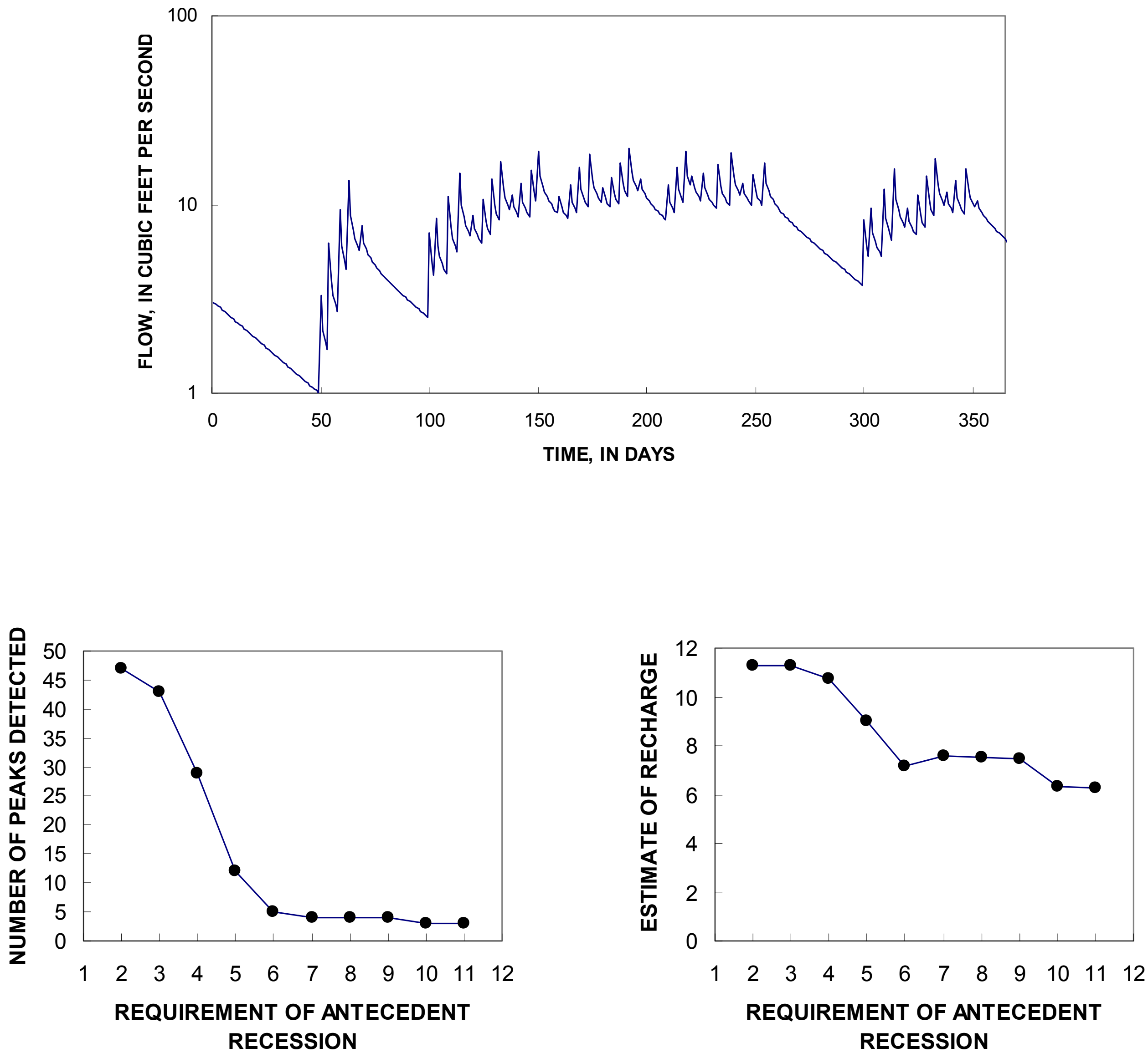


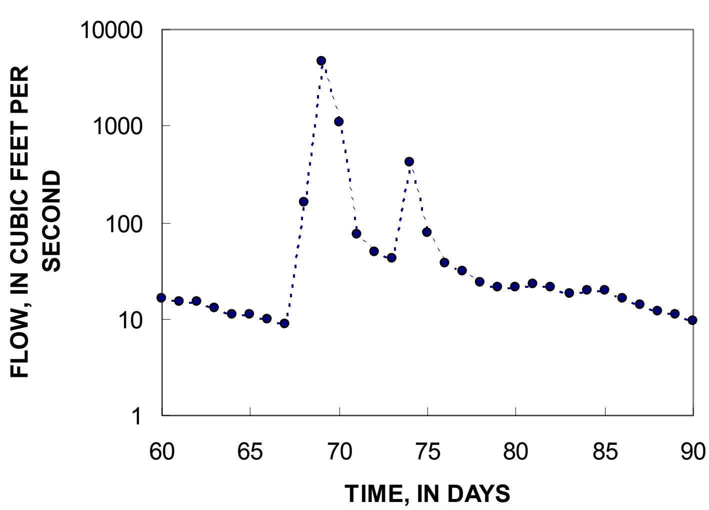
Figure 15. Hydrograph of ground-water discharge generated using the PULSE model, and results of RORA showing the number of peaks detected and the estimate of recharge, as the requirement of antecedent recession is increased above default value.

