Computer Programs for Describing the Recession of Ground-Water Discharge and for Estimating Mean Ground-Water Recharge and Discharge from Streamflow Records

By A.T. Rutledge

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CONVERSION FACTORS

Multiply	By	To obtain
inch (in.)	2.54	centimeter
foot (ft)	0.3048	meter
foot squared per day (ft^2/d)	0.09290	meter squared per day
inch per year (in/yr)	2.54	centimeter per year
cubic foot (ft^3)	0.02832	cubic meter
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
cubic foot per second per square mile $(ft^3/s)/mi^2$	0.01093	cubic meter per second per square kilometer

COMPUTER PROGRAMS FOR DESCRIBING THE RECESSION OF GROUND-WATER DISCHARGE AND FOR ESTIMATING MEAN GROUND-WATER RECHARGE AND DISCHARGE FROM STREAMFLOW RECORDS

By A.T. Rutledge

Abstract

The computer programs included in this report develop a mathematical expression for recession of ground-water discharge and estimate mean ground-water recharge and discharge. The programs are intended for analysis of the daily streamflow record of a basin where one can reasonably assume that all, or nearly all, ground water discharges to the stream except for that which is lost to riparian evapotranspiration, and where regulation and diversion of flow can be considered to be negligible. The program RECESS determines the master recession curve of streamflow recession during times when all flow can be considered to be ground-water discharge and when the profile of the ground-water-head distribution is nearly stable. The method uses a repetitive interactive procedure for selecting several periods of continuous recession, and it allows for nonlinearity in the relation between time and the logarithm of flow. The program RORA uses the recession-curve displacement method to estimate the recharge for each peak in the streamflow record. The method is based on the change in the total potential ground-water discharge that is caused by an event. Program RORA is applied to a long period of record to obtain an estimate of the mean rate of ground-water recharge. The program PART uses streamflow partitioning to estimate a daily record of base flow under the streamflow record. The method designates base flow to be equal to streamflow on days that fit a requirement of antecedent recession, linearly interpolates base flow for other days, and is applied to a long period of record to obtain an estimate of the mean rate of ground-water discharge. The results of programs RORA and PART correlate well with each other and compare reasonably with results of the corresponding manual method.

INTRODUCTION

This report documents computer programs that read data files of daily mean streamflow and then perform the following procedures:

1. Develop a mathematical expression that describes streamflow recession during times when all flow can be considered to be ground-water discharge,
2. Estimate mean ground-water recharge by use of the recession-curve displacement method, and
3. Estimate mean ground-water discharge by use of a method of base-flow record estimation.

Past work, theory, and mathematical basis for each of the procedures are described, the steps required to execute the programs are itemized, and the output files are explained. Where appropriate, the report includes comparisons between the results of the programs and results of corresponding manual methods.

The programs included at the back of this report are written in Fortran-77 and do not depend on separate software (such as statistical or graphical software). The programs were designed for analysis of records of daily mean streamflow because this is the common mode by which streamflow data are stored by the U.S. Geological Survey (USGS). The USGS collects and stores records of daily streamflow for several thousand gaging stations in the United States. The programs are intended primarily for use by the worker who has access to a USGS data base, but some guidelines are included to allow for the transfer and analysis of data from other sources.

The computer programs were developed as part the USGS Regional Aquifer System Analysis (RASA) of the area that includes the Appalachian Valley and Ridge, Piedmont, and Blue Ridge physiographic provinces (Appalachian-Piedmont RASA, or APRASA) (Swain and others, 1991). Although the programs were developed for application in the APRASA project, they are documented here because of the potential application in other settings.

Applicability of Methods

The methods described in this report are intended for the analysis of the ground-water-flow system of a basin for which a streamflow-gaging station at the downstream end can be considered the only point of outflow. For most applications, it should be reasonable to assume that all or nearly all ground water in the basin discharges to the stream, except for that which is lost by evapotranspiration. The area of contribution in the ground-water system is equal to the surface-drainage area for the purpose of expressing flow in units of specific discharge (for example, inches per year). Regulation and diversion of flow should be negligible.

It is preferable, but not required, that the record of daily mean streamflow is at least several years in duration. Results are most useful if the programs are executed to give long-term (at least yearly) results. Interbasin comparisons should be made only when the programs are executed for a uniform time period because of climatic variations. The programs work on the basis of the calendar year. In the application of the methods for estimating recharge or discharge, the record should be complete for each year in the period of analysis (365 or 366 daily values per calendar year).

The procedure for defining the recession of ground-water discharge selects several individual periods of continuous streamflow recession (periods during which each pair of subsequent daily values must meet the condition that the first value exceeds or is equal to the second). Periods of reduced precipitation must be long enough that the profile of the ground-water head distribution is nearly stable and ground-water discharge will plot with characteristic linearity or near-linearity on the graph of the logarithm of flow as a function of time. This condition may not be met for ground-water-flow systems of very low diffusivity (transmissivity divided by storage coefficient).

The procedure for defining streamflow recession allows for the possibility of nonlinearity in the relation between the logarithm of ground-water discharge and time when the profile of the ground-water head distribution is nearly stable. Nonlinearity can result from variation in saturated thickness, geologic heterogeneities, and attrition of ground water to leakage or evapotranspiration.

The methods for estimation of recharge or discharge are intended for the analysis of flow systems that are driven by areally diffuse recharge events that can be considered to be roughly concurrent with peaks in streamflow. The stream is the sink (discharge boundary) of the ground-water-flow system. Results of these methods may not be reliable for flow systems dominated by leakage to or from regional-flow systems, snowmelt runoff, recharge from losing streams, or ground-water withdrawals. The methods for estimating recharge or discharge should be used only if the drainage area is larger than 1 square mile, so that the time base of surface runoff will exceed the time increment of the data (1 day). The upper limit of drainage area may depend on the degree of nonuniformity of weather systems. Linsley and others (1982) suggest that the unit-hydrograph concept should not be applied for basins that are larger than 2,000 square miles and that the upper limit may be much smaller where convective rainfall predominates. The upper limit for the unit-hydrograph concept may also apply to the methods described here for estimating recharge and discharge. For the application of these methods in the APRASA project, the author used 500 square miles as an upper limit for selection of streamflow-gaging stations for data analysis.

In addition to the above, the user should assess the validity of the mathematics described in following sections to the study area. For example, the procedure for defining streamflow recession uses the assumption that the recession index is linearly related to the logarithm of flow, and the methods for estimating ground-water recharge and discharge use an empirical equation for determining the time base of surface runoff, to estimate the number of days after a peak in streamflow when most flow can be considered ground-water discharge. Output of the programs allow for some degree of adjustment for variation between the real problem and the default mathematics of the programs.

Overview of Programs and Files

This report describes three programs--RECESS, RORA, and PART.

RECESS This program determines the master recession curve (MRC) of streamflow recession during times when all flow can be considered to be ground-water discharge and when the profile of the ground-water head distribution is nearly stable. The program uses a repetitive interactive procedure for selecting several periods of continuous recession, determines a best-fit equation for the rate of recession as a function of the logarithm of flow, then uses the coefficients of this equation to derive the MRC, which is an equation of time as a function of the logarithm of flow. The program thus allows for the possibility of nonlinearity in the relation between time and the logarithm of flow.