Time Scale for Reporting Results

Results from RORA should be reported or used only for a large time scale when the program is used to analyze a streamflow record. The following quotation (Rutledge, 1998, p. 25) is in reference to a figure that is similar to figure 5 of this report:

> The user should exercise caution in presenting and interpreting results at such a small time scale because of complex sets of recharge events: that is, multiple events that occur within such a short period of time that the period of ground-water-flow recession cannot be adequately measured between events. The resulting errors tend to compensate for each other when a longer time period is used. For example, the first peak of a pair of closely-spaced peaks may be assigned a recharge that is anomalously large, but the second may be assigned a recharge that is anomalously small.

Some insight about errors at the small time scale might come from considering calculations for March 1974 for Big Hill Creek near Cherryvale, Kansas (fig. 16). The estimate of recharge for the second peak has a negative sign. Although negative estimates may result from GWET, the likelihood of significant GWET in March is low. If the quotation above is a reasonable statement of program limitations, then the sum of recharge for March might be a useful estimate even though the estimates for particular peaks are not. Possible hydrographs of ground-water discharge generated by the PULSE program, designating total March recharge equal to the amount that RORA calculates, are shown in figure 17. The match between the hydrographs of ground-water discharge calculated by PULSE and streamflow on days that represent ground-water discharge seems to indicate that the estimate of total recharge for the month is reasonable.



Day of recharge	Recharge estimated by RORA (inches)
69	0.783
74	-0.075
81	0.024

Figure 16. Hydrograph of streamflow for Big Hill Creek near Cherryvale, Kansas, for March 1974, and estimates of recharge from RORA (RORA detects three peaks in this time period.)

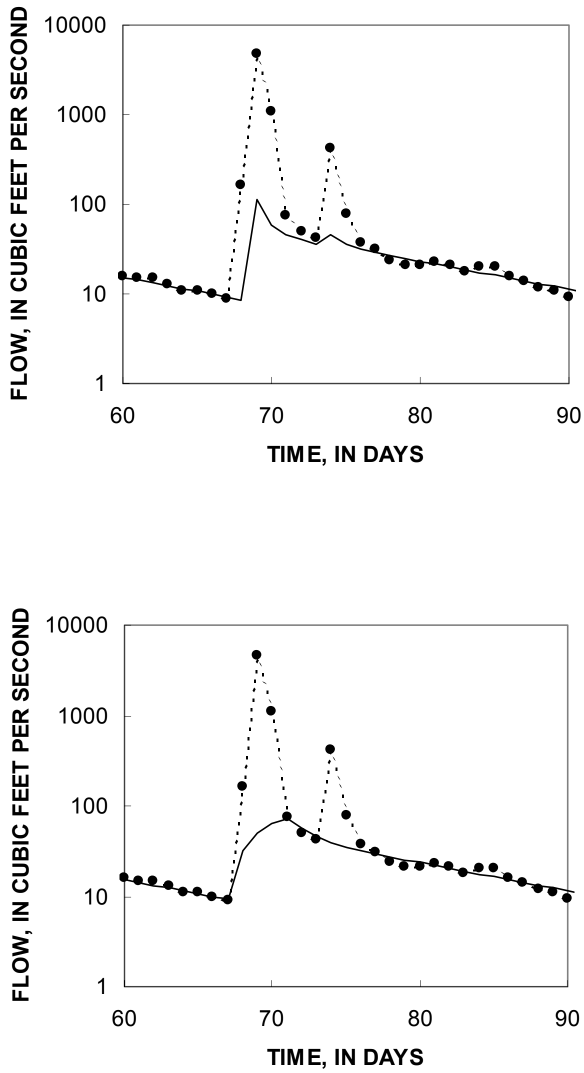


Figure 17. Hydrographs of streamflow for Big Hill Creek near Cherryvale, Kansas, for March 1974 (solid circles and dashed line), and hydrograph of estimated ground-water discharge using the PULSE model (solid line). (Note: In each case, the total recharge modeled is 0.73 inch, which is the same as the total recharge estimated from RORA for this period. In case A, recharge is modeled as 0.65 inch on day 69 and 0.08 inch on day 74. In case B, recharge is modeled as a gradual process that is constant from day 68 to day 72.)

Further analysis of problems at the small time scale includes a data set that was used earlier to evaluate RORA. The data set consisted of estimates of recharge that were obtained by the manual application of the recession-curve-displacement method (Daniel, 1990). Yearly estimates from this method were compared with estimates from RORA (Rutledge and Daniel, 1994). With reference to the same data set, the following shows comparability at various time scales:

Time scale (months)	Coefficient of determination
1	0.775
2	.869
3	.899
6	.920
12	.935

These results show a considerable decline in the comparison between results of RORA and the results of the manual data set when the time scale is less than a quarter year. The author recommends that the quarter year (or the season) should be the minimum time scale for reporting or using results of this program.

It is noteworthy that RORA is not a method of "hydrograph separation" in the sense that this term is frequently used. The program does not calculate a hydrograph of ground-water discharge under the streamflow hydrograph. The hydrographs of ground-water discharge in figure 17 were obtained from the PULSE program. The RORA program is intended to give estimates of time-integrated recharge.

Results of the program are written in four files: (1) outrora.sum, (2) outrora.qrt, (3) outrora.mon, and (4) outrora.pek. File 1 gives the average recharge for the period analyzed. File 2 includes a tabulation of recharge for each quarter year and each calendar year in the period analyzed. File 3 gives a tabulation for each month in the period analyzed. Although results at this time scale should not ordinarily be used, they are helpful for obtaining estimates for other fractions of the year that are not included in file 2. For example, the summer recharge might be obtained by summation of results from June, July, and August. Results in file 4 include a tabulation of calculations for each peak; these are provided only for screening purposes and should not be reported or used in other analyses.

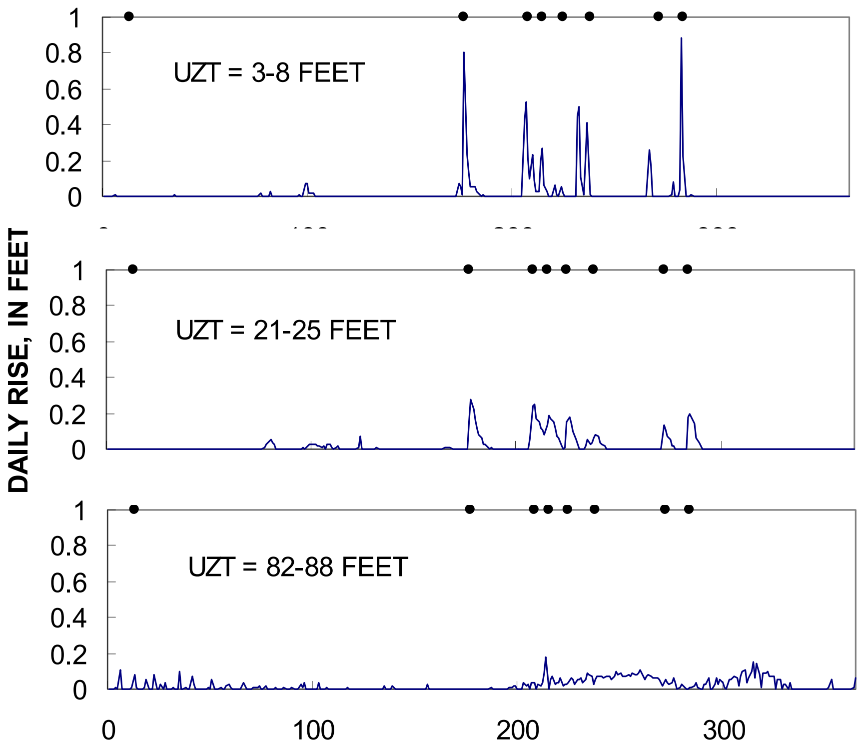
RELATIONS AMONG METHODS

The RORA program for estimating recharge may be used in conjunction with other methods. These can include methods for describing the recharge process, evaluating the timing of recharge, providing independent estimates of recharge or discharge, and making inferences about recharge based on statistical analysis of streamflow records. The purpose of this section is to describe relations between results of the RORA program and the results of other methods.

Use of Ground-Water-Level Data

Ground-water-level data might be used in conjunction with the RORA program in several ways. Changes in ground-water levels can be used to (1) evaluate basic assumptions of the method, (2) evaluate the timing of recharge through the annual cycle, and (3) provide independent estimates of recharge. Procedures based on water-level changes generally require that water level in the well represents the elevation of the water table. Although a well may be open to a zone of the aquifer near the water table, the response of water levels in the well to changes in the water table may be delayed for various reasons, such as less than ideal hydraulic connection between the aquifer and the well. Another consideration is that data collected at a well site represents a very small area, but estimates from hydrograph separation (RORA and other methods) will tend to give the average recharge for a larger area (the basin). Most of the following discussion relates to the RORA program but may apply to hydrograph separation in more general terms. For example, there is discussion of the relation between ground-water levels and ground-water discharge, a relation that may be complex at the small time scale.

The RORA program is based on the assumption that recharge occurs as discrete events that are roughly concurrent with peaks in streamflow (Rutledge, 1998, p. 3). This assumption may be reasonably met in hydrologic settings where the thickness of the unsaturated zone is fairly thin, but may not apply elsewhere. O'Reilly (1998, fig. 12) gives water-level data that are relevant to this topic. The data are processed here to show daily rises of water level in three observation wells (fig. 18). Graphs for the two wells representing the thin unsaturated zones exhibit discrete recharge events, but the graph for the well representing the thick unsaturated zone exhibits a very slow, temporally dispersed response. The data set includes a streamflow hydrograph for Reedy Creek near Vineland, Florida (fig. 18), which shows that some of the largest rises of water level are roughly concurrent with the largest peaks in flow. Although the thickness of the unsaturated zone in some localities in this basin may be as great as 100 ft, the average for the basin is about 10 ft (A.M. O'Reilly, U.S. Geological Survey, written commun., 1999). The data in the top two frames may be more representative of average basin processes than the data in the third frame. Although this is a very useful data set, a comprehensive analysis of unsaturated-zone lagtime should include many sites in many hydrogeologic settings.