RORA This program uses the recession-curve-displacement method to estimate the recharge for each peak in the streamflow record. The method, also called the Rorabaugh Method (Rorabaugh, 1964; Daniel, 1976), is based on the measurement of the change in the total potential ground-water discharge as estimated at critical time after the peak by extrapolation from the pre-peak and the post-peak recession periods. The method is applied to a long period of record and gives an estimate of the mean rate of ground-water recharge.

PART This program uses streamflow partitioning to estimate a daily record of base flow under the streamflow record. The program scans the record for days that fit a requirement of antecedent recession, designates base flow to be equal to streamflow on these days, then linearly interpolates the daily record of base flow for days that do not fit the requirement of antecedent recession. The program is applied to a long period of record to give an estimate of the mean rate of ground-water discharge.

Other support programs included are TRANS, which translates data into a format that can be read by the programs above; STREAM, which allows the user to screen the daily-values data file for periods of continuous record; and CURV, which reads an output file from program RECESS, then creates a simple file that can be used as input to separate graphical software from which an MRC can be drawn. Other files that are included with this documentation include GAGING, which is a data file that consists of properties of the gaging stations of interest, and OUTREC, OUTROR, and OUTPART, which are headings for output files of programs RECESS, RORA, and PART, respectively. Other output files are automatically created when the programs are executed. File EXAMPLE shows example input and output files that have been appended together.

Compiling, Loading, and Executing Programs

All six programs, which are provided in the form of Fortran source code, should be compiled and loaded at one time before execution. The keyboard should be kept in lower case when working with these programs. Although file names in this publication are in upper case letters, the actual file names are in lower case if the computer operating system is case sensitive.

One way to compile and load on a Data General AViiON Workstation, is to enter the command

```
ghf77 program.f -o program.b
```

This creates an executable file "program.b" from the original fortran file "program.f."

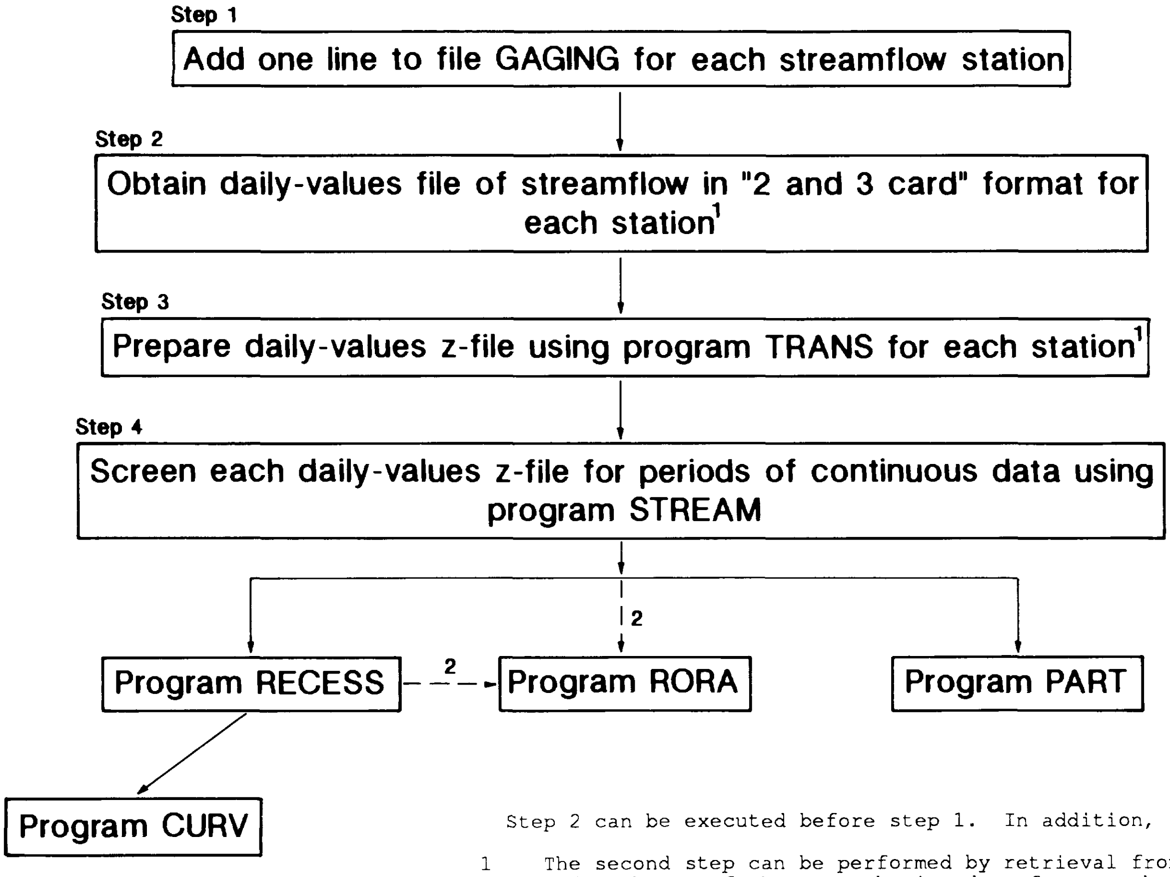
One way to compile and load on a Prime computer is to enter the following commands (note that the first line simply changes the name of the Fortran code file to a name that is compatible with the Prime compiler):

```
cn program.f program.f77
 f77 program
seg -load
load program
 li
 sa
qu
```

The programs should be executed later, according to the steps recommended in following sections. One way to execute the program is to enter ./program.b on the Data General AViiON Workstation, or seg program on the Prime.

Preparation of Data Files

Before the programs RECESS, RORA, or PART can be executed, steps must be taken to prepare required data files. After these procedures (illustrated as steps 1-4 in fig. 1) are completed, any one of RECESS, RORA, or PART can be executed. The user might execute RECESS before RORA to obtain the median recession index, which program RORA can read from a file that is written by program RECESS.



Step 2 can be executed before step 1. In addition,

1 The second step can be performed by retrieval from a USGS data base. If the user obtains data from another source, then steps 2 and 3 could be superseded by customized methods. These methods should result in daily values z-files as described in figure 2.

2 It is recommended (but not required) that RECESS be executed before RORA so that RORA can obtain the median recession index from a file that is filled by RECESS (file OUTREC). Otherwise, the user will be required to enter the median recession index interactively during execution of RORA.

Figure 1. Recommended order of procedures for preparing data files and executing the programs documented in this report.

Catalogue File GAGING

The user should add a one-line entry to file GAGING for each streamflow-gaging station of interest. Each line of file GAGING gives the following information for a station:

(1) latitude in degrees, minutes, and seconds (columns 1-6),
(2) longitude in degrees, minutes, and seconds (columns 7-13),
(3) an optional two-digit sequential number (usually left blank, columns 14-15),
(4) the USGS eight-digit gaging-station number (columns 16-23),
(5) the drainage area, in square miles (columns 24-31),
(6) the name of the daily-values z-file (columns 34-49), and
(7) an abbreviated station name (columns 53-80).

The user can observe this format list for all new entries: A6, A7, A2, A8, 1F8.2, 2X, A16, 3X, A29. Alternatively, entries in the version of GAGING that is included with this report can be used as guides to the correct format. The only items that are required are the drainage area and the name of the daily-values z-file (the latter should be a short, unique name for the stream preceded by the letter "z"). Other items could be left blank, but it is recommended that they are filled in for the purpose of clarity. The line in GAGING that corresponds to a given station can be automatically written to the daily-values z-file when program TRANS is executed. Although the entry of data to GAGING is illustrated as step 1 in figure 1, data could be entered after step 2. It is nonetheless recommended that step 3 be executed after step 1 so that program TRANS will read data from GAGING.

Creating Daily-Values Files

Programs RECESS, RORA, PART, and STREAM read data from a daily-values z-file (fig. 2). If the user has access to a USGS data base, the z-files are created in two steps:
(1) obtaining a daily-values file from the data base in the "2 and 3-card" format, and
(2) translating the data from this file to a z-file using program TRANS. Each of these steps, illustrated as steps 2 and 3 in figure 1 and described below, can be executed for several streamflow stations at one time.

A data file of daily mean streamflow can be obtained from a USGS Prime data base by use of ADAPS. The menu options to "retrieve/write ADAPS data" followed by "retrieve/write daily-values data" are selected. Calendar years are selected ("years beginning January"). The time period of the retrieval should begin after 1910 and must not exceed 90 years in duration because of dimension limitations of the programs documented here. For the "station" option, the 8-digit USGS station number is entered, and the variable selected is "discharge in cfs." The user must enter a file name for the resulting data file that will be in "2 and 3-card" format. The file name, which should be 14 characters or less, must be identical to the file name listed in file GAGING, without the "z" at the beginning (the z-file will be created with program TRANS). The user should enter the option for "DV card output," and the statistic code should be 3 (which represents the mean value). When the prompt is "final data only?," the user should push the "enter" key.

```
 LAT--LONG......STA.#...DR.AREA....FILENAME..............STA.NAME.......
373957 795442  02018000  329.00  zva.q.craig         Craig Cr at Parr

 THIS FILE NAME:zva.q.craig
 THE FIRST "2 CARD" IN THE ORIGINAL ADAPS FILE:
2 02018000                   0006000003              ENT

 -999=before period of record,  -99=missing data,  -9999=nonexistent date.     Date of ADAPS retrieval=June 16, 1992

 MAXIMUM ON RECORD:
   21000.00
 MINIMUM ON RECORD:
      25.00
```

1925	1	2	3	4	5	6	7	8	9	10	11	12
1	-999.00	-999.00	-999.00	150.00	900.00	75.00	78.00	40.00	42.00	46.00	85.00	82.00
2	-999.00	-999.00	-999.00	150.00	708.00	68.00	68.00	42.00	47.00	51.00	82.00	78.00
3	-999.00	-999.00	-999.00	140.00	557.00	64.00	59.00	43.00	45.00	56.00	83.00	92.00
4	-999.00	-999.00	-999.00	140.00	472.00	62.00	58.00	42.00	43.00	60.00	86.00	88.00
5	-999.00	-999.00	-999.00	132.00	419.00	64.00	59.00	43.00	39.00	59.00	85.00	92.00
6	-999.00	-999.00	-999.00	129.00	344.00	67.00	59.00	46.00	39.00	52.00	85.00	98.00
7	-999.00	-999.00	-999.00	103.00	282.00	75.00	71.00	49.00	40.00	48.00	85.00	118.00
8	-999.00	-999.00	-999.00	99.00	260.00	72.00	57.00	48.00	38.00	47.00	88.00	116.00
9	-999.00	-999.00	-999.00	96.00	234.00	77.00	72.00	46.00	38.00	48.00	94.00	111.00
10	-999.00	-999.00	-999.00	92.00	247.00	78.00	72.00	43.00	38.00	46.00	125.00	107.00
11	-999.00	-999.00	-999.00	107.00	252.00	67.00	59.00	42.00	36.00	46.00	135.00	103.00
12	-999.00	-999.00	-999.00	125.00	472.00	58.00	55.00	45.00	38.00	46.00	164.00	103.00
13	-999.00	-999.00	-999.00	116.00	557.00	57.00	51.00	51.00	60.00	49.00	1290.00	101.00
14	-999.00	-999.00	-999.00	109.00	500.00	57.00	46.00	47.00	78.00	55.00	616.00	96.00
15	-999.00	-999.00	-999.00	101.00	419.00	56.00	51.00	49.00	62.00	82.00	368.00	92.00
16	-999.00	-999.00	-999.00	90.00	368.00	60.00	51.00	42.00	58.00	143.00	264.00	99.00
17	-999.00	-999.00	-999.00	85.00	301.00	67.00	56.00	41.00	50.00	107.00	207.00	99.00
18	-999.00	-999.00	-999.00	101.00	269.00	75.00	62.00	39.00	54.00	82.00	167.00	101.00
19	-999.00	-999.00	-999.00	107.00	239.00	74.00	56.00	43.00	55.00	72.00	146.00	98.00
20	-999.00	-999.00	-999.00	98.00	214.00	68.00	51.00	47.00	57.00	69.00	129.00	92.00
21	-999.00	-999.00	-999.00	90.00	188.00	59.00	77.00	47.00	49.00	64.00	125.00	96.00
22	-999.00	-999.00	-999.00	111.00	171.00	56.00	49.00	46.00	49.00	63.00	111.00	103.00
23	-999.00	-999.00	-999.00	226.00	154.00	55.00	55.00	46.00	49.00	63.00	103.00	111.00
24	-999.00	-999.00	-999.00	305.00	140.00	60.00	49.00	42.00	49.00	67.00	96.00	137.00
25	-999.00	-999.00	-999.00	247.00	129.00	80.00	49.00	39.00	47.00	85.00	92.00	140.00
26	-999.00	-999.00	-999.00	214.00	120.00	80.00	52.00	38.00	48.00	143.00	88.00	149.00
27	-999.00	-999.00	-999.00	247.00	107.00	92.00	47.00	36.00	46.00	191.00	94.00	122.00
28	-999.00	-999.00	-999.00	247.00	101.00	88.00	46.00	39.00	38.00	129.00	96.00	114.00
29	-999.00	-9999.00	-999.00	1180.00	94.00	146.00	43.00	38.00	44.00	103.00	88.00	120.00
30	-999.00	-9999.00	-999.00	1040.00	86.00	109.00	42.00	36.00	44.00	90.00	83.00	114.00
31	-999.00	-9999.00	-999.00	-9999.00	78.00	-9999.00	42.00	[illegible]	-9999.00	85.00	-9999.00	103.00
1926	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
1	99.00	1650.00	586.00	900.00	181.00	90.00	48.00	116.00	64.00	52.00	96.00	319.00
2	99.00	1200.00	586.00	677.00	171.00	85.00	47.00	88.00	62.00	56.00	108.00	310.00
3	98.00	900.00	586.00	586.00	164.00	82.00	47.00	72.00	63.00	82.00	85.00	273.00
4	107.00	803.00	500.00	500.00	157.00	78.00	55.00	62.00	62.00	68.00	79.00	255.00
5	120.00	771.00	472.00	446.00	149.00	80.00	58.00	58.00	58.00	65.00	76.00	238.00
6	135.00	708.00	419.00	394.00	140.00	86.00	116.00	67.00	60.00	59.00	73.00	229.00
7	151.00	616.00	472.00	344.00	135.00	88.00	103.00	103.00	62.00	54.00	73.00	205.00
8	164.00	586.00	1040.00	344.00	132.00	92.00	78.00	67.00	67.00	52.00	72.00	189.00
9	291.00	586.00	803.00	368.00	129.00	72.00	67.00	72.00	63.00	51.00	79.00	201.00
10	177.00	557.00	646.00	419.00	132.00	69.00	59.00	54.00	59.00	50.00	121.00	301.00
11	140.00	472.00	557.00	394.00	132.00	64.00	55.00	49.00	55.00	50.00	213.00	557.00
12	135.00	368.00	528.00	740.00	129.00	62.00	56.00	44.00	50.00	48.00	168.00	472.00
13	107.00	446.00	472.00	1040.00	135.00	62.00	57.00	51.00	48.00	54.00	143.00	646.00
14	107.00	835.00	446.00	1200.00	137.00	60.00	57.00	45.00	48.00	60.00	129.00	835.00
15	103.00	2890.00	394.00	1040.00	132.00	59.00	57.00	47.00	48.00	70.00	186.00	646.00
16	94.00	1380.00	394.00	835.00	160.00	57.00	55.00	54.00	48.00	69.00	5310.00	528.00
17	96.00	900.00	394.00	708.00	139.00	55.00	52.00	63.00	47.00	66.00	1650.00	446.00
18	1120.00	740.00	394.00	586.00	139.00	55.00	48.00	57.00	46.00	63.00	970.00	394.00
19	4970.00	708.00	446.00	500.00	199.00	55.00	46.00	50.00	46.00	60.00	835.00	310.00
20	1950.00	708.00	528.00	419.00	177.00	62.00	45.00	264.00	45.00	63.00	646.00	287.00
21	1040.00	646.00	557.00	368.00	157.00	59.00	44.00	301.00	46.00	65.00	500.00	319.00
22	970.00	557.00	500.00	344.00	146.00	64.00	42.00	191.00	46.00	72.00	394.00	2640.00
23	803.00	500.00	472.00	319.00	132.00	67.00	40.00	129.00	46.00	68.00	319.00	2060.00
24	646.00	419.00	446.00	301.00	122.00	63.00	52.00	118.00	46.00	73.00	273.00	1200.00
25	528.00	500.00	394.00	278.00	116.00	58.00	51.00	129.00	46.00	205.00	238.00	1290.00
26	419.00	1380.00	394.00	252.00	107.00	57.00	57.00	154.00	47.00	296.00	229.00	9090.00
27	394.00	900.00	446.00	230.00	107.00	55.00	85.00	151.00	45.00	197.00	319.00	3020.00
28	319.00	708.00	394.00	214.00	103.00	52.00	62.00	120.00	45.00	148.00	394.00	1560.00
29	273.00	-9999.00	368.00	207.00	103.00	50.00	62.00	96.00	46.00	121.00	368.00	2520.00
30	230.00	-9999.00	344.00	191.00	98.00	48.00	96.00	[illegible]	51.00	103.00	344.00	1560.00
31	305.00	-9999.00	528.00	-9999.00	92.00	-9999.00	214.00	[illegible]	-9999.00	99.00	-9999.00	1120.00
9999												