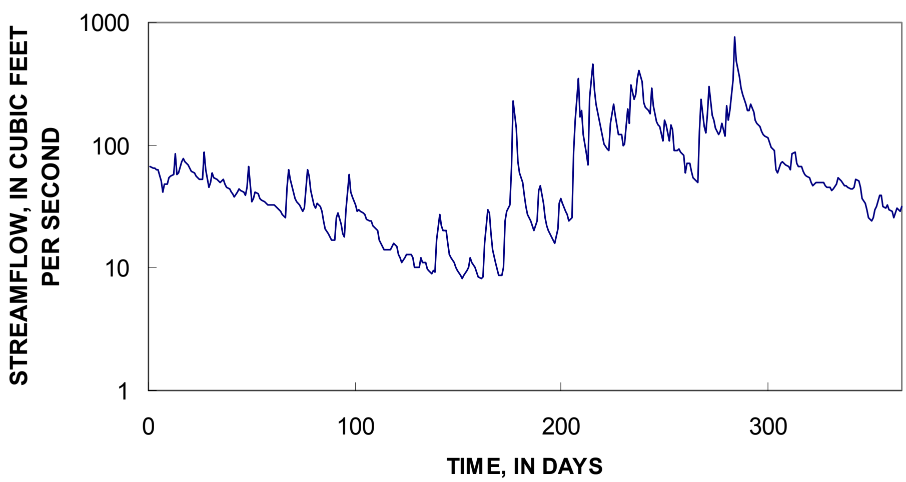


Figure 18. Daily water-level rise in three wells and streamflow in Reedy Creek near Vineland, Florida. (Modified from O'Reilly, 1998. UZT represents the unsaturated-zone thickness, for each of these wells. The eight markers in each frame represent the time of the eight largest recharge events detected by RORA from the analysis of the Reedy Creek streamflow record. The three wells are located at different locations within the drainage area of the streamflow station or near the basin boundary. Time period shown is the 1995 calendar year. There is a data gap for the well represented in the top frame: the last 40 days of the year.)

The timing of RORA-estimated recharge through the annual cycle might be evaluated in conjunction with water-level records. The streamflow record from this station (fig. 18) was analyzed by use of the program, with a designated recession index of 70 days per log cycle. The program detected 37 recharge events in this 1-year record. The eight largest recharge events, which are marked on figure 18, account for more than 90 percent of the total recharge. These eight events are roughly concurrent with some of the greatest water-level rises for the two wells representing thin unsaturated zone. The recharge estimated in June through October (roughly days 150-300 on the graph) account for about 80 percent of the total for the year. If a storm causes significant recharge, the streamflow recession curve after the event will show a net displacement relative to the pre-event recession. Such displacement is evident in June through October but not in other parts of this hydrograph. The water-level data shown here (fig. 18) indicate that recharge may be restricted to small time increments in hydrologic settings where the unsaturated zone is thin. The rate of recharge during these periods may be considerable. For example, if the annual recharge in this basin is 10 inches and occurs in one-tenth of the year, then the rate of recharge is several hundred cubic feet per second during periods of recharge.

Although data from Reedy Creek near Vineland, Florida are analyzed, characteristics of this basin may violate basic assumptions about the ground-water system that are required for the RORA program to be valid. According to A.M. O'Reilly (written commun., 1999), much of the drainage in the basin is internal (not to the stream), and ground-water flow is dominated by downward leakage to a deeper flow system. Although these qualifications are noted, observations about temporal distribution of recharge to the shallow aquifer may be reasonable.

In addition to defining the time of recharge, water-level rises can be used to estimate the amount of recharge. The method is based on the following equation:

$$R = S_y \times \Delta h \, , \qquad (11)$$

where R is recharge, S_y is specific yield, and Δh is rise of the water level that results from recharge. This method has been used by several hydrologists (Gerhart, 1986; Hall and Risser, 1993; Meinzer and Stearns, 1929; Rasmussen and Andreasen, 1959). To isolate the rise caused by recharge, one must allow for any recession of ground-water level before the recharge event. Sophocleous (1991) described various weaknesses in this method that result from changes in ground-water levels not associated with recharge and uncertainty in specific yield. As noted earlier, if this method is used in conjunction with hydrograph separation, allowances must be made for the extreme difference in the scale of estimates. Results from RORA will represent average recharge over a large area. The use of ground-water-level changes to estimate recharge in conjunction with RORA may not be extremely meaningful unless data are available from numerous wells in the basin.

The discussion up to this point pertains to the rise of ground-water level that is caused by a specific recharge event. Another topic that has been addressed in hydrologic studies is the relation between ground-water levels (not the change in levels, but the level itself) and ground-water discharge (Johnston, 1976; Olmsted and Hely, 1962; Rasmussen and Andreasen, 1959; Walton, 1967). The relation may be most reliable when the time scale of interest is a month or larger. A linear relation between total discharge from springs and ground-water levels was indicated in one study (Puente, 1976).

Relations between ground-water level and ground-water discharge from shallow flow systems may be complex at the small time scale. As an example, a finite-difference model (McDonald and Harbaugh, 1988) is used to simulate flow in a simple cross-section consisting of 20 cells, each measuring 100 ft in width (along the axis perpendicular to the stream). In the other dimension (parallel to the stream), the model measures 13,940 ft. The area of the model (the "basin") is thus 1.00 mi^2. The stream is simulated by means of drains along the 13,940-ft dimension. At the opposite side is a no-flow boundary that represents the hydrologic divide. Transmissivity is 5,000 ft^2/d and the storage coefficient is 0.1. The initial ground-water level is designated to be 0.6 ft above the drain. Three recharge events were simulated, each lasting 1day and applying 1 inch uniformly over the entire area. Shown here is simulated discharge to the drain and ground-water level at a point that is midway between the stream and the hydrologic divide (fig. 19). The level shown here is referenced to the elevation of the drain. The relation between ground-water level and ground-water discharge is shown in figure 20.