Figure 2. Example of daily-values z-file constructed by program TRANS. (The record for this station is actually complete from April 1, 1925, to the date of this publication. The above illustrates the entire z-file that would result if the last day of record were December 31, 1926.)

Program TRANS is executed to translate data from the data file that is in "2 and 3-card" format to a daily-values z-file. When executed, TRANS will prompt the user to enter the date of the retrieval, which will be written to the top of every z-file to be created. The program then initiates a repetitive process of reading a file in the "2 and 3-card" format and creating a corresponding z-file, then moving on to the next "2- and 3-card" file. The user is given the choice of controlling this process by manually entering the name of each file to read, or letting the program automatically read every daily-values file that is listed in GAGING. If the manual option is picked, the user is prompted for the name of each daily-values file, and should enter the same name as given during the retrieval. The name of the resulting z-file will be identical to this with the exception of the letter "z," which will be placed at the beginning. If the automatic option is picked, the program will read each line in GAGING and (for each) will read the file in the directory that has the same name as the file name without the z at the beginning, then will create a new z-file which will have a name that is identical to the z-file name in GAGING. The automatic procedure will terminate when a blank line is reached in GAGING. In the automatic procedure, program TRANS writes the single-line entry for the station of interest to the top of the z-file, for identification purposes. The reading of GAGING is optional for each file when the manual procedure is used. Program TRANS writes other information near the top of the z-file, such as the first "2 card" from the original daily-values file obtained from the USGS data base. This information could serve as a verification check that the correct data retrieval was made. Program TRANS determines the maximum and the minimum streamflow for the station, then writes this information near the top of the z-file (fig. 2). The range of streamflow is used by programs RECESS and PART for determining the limits of simple graphics that can be produced during execution.

If the user obtains a daily record of streamflow from a source other than USGS data files, it may be necessary to construct z-files by customized methods. The z-file must be in a particular format so that it can be read by programs STREAM, RECESS, RORA, and PART. For construction of these z-files, the user can observe the format illustrated in figure 2 and the statements in program TRANS that write to unit 10. The following guidelines also could be useful:

1. The reading program will skip all lines until it reads the line with the word MAXIMUM (beginning at the third space). After this, the program reads the maximum on the next line, skips the next line, reads the minimum, and begins a repetitive procedure of reading data for each year of record. For simplicity, a customized z-file could begin with the line with the word MAXIMUM.
2. Each line that indicates a year is read with the format I4.
3. If the year is 9999, the program stops reading. Therefore, the number 9999 should be written at the bottom of the z-file.
4. Each line that indicates a year is followed by 31 lines that are written with the format I4,12(1F9.2,1A1). The F9.2, which is for the daily streamflow, can be alternatively written F9.1 or F9.0. The 1A1 is reserved for a character that can indicate whether the streamflow that precedes it is an estimate (because this field has not been used as of the time of this publication, the user could use it for any purpose).

5. Each of the 31 lines that follows a year consists of the day of the month (first number on the left) followed by the daily streamflow on that day of January, then February, and so on, ending with December.
6. Nonexistent dates (such as February 31) are indicated with a streamflow of -9999. Missing data on real dates are indicated with a streamflow of -999 for days that precede the period of record or with streamflow of -99 for days that occur within gaps in record.

Screening Daily-Values Files

The auxiliary program STREAM can read a daily-values file and provide the user with a simple tabulation that shows the number of daily values per calendar year. This is useful because programs RORA and PART should only be executed for periods of complete calendar years of record (365 or 366 values per year). The program also calculates the mean streamflow for each year.

When program STREAM is executed, it will ask for the name of the daily-values file of interest. The user should enter the name of the original data file that was obtained from the data base (the file name without the "z" in the beginning). The program actually reads the z-file. Next, the program will ask for the time period of interest, and the user should enter the starting and ending years as four-digit integers. The program will calculate a yearly tabulation of the mean flow and the number of days of data. The program writes a yearly tabulation to the monitor screen and to file OUTSTR.