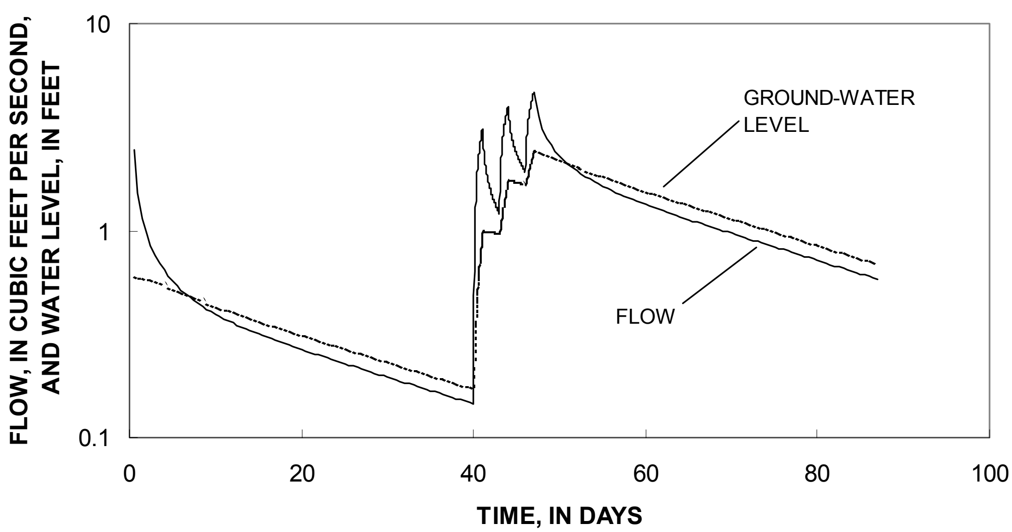


Figure 19. Simulated flow and ground-water level, for a finite-difference model described above.

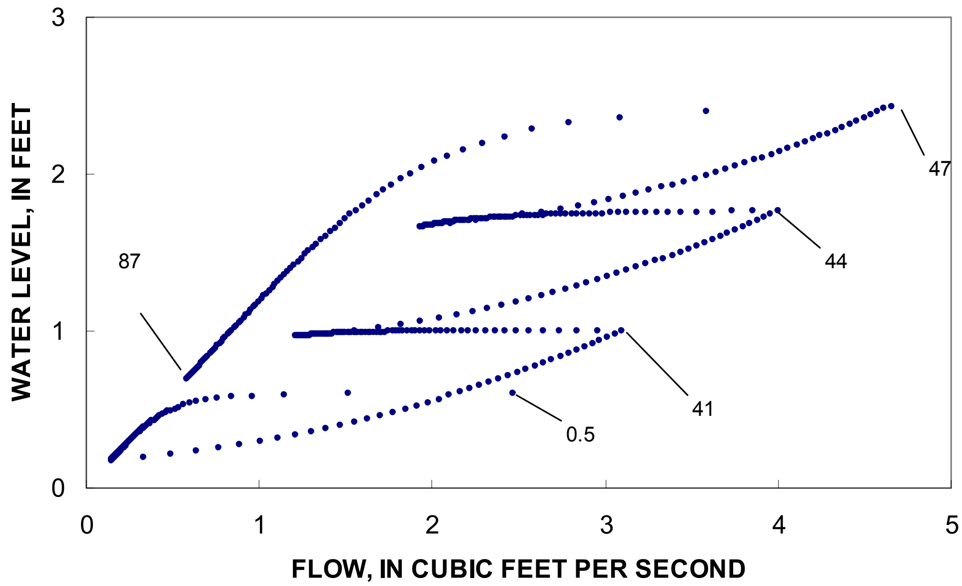


Figure 20. Graph showing relation between simulated ground-water discharge and water level for a finite-difference simulation described on previous page. (Numbers on graph indicate time, in days.)

Two observations can be made about the relation between ground-water level and ground-water discharge. First, the relation between the two variables may not be unique. Second, the variation in ground-water discharge may exceed the variation in ground-water level. These observations may not be apparent if the only data pairs considered were from periods of linear or nearly-linear recession on the semilog hydrograph of flow. If data were selected from periods such as days 10-40 and days 60-87 on figure 19, it would appear that the relation between ground-water level and ground-water discharge is generally unique. Another observation is that the highest ground-water level will occur at the end of the period of recharge.

This simulation demonstrates the complexity of relations between ground-water level and ground-water discharge at the small time scale. For more information, the reader is referred to Kraijenhoff van de Leur (1958). Analytical solutions that can be used to evaluate these relations have been developed by Barlow and Moench (1998).

Base-Flow-Record Estimation

Base-flow-record estimation is a relatively arbitrary method of estimating a continuous record of ground-water discharge, or base flow, under the streamflow hydrograph. The method is applied over a long period of record to obtain an estimate of the mean ground-water discharge. Several techniques, some manual and some computerized, are described by Rutledge (1998, pages 33-34). The results of the application of one of these methods, the PART program (Rutledge, 1998) correlate very closely with results of RORA at the time scale of the decade, based on analysis of streamflow stations in the AP-RASA project (fig. 21). Ground-water recharge and discharge may be nearly equal at that time scale if other gains and losses are small relative to recharge. The illustration shows that long-term estimates from RORA exceed estimates from PART by roughly 10 percent for this data set.

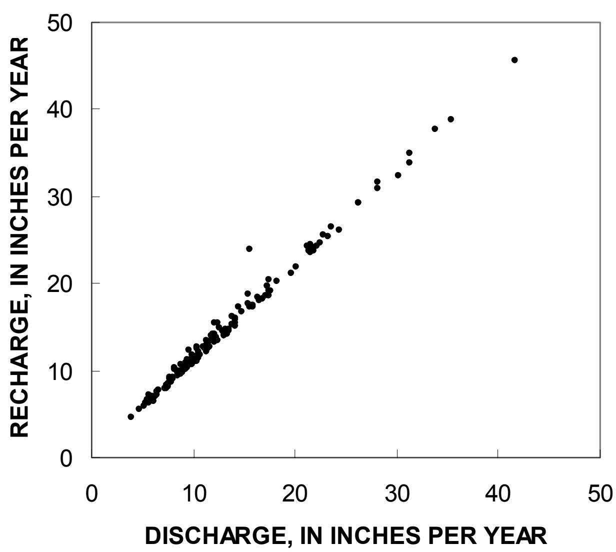


Figure 21. Relation between recharge estimates from the RORA program and discharge estimates from the PART program, on the basis of a large time scale. (Each point represents one of 157 streamflow stations in the AP-RASA project and gives the mean for the time period 1981-90.).