COMPUTER PROGRAMS FOR DESCRIBING THE RECESSION OF GROUND-WATER DISCHARGE

The mathematical description of the recession of ground-water discharge can be useful for estimating aquifer diffusivity and for discerning qualitative similarities or dissimilarities between ground-water-flow systems of various basins. There may also be applications in the comparison of ground-water-supply potential of various basins and the estimation of the rate of loss of ground water to evapotranspiration or the rate of leakage to regional ground-water-flow systems.

Mathematical Basis

For the purpose of this report, the master recession curve (MRC) represents the recession of streamflow during times when all flow is from ground-water discharge, when no ground-water recharge is occurring, and when the profile of the ground-water head distribution is nearly stable. The MRC is usually assembled from numerous intervals of continuous recession; thus, it illustrates the recession that would occur given a period without direct surface runoff that is greater than any such time period in the original data. The matching strip method has been used for assembly of the MRC (Snyder, 1939; Toebes and Strang, 1964; Nathan and McMahon, 1990). The MRC is often constructed from non-summer data, so that the result will not be affected by evapotranspiration.

Although the linear model of streamflow recession (on the graph that shows flow on a logarithmic scale as a function of time on a linear scale) may be applicable (Barnes, 1939; Ineson and Downing, 1964; Rorabaugh, 1964; Bevans, 1986), many factors can cause nonlinearity, most of which cause continuous variation in recession slope as streamflow recedes. Physical and mathematical models have shown that the presence of the moving free surface (water table) can cause nonlinearity of streamflow recession for a stream fed by an unconfined aquifer (Ibrahim and Brutsaert, 1965; Hornberger and others, 1970), and this nonlinearity can be enhanced by variable head at the ground-water-outflow boundary (Werner and Sundquist, 1951; Singh, 1969; Singh and Stall, 1971). Nonlinearity can result from the gain or loss of ground water because of leakage or evapotranspiration (Singh, 1969; Daniel, 1976) or from geologic heterogeneities in the basin (Horton, 1933; Riggs, 1964; Ineson and Downing, 1964; Trainer and Watkins, 1974, 1975; Petras, 1986). Anderson and Burt (1980) suggest that curvature can result from "combined changes in the slope and size of the saturated wedge." Wood and others (1972) developed nonlinear MRC's for several streams in eastern Pennsylvania, and Nutbrown and Downing (1976) indicate that nonlinearity can be common for even the simplest of ground-water systems in England. The methods described here allow for the possibility that the MRC can be nonlinear.

For the purpose of constructing the MRC, it is assumed that the nonlinearity of the MRC is slight compared with the nonlinearity of streamflow recession during times when surface (direct) runoff is significant or when the profile of the ground-water head distribution has not yet become nearly stable. Therefore, it is possible to extract segments of continuous recession from the record and select "near-linear" parts of each segment that are indicative of the MRC. As a mathematical convenience, it is assumed that the recession index, which is the time per log cycle of streamflow recession, varies linearly with the logarithm of flow (LogQ). Because the actual relation may be more complex for a given stream, the user has the opportunity to test the validity of this assumption.

The method described here includes the selection of several individual segments of continuous recession only--periods during which each pair of subsequent daily values must meet the condition that the first value exceeds or is equal to the second. The resulting tendency to avoid time periods during which some recharge might be occurring is different from the approach taken in use of many manual methods; that is, simply connecting the minimums or roughing-in a straight line over a part of the hydrograph that shows a period of general downward trend. These manual methods can be crude because they are based on the tacit assumption of no recharge during the period. Conversely, the method of selecting only segments of continuous recession can be disadvantageous because it requires periods of reduced precipitation that are of sufficient duration that the recession of ground-water discharge can obtain the characteristic linearity or near-linearity that will develop when the profile of the ground-water head distribution is nearly stable. As mentioned previously, this condition may not be met for ground-water-flow systems of very low diffusivity (transmissivity divided by storage coefficient). Analysis of such systems may require manual methods of estimation.

The computerized methods described in this report involve the automatic location of a period of continuous recession, the display of the recession period for user evaluation, and the manual selection of the part of the recession period that is representative of the MRC. The recession period is displayed as streamflow as a function of the number of days since the last peak. In most cases, the data at the beginning of the recession period should not be used because a significant part of the streamflow is surface runoff or interflow. The duration of time after a peak in streamflow during which the components of streamflow due to surface runoff and interflow are significant can be estimated from the following empirical relation (Linsley and others, 1982:

$$N = A^{0.2} \tag{1}$$

where

N is number of days after the peak, and

A is drainage area in square miles.

The presence of surface runoff or interflow at the beginning of the recession period is usually evident from an upward departure from linearity (on the graph of the logarithm of flow as a function of time) for the first few days of the period, relative to the linear extrapolation of data from later in the recession period.

Upward departure from linearity can also occur because the profile of the ground-water head distribution, soon after the recharge event, has not yet obtained a nearly stable shape. An estimate of the amount of time after a recharge event (or peak) during which nonlinearity may result from this effect can be obtained from Rorabaugh (1964), who expressed ground-water discharge to a stream as an infinite series function of time after the recharge event; he found, however, that the function can be approximated after "critical time" by an equation that expresses the logarithm of ground-water discharge as a linear function of time. Critical time is expressed by the following equation (Rorabaugh, 1964):

$$Tc = \frac{0.2\,(a^2)\,S}{TR} \tag{2}$$

where

Tc is critical time (T),

a is the average distance from the stream to the hydrologic divide (L),

S is the storage coefficient, and

TR is transmissivity (L^2/T).

A formulation that gives critical time as a function of the streamflow recession rate can be obtained by combining equation 2 with the following equation from Rorabaugh and Simons (1966):

$$K = \frac{0.933\,(a^2)\,S}{TR} \tag{3}$$

where K is the recession index (T), which is the time required for ground-water discharge to decline through one log cycle after critical time. By solving for $(a^2)S/TR$, and substituting into equation 2, Tc can be expressed as:

$$Tc = 0.2144 \times K \tag{4}$$

The strict conclusion from the preceding analysis--that no recession data should be used until a period of time after the peak that is approximately one-fifth of the recession index--is not valid for all recession periods. The computer program displays the streamflow on each day since the last peak, where the last peak is operationally defined as the last day on which the daily streamflow exceeded streamflow of both the day that precedes it and the day that follows it. If this peak was caused by a minor precipitation event resulting in negligible recharge, then the period of nonlinearity may be much shorter than critical time. Equation 4 can be used as an estimate of the duration of time during which instability in shape of the ground-water profile might cause nonlinearity for large recharge events. Equation 4 is approximate because Rorabaugh's model is based on an aquifer in which permeability, storage coefficient, and aquifer thickness do not vary in space or time.

Program RECESS

Program RECESS (Rutledge, 1991) uses a combination of interactive and automatic procedures to calculate the mathematical expression for the MRC for a streamflow-gaging station. Because of the reliance on user decisions for the selection of recession segments, allowances should be made to ensure consistency in program execution, especially if the program is used to compare recession properties of various stations. In such situations it is advisable that only one user works with the program. Some experimentation with the program may be useful prior to doing the analysis.

The Algorithm

The basic steps for determining the MRC are illustrated in figure 3. First, the program locates periods of streamflow recession and allows the user to select nearly-linear segments (fig. 3*A*). Then, for each segment, the program determines the best linear equation for time as a function of LogQ (logarithm of flow), and extracts from this equation a coefficient that is the recession index (K) of the segment (data points, fig. 3*B*). The program then determines the best linear equation for K as a function of LogQ, which is the line in figure 3*B*. Coefficients of this equation are used to obtain the MRC (fig. 3*C*), which is a second-order polynomial expression for time as a function of LogQ. These steps are described in greater detail below.

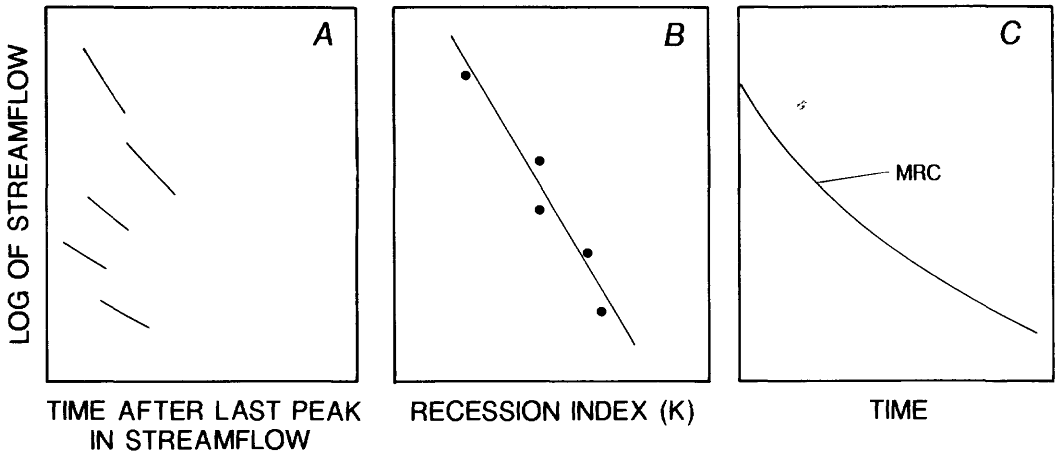


Figure 3. Schematic representation of the method used to determine the master recession curve: (*A*) selected recession segments, (*B*) recession index (K) (time per log cycle of streamflow recession) and best-fit line, and (*C*) the master recession curve, obtained from coefficients of function in *B*.

Program Execution

Before program execution, one line must exist in file GAGING and one daily-values z-file must be prepared for each gaging station of interest. It is advisable, but not required, for the daily-values z-file to be screened so that the user can select a period of continuous record when RECESS is executed (see "Preparation of Data Files"). File OUTREC, which is an output file for program RECESS, must also exist (see "Overview of Programs and Files").

When the program is executed, it asks for the number of days to be displayed on the computer monitor when recession periods are displayed. To maximize this without loss of the display of program menu options, the user enters the number of lines that the monitor displays minus five. Next, when the program asks for the file of interest, the user enters the name of the original data file that was obtained from the data base (the file name without the "z" in the beginning). The program actually reads the z-file. Next, the program finds the single-line entry in file GAGING that represents the station of interest, so that the drainage area and other variables are known. When the program requests the time period of interest, the user enters the beginning and the ending calendar years as four-digit integers. Next, the program requests the months of interest. The user enters the number of months, then integers to represent each month. For example, if the months of interest are January, February, and December, then the user enters the number 3, then the numbers 1, 2, and 12. The program will detect only recession periods that begin in the months specified. A single letter is entered to designate the season, such as "w" for winter.

The next entry is the minimum number of days required for detection of a recession period. The number entered may depend on the desired degree of restrictiveness in selection, which may in turn depend on the duration of record that is available for analysis. If the number selected is too large, then few recession periods will be found, and the result will be poor definition of the MRC. If the number is too small, then too many recession periods will be detected, and the user may be required to skip the analysis of many. For the analysis of streamflow-gaging stations in the APRASA project, the number entered is generally 10 to 20. Records for most of these stations are 15 to 40 years in duration.

The program then starts a repetitive procedure of searching through the period of interest from the start to the end, detecting periods of recession, allowing the user to select a near-linear segment to be included in analysis, and proceeding to the next period of recession. With each new period of recession, the program displays the data in graphic (fig. 4) or tabular form and gives the user various options for the course of action, as itemized below. The only options that will cause the program to proceed to the next period of recession are "r" and "a." The number of periods skipped depends on the desired number of periods to analyze. As a rough guideline, a satisfactory execution of program RECESS might include 20 to 30 periods of recession. For most periods of recession, option "c" should be entered before option "r." The repetitive procedure of searching through the record for periods of recession will be terminated if (1) the end of record is reached, (2) the maximum number of recession periods (50) has been reached, or (3) the user enters option "q."

```
LOG Q =        1.00                                                         3.20
 1 1959 10 25                                                            *
 2 1959 10 26                                                   *
 3 1959 10 27                                              *
 4 1959 10 28                                         *
 5 1959 10 29                                    *
 6 1959 10 30                                 *
 7 1959 10 31                               *
 8 1959 11  1                             *
 9 1959 11  2                           *
10 1959 11  3                         *
11 1959 11  4                        *
12 1959 11  5                       *
13 1959 11  6                     *
14 1959 11  7                     *
15 1959 11  8                    *
16 1959 11  9                   *
17 1959 11 10                  *
18 1959 11 11                 *
19 1959 11 12                 *
20 1959 11 13                *
21 1959 11 14               *
22 1959 11 15               *
23 1959 11 16              *
24 1959 11 17              *
25 1959 11 18             *
26 1959 11 19             *
27 1959 11 20            *
28 1959 11 21           *
29 1959 11 22           *
30 1959 11 23           *
```

Figure 4. Example of graphical output generated on the computer monitor by program RECESS for the purpose of user selection of a near-linear recession segment for analysis. (This graphic, produced by option g in the program, shows recession data for North Fork Shenandoah River at Cootes Store, Virginia. Each line except the first shows days since the last peak, year, month, and day of month, followed by a graphical representation of streamflow on logarithmic scale, the range of which is indicated on the first line.)

Options are the following

- g Generates a graphical representation of the data, where time is in the vertical (proceeding downward) and the logarithm of flow is in the horizontal. The first day shown is the first day after the peak, and each subsequent day is represented by one line of data. Figure 4 shows an example of graphical display produced by option g.
- g2 Same as g, except that the user can specify the starting day and the time interval between subsequent lines
- e Changes the extremes for the graphical representation of the data to values that the user will enter (the minimum and the maximum logarithm of flow).
- o Changes the extremes for the graphical representation of the data back to the default values (the logarithms of the minimum and maximum streamflow as read near the top of the daily-values z-file).
- t Generates a tabular display of the data, where time proceeds in the vertical. The data displayed for each day include streamflow, the logarithm of streamflow, and the daily change in the logarithm of streamflow (log of present day's flow minus log of previous day's flow). The first day shown is the first day after the peak, and each subsequent day is represented by one line of data.
- t2 Same as t except the user can specify the starting day.
- a Skips the present period of recession and advances to the next period. This option is chosen if the user decides that the present period of recession does not favorably represent the MRC (for example, if the period of recession is too short or if there are variations in flow that are caused by other processes). This option may also be used simply to reduce the number of selected recession segments.
- c Allows the user to select the time limits of the nearly linear segment of recession that is to be used (the first and the last days will be entered). As an example, this option could be used to select the range of day 16 to day 29 for the recession data shown in figure 4.
- b Allows the user to negate the time limits that were entered after option c (this can be used if the user mistakenly entered a shorter time period than desired).
- r Instructs the program to analyze the recession segment that has been selected--determines the best-fit linear equation of time as a function of LogQ, then extracts from this equation a coefficient that is the recession index of this segment (equivalent to differentiation of the equation), stores this recession index with the mean LogQ for the segment (this data pair, represented by a point in figure 3*B*, is used later to estimate the MRC), and then proceed to the next period of recession (or to the end of the period of record if no more suitable periods of recession exist).
- q Terminates the repetitive procedure of searching for periods of recession.