Results from RORA and PART may not correlate as well at the small time scale, as evident from scatter in quarter-year estimates from one station in the AP-RASA project (fig. 22). Correlation between results at this time scale is poor because the processes of ground-water recharge and ground-water discharge are not synchronous. The estimates from RORA for a given quarter year will represent the recharge during that quarter year. Estimates from PART for a given quarter year, which are obtained by general estimation of a base-flow hydrograph under the streamflow hydrograph, may depend on the recharge during that quarter year, but may be affected by recharge before that time interval. Results from the application of the two programs are shown sequentially for this station (fig. 23). It is apparent that recharge exceeds discharge in the first half of the water years shown, and discharge exceeds recharge in the second half of the water years shown.

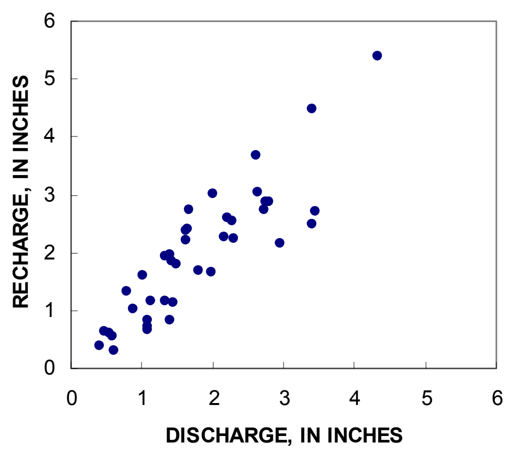


Figure 22. Relation between recharge estimates from the RORA program and discharge estimates from the PART program, on the basis of the quarter year. (Holiday Creek near Andersonville, Virginia. The time period is 1981-90.)

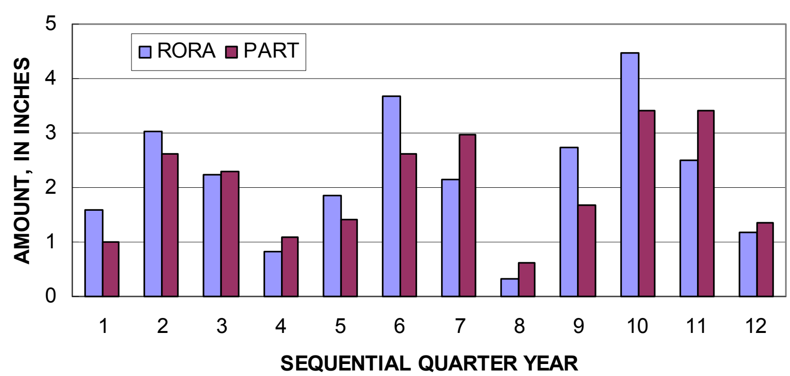


Figure 23. Relation between recharge estimates from the RORA program and discharge estimates from the PART program, on the basis of the quarter year. (Station is Holiday Creek near Andersonville, Virginia. The first quarter year shown is October-December 1981, and the last is July-September 1984.

The simulation illustrated in figure 2 of this report shows how recharge and discharge are not synchronous. The tabulation below shows recharge and discharge on the basis of the quarter year:

Quarter Year	Ground-water recharge (inches)	Ground-water discharge (inches)
1	3.5	1.81
2	3.1	3.73
3	1.5	1.50
4	1.9	2.36
Total	10.0	9.4

Some of the findings here may relate to the previous section on ground-water levels. If the annual cycles of (1) recharge, (2) ground-water levels, and (3) ground-water discharge are considered, one can reasonably expect that changes in 2 and 3 will generally lag behind changes in 1.

Use of Low-Flow Variables

Low-flow variables may be used in conjunction with hydrograph separation to add to the understanding of the ground-water system. These variables are usually obtained from statistical analysis of the streamflow record and tend to represent the sustainability of ground-water discharge under conditions of prolonged drought. An example is the 7Q2, which is the annual minimum average 7-consecutive-day low-flow discharge with a 2-year recurrence interval. Although a low-flow variable will represent ground-water discharge during periods of negligible recharge, it may be used as a relative indicator of the amount of water that gets into the system during periods of time that precede the period of negligible recharge. If all other variables are the same, then a basin that receives more recharge than some other basin will exhibit a larger low-flow variable than the other basin. This can be demonstrated by considering the hydrograph in figure 2, which was generated using PULSE, designating annual recharge equal to 10 in. In an experiment (not illustrated) recharge was designated to be 20 in, with the same relative distribution of recharge over time. Considering the flow on day 239 to be the low-flow variable of interest, the following shows how recharge can effect such variables:

Annual recharge (inches)	Low flow (cubic feet per second)
10	1.76
20	3.51

Another experiment was done in which recharge was maintained at 10 in (identical to the recharge used to generate fig. 2) but the recession index was changed. There is a clear effect on the shape of the hydrograph (fig. 24), and the also the low-flow variable:

Recession index (days)	Low flow (cubic feet per second)
50	0.38
100	1.76

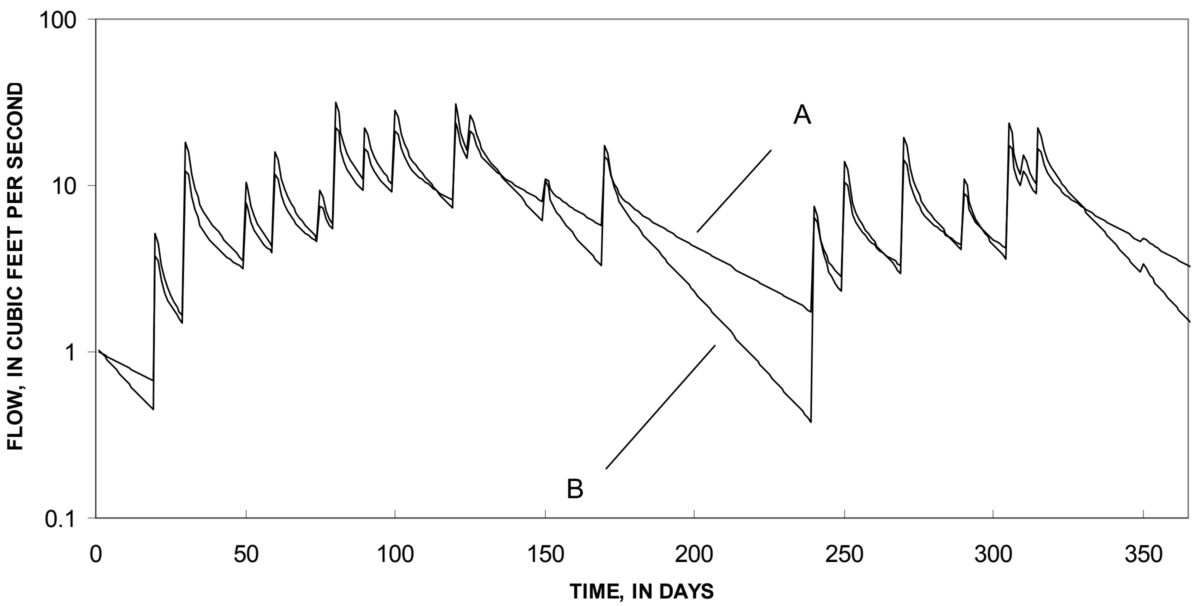


Figure 24. Hydrographs of ground-water discharge generated with the flow model PULSE for the same amount of recharge (table 1) but using a recession index (K) equal to 100 days per log cycle in one simulation (A) and 50 days per log cycle in another simulation (B).

The RORA program was used to analyze the hydrograph in fig. 2 and the hydrographs described above that include changes in model-designated recharge and recession index. For consistency with other testing described in this report, the recession index was obtained using the RECESS program, selecting the segment from 21 to 30 days after the peak on day 170. All estimates of recharge calculated by RORA agree with model-designated recharge within 1 percent.

The experiments described above show that a low-flow variable can depend on recharge but also may depend on other variables such as the recession index. This finding is consistent with analysis of streamflow records in the AP-RASA project. In that study, the 7Q2 was shown to correlate with recharge, and the 7Q2 was also shown to correlate with the recession index. Both relations, however, exhibit considerable scatter. Another variable, which is a function of both recharge and recession index, was introduced. This variable also correlated well with the 7Q2, but the scatter was much less (Rutledge and Mesko, 1996, figs. 15-16).

Another statistical-analysis tool that is used to interpret streamflow data is the flow-duration curve (Searcy, 1959), a cumulative frequency curve that shows the percentage of time that specified flow rates are exceeded. Similar to low-flow variables, these curves can be used to make inferences about ground-water systems. Curve shape may be affected by the recession index.

SUMMARY

The RORA program estimates ground-water recharge in a basin from analysis of a streamflow record. The program can be appropriate for use if the flow system is characterized by diffuse areal recharge to the water table and ground-water discharge to a stream. The application of RORA may be limited, however, by considerations of drainage area, basin relief, and thickness of the unsaturated zone. The shape of the streamflow hydrograph may provide a tool for assessing method applicability.

The use of the program requires an estimate of the recession index, which is the time required for ground-water discharge to recede by one log cycle after recession becomes linear or near-linear on the semilog hydrograph. Although considerable uncertainty is inherent in the recession index, the results of the RORA program may not be sensitive to this variable.

Testing shows that the RORA program can yield consistent estimates under conditions that include leakage to or from deeper aquifers and ground-water evapotranspiration. These tests indicate that RORA can be used to estimate the net recharge, which is recharge to the water table minus leakage to a deeper aquifer, or recharge minus ground-water evapotranspiration.

Before the program begins making calculations, it designates days that fit a requirement of antecedent recession, and these days are used in calculations. The program determines a default value for this requirement, but the program user has the option of increasing it. An increase in this variable may reduce errors that are caused by direct-surface runoff, but other errors can result from the reduction in the number of peaks detected.

Recharge estimates obtained from manual calculations are compared with RORA results at various time scales. On the basis of this comparison, it is advised that results of the program should be reported or used only at a time scale greater than or equal to the quarter year.

To gain a more complete understanding of flow systems, results from the RORA program might be used in conjunction with other methods such as analysis of ground-water levels, estimates of ground-water discharge from other forms of hydrograph separation, and low-flow variables. Relations among variables may be complex for a variety of reasons; for example, there may not be a unique relation between ground-water level and ground-water discharge, ground-water recharge and discharge are not synchronous, and low-flow variables can be related to other factors such as the recession index.