The display options enhance the user's ability to select recession segments that most accurately represent the MRC. The graphical display options (g or g2) can be used to find, on a recession period, the time at which near-linearity is reached. The option "e" can be used to expand the LogQ scale on these graphics, allowing the user to see more easily when near-linearity is reached. For example, if the default values for the minimum and maximum values of LogQ are 1 and 4, yet most recession data fall in the range of 1.5 to 3, the user can change the extremes to 1.5 and 3. The options of tabular display (t and t2) can be used in deciding the limits of the segment to use. For example, the column that shows the daily change in LogQ can be scanned from top to bottom. The condition of near-linearity may be evident when there is no longer a trend in these numbers with time. A trend would cause a gradual increase (or decrease) in the daily change from top to bottom. When observing the data in the graphical or tabular mode, the user should be aware that rounding of the original data will cause an apparent "stepping" in the relation between LogQ and time. Some tendency of stepping in the data will also be caused by the simple graphical procedure that is executed by options "g" and "g2" -- for example, the stepping evident for the near-linear recession segment from day 16 to day 29 in figure 4. The selected recession segment should be long enough to define a recession slope, but short enough to be considered linear or nearly linear.

After recession segments are selected, the program generates a list that shows for each segment, the mean of the LogQ, the recession index (K), and a simple graphical representation of K. Because this listing is generated in order of decreasing value of the mean of LogQ, it gives the user a rough idea of the relation between K and LogQ. The user has the option of eliminating outliers--values of K that depart significantly from the general trend. Particular types of departures that may be evident are those caused by prolonged periods of slight precipitation or by slight regulation of flow when flow is small. The elimination of outliers depends on the strategy of the individual program user.

Because the next procedure executed by the program is determination of the best linear equation for K as a function of LogQ, the user can, at this point, assess the validity of the assumed linear relation. The user should be aware that the graphic generated simply shows K for each ordered value of LogQ--apparent curvature in this simple graphic can be caused by a nonuniform sampling of LogQ. Linearity could be tested by manually transposing some of the data pairs to a graph. A rigorous test of linearity between K and LogQ could be done with separate computer graphical or statistical software. The testing of linearity can be done after program execution because this listing is also produced in one of the output files (the x-file). Because subsequent calculations are based upon linearity, nonlinearity may require that the user exercise caution in interpretation of results, or it may require other methods for obtaining the best MRC. For example, discontinuities in the relation between K and LogQ might require manual estimation of the MRC (Trainer and Watkins, 1974, 1975). Other methods may nonetheless use the x-file.

Next, the program determines the best-fit linear equation for K as a function of LogQ (fig. 3*B*) by using only the recession segments that have not been eliminated. The program then uses the coefficients of this equation to derive the following polynomial expression of time as a function of LogQ:

$$T = A\,(LogQ^2) + B\,(LogQ) + C \qquad (5)$$

where

T is time (T), and

A, B, and C are coefficients.

This equation, which is the MRC (fig. 3*C*), is the result of integration of the best-fit linear equation for K as a function of LogQ. It is unique because at time=0, LogQ is the maximum value of the LogQ from all selected recession segments. The coefficients are written to file OUTREC and to the x-file.

Output Files

Results of program RECESS are written to three output files, as described below:

OUTREC — Each time RECESS is executed, one new line is written to the bottom of OUTREC. This line gives a summary of results of the session: name of daily-values file; single-letter designation of the season; time period of analysis; number of recession segments used; the minimum, median, and maximum recession indexes of the segments used; the minimum and maximum LogQ of all segments used; and the three coefficients of the MRC (eq. 5). Program CURV reads file OUTREC for the purpose of generating an x-y file for producing a graph of the MRC by use of separate graphics software. Program RORA will read file OUTREC to obtain the median value of the recession index for wintertime recession data (season = "w").

X-file — A new x-file gives details about one execution of RECESS. The x-file is assigned a name equal to the name of the original daily-values file that is obtained from the USGS data base, except two letters have been added to the beginning of the name. The first is the letter "x" and the second is the letter that designates the season. Included in the x-file is detailed information about each recession segment that was initially selected--date of the peak and designation of the starting and ending of the recession segment (days after the peak). Also included is a listing of each data pair of LogQ and K for each recession segment and a graphical representation of K for each segment. This listing is shown twice: once before and once after the user eliminates segments not wanted. The x-file also shows the best-fit linear equation for K as a function of LogQ and the resulting second-order polynomial that is the MRC (simple graphics of both equations also are shown). Because of the name of the x-file, if RECESS is executed twice for the same streamflow-gaging station and season, the first x-file will be overwritten.

Y-file A new y-file gives detailed information about the time and flow for each day of each selected recession segment. The y-file is assigned a name equal to the name of the original daily-values file that is obtained from the USGS data base, except two letters have been added to the beginning of the name. The first is the letter "y" and the second is the letter that designates the season. The y-file can be used to generate a graph of each recession segment. One such graph could be the flow as a function of the time since the last peak. Another could be the flow as a function of time, where the time has been adjusted so that all recession segments are drawn on the same MRC. The variables for each day of each recession segment are the adjusted time, the flow, the logarithm of flow, and the unadjusted time (days since the last peak). In figure 5*A*, which is generated from a y-file, flow is plotted as a function of the adjusted time. Figure 5*A* represent an analysis that is deliberately simplified for illustration purposes--a rigorous analysis would include a larger number of recession segments. As with the x-file, if RECESS is executed twice for the same streamflow-gaging station and season, the first y-file will be overwritten. The y-file is used to illustrate one MRC showing each recession segment that is selected in program RECESS. Program CURV (described below) is used to illustrate the exact solution of the equations for several MRC's on the same graph, without showing each recession segment.

Program CURV

Program CURV, which is provided here as an auxiliary program to RECESS, provides a way of displaying the MRC (eq. 5) for more than one stream on the same graph. It may also be used to display more than one MRC for the same stream, each representing different seasons. The flow can be drawn in units of specific discharge, normalizing for drainage area (the units used are cubic feet per second per square mile). Program CURV produces a simple output that can be read by separate graphical software.

For execution, there should be one line in file GAGING for each streamflow-gaging station of interest, and there should be one line in file OUTREC that represents each combination of station and season of interest. For example, if two MRC's, representing the summer and the winter for one station are to be illustrated, then program RECESS must be executed for each season such that file OUTREC includes two lines for this station--one would specify "w" for winter, and the other would specify "s" for summer.