REFERENCES

Barlow, P.M., and Moench, A.F., 1998, Analytical solutions and computer programs for hydraulic interaction of stream-aquifer systems: U.S. Geological Survey Open-File Report 98-415A, 85 p.

Bevans, H.E., 1986, Estimating stream-aquifer interactions in coal areas of eastern Kansas by using streamflow records, *in* Subitzky, Seymour, ed., Selected papers in the Hydrologic Sciences: U.S. Geological Survey Water-Supply Paper 2290, p. 51-64.

Daniel, C.C., III, 1990, Comparison of selected hydrograph separation techniques for estimating ground-water recharge from streamflow records [abs.]: Geological Society of America Abstracts with Programs, v. 22, no. 4, p. 9.

Daniel, J.F., 1976, Estimating groundwater evapotranspiration from streamflow records: Water Resources Research, v.12, no. 3, p. 360-364.

Gerhart, J.M., 1986, Ground-water recharge and its effects on nitrate concentration beneath a manured field site in Pennsylvania: Ground Water, v. 24, no. 4, p. 483-489.

Hall, D.W., and Risser, D.W., 1993, Effects of agricultural nutrient management on nitrogen fate and transport in Lancaster, Pennsylvania: Water Resources Bulletin, v. 29, no. 1, p. 55-76.

Johnston, R.H., 1976, Relation of ground water to surface water in four small basins of the Delaware Coastal Plain: Delaware Geological Survey Report of Investigations 24, 56 p.

Kraijenhoff van de Leur, D.A., 1958, A study of non-steady groundwater flow with special reference to a reservoir-coefficient: De Ingenieur, v. 70, no. 19, p. 87-94.

Linsley, R.K., Jr., Kohler, M.A., and Paulhus, J.L.H., 1982, Hydrology for engineers (3d ed.): New York, McGraw-Hill, 508 p.

McDonald, M.G., and Harbaugh, A.W., 1988, A modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Techniques of Water-Resources Investigations, book 6, chap. A1, 586 p.

Meinzer, O.E., and Stearns, N.D., 1929, A study of ground water in the Pomperaug Basin, Connecticut, with special reference to intake and discharge: U.S. Geological Survey Water-Supply Paper 597-B, p. 73-146.

Olmsted, F.H., and Hely, A.G., 1962, Relation between ground water and suface water in Brandywine Creek basin Pennsylvania: U.S. Geological Survey Professional Paper 417-A, 21 p.

O'Reilly, A.M., 1998, Hydrogeology and simulation of the effects of reclaimed-water application in west Orange and southeast Lake Counties, Florida: U.S. Geological Survey Water-Resources Investigations Report 97-4199, 91 p.

Puente, Celso, 1976, Statistical analyses of water-level, springflow, and streamflow data for the Edwards aquifer in south-central Texas: U.S. Geological Survey Open-File Report 76-393, 58 p.

Rasmussen, W.C., and Andreasen, G.E., 1959, Hydrologic budget of the Beaverdam Creek basin Maryland: U.S. Geological Survey Water-Supply Paper 1472, 106 p.

Rorabaugh, M.I., 1964, Estimating changes in bank storage and ground-water contribution to streamflow: International Association of Scientific Hydrology, Publication 63, p. 432-441.

Rorabaugh, M.I., and Simons, W.D., 1966, Exploration of methods relating ground-water to surface water, Columbia river basin -- second phase: U.S. Geological Survey Open-File Report, 62 p.

Rutledge, A.T., 1997, Model-estimated ground-water recharge and hydrograph of ground-water discharge to a stream: U.S. Geological Survey Water-Resources Investigations Report 97-4253, 29 p.

Rutledge, A.T., 1998, Computer programs for describing the recession of ground-water discharge and for estimating mean ground-water recharge and discharge from streamflow data – update: U.S. Geological Survey Water-Resources Investigations Report 98-4148, 43 p.

Rutledge, A.T., and Daniel, C.C., 1994, Testing an automated method to estimate ground-water recharge from streamflow records: Ground Water, v. 32, no. 2, p. 180-189.

Rutledge, A.T., and Mesko, T.O., 1996, Estimated hydrologic characteristics of shallow aquifer systems in the Valley and Ridge, the Blue Ridge, and the Piedmont Physiographic Provinces based on analysis of streamflow recession and base flow: U.S. Geological Survey Professional Paper 1422-B, 58 p.

Searcy, J.K., 1959, Flow-duration curves, *in* Low-flow techniques, pt. 2 of Manual of hydrology: U.S. Geological Survey Water-Supply Paper 1542-A, 33 p.

Sophocleous, M.A., 1991, Combining the soilwater balance and water-level fluctuation methods to estimate natural ground-water recharge --- practical aspects: Journal of Hydrology, v. 124, p. 229-241.

Sun, R.J., and Weeks, J.B., 1991, Bibliography of regional aquifer-system analysis program of the U.S. Geological Survey, 1978-91: U.S. Geological Survey Water-Resources Investigations Report 91-4122, 92 p.

Swain, L.A., Hollyday, E.F., Daniel, C.C., III, and Zapecza, O.S., 1991, Plan of study for the regional aquifer-system analysis of the Appalachian Valley and Ridge, Piedmont, and Blue Ridge physiographic provinces of the eastern and southeastern United States, with a description of study-area geology and hydrology: U.S. Geological Survey Water-Resources Investigations Report 91-4066, 44 p.

Walton, W.C., 1967, Selected analytical methods for well and aquifer evaluation: Illinois State Water Survey Bulletin 49, 81 p.