When executed, program CURV asks for the daily-values file name of interest. The user enters the name of the original data file that was obtained from the data base (the file name without the "z" in the beginning). Next, the program asks for the single-letter designation of the season of interest. The program then reads files GAGING and OUTREC. After the appropriate lines in these files have been read, the program asks if there is another station of interest, and the process repeats. If the user wants an MRC for the same station as before but for a different season, the same daily-values file name should be entered, followed by the single-letter designation for the different season.

For each combination of station and season requested, the program determines 50 evenly-spaced values of LogQ--from the maximum of the LogQ to the minimum of the LogQ for all recession segments selected in the execution of RECESS (these limits are read from OUTREC). Then, for each LogQ, the time (T) is calculated according to equation 5 (by use of the appropriate coefficients in OUTREC). Each pair of LogQ and time thus results in one data point for plotting the MRC.

For each requested combination of station and season, the program writes 50 lines to its output file OUTCURV. Each line gives (1) time in days, (2) logarithm of flow, in cubic feet per second, (3) logarithm of flow, in cubic feet per second per square mile, (4) flow, in cubic feet per second, and (5) flow, in cubic feet per second per square mile. Some editing may be necessary before file OUTCURV is used as input to the graphical software that the user might have; for example, removal of header information at the top of the file. File OUTCURV was used to generate figure 5*B*, which results from the same recession data illustrated in figure 5*A*.

COMPUTER PROGRAM FOR ESTIMATING MEAN GROUND-WATER RECHARGE

The recession-curve-displacement method is a theoretically based procedure for estimating total recharge from streamflow records. The method should be used only if the conditions described in "Applicability of Methods" are met. When a long time period is considered, the total recharge should exceed the ground-water discharge (base flow) by an amount equal to riparian evapotranspiration.

Theory and Method Development

The recession-curve displacement method is based on the upward shift in the streamflow recession curve that occurs as a result of a recharge event. A recharge event will increase the total potential ground-water discharge, V, which is the total volume of water that will drain from the system if allowed to do so for infinite time without further recharge. Meyboom (1961) expressed V in the following expression, which is based upon a linear relation between the logarithm of ground-water discharge and time:

$$V = \frac{Q \times K}{2.3026} \tag{6}$$

where

V is total potential ground-water discharge (L^3), and

Q is ground-water discharge at initial time (L^3/T).

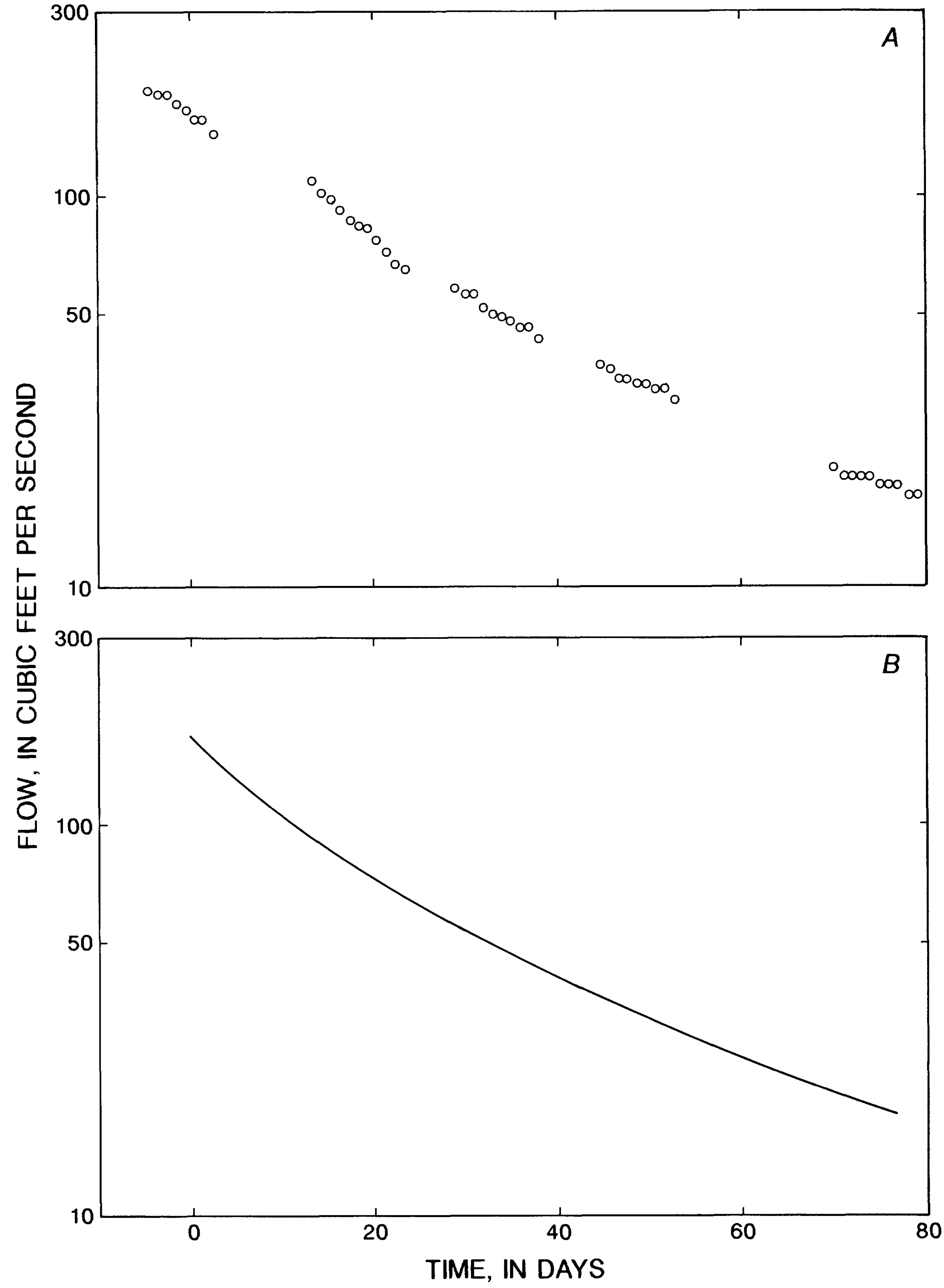


Figure 5. Example of graphical representation of the master recession curve that can be generated from program output files: (*A*) plot showing each individual recession segment (in this case, five were selected) with time adjusted so that the segments fall on the master recession curve (this plot is generated from the y-file produced by program RECESS); and (*B*) plot showing the exact mathematical equation that is the master recession curve (this plot is generated from the 50 x-y data points listed in the output file OUTCURV that is generated by program CURV, and results from the same recession segments that are used in *A*).

(Results here, which are for Johns Creek at New Castle, Va., represent an application that is deliberately simplified for illustration purposes. A rigorous analysis of recession would include a larger number of recession segments.)

The formulations of Glover (1964) and Rorabaugh (1964) show that the total potential ground-water discharge to the stream at critical time (eqs. 2 and 4) after a peak in streamflow is equal to approximately one-half of the total volume of water that recharged the ground-water system during the peak. This finding, combined with the principle of superposition, is the basis for the method--total recharge is thus calculated by use of the following equation:

$$R = \frac{2\,(Q2 - Q1)\,K}{2.3026} \qquad (7)$$

where

R is total volume of recharge due to the event (L^3),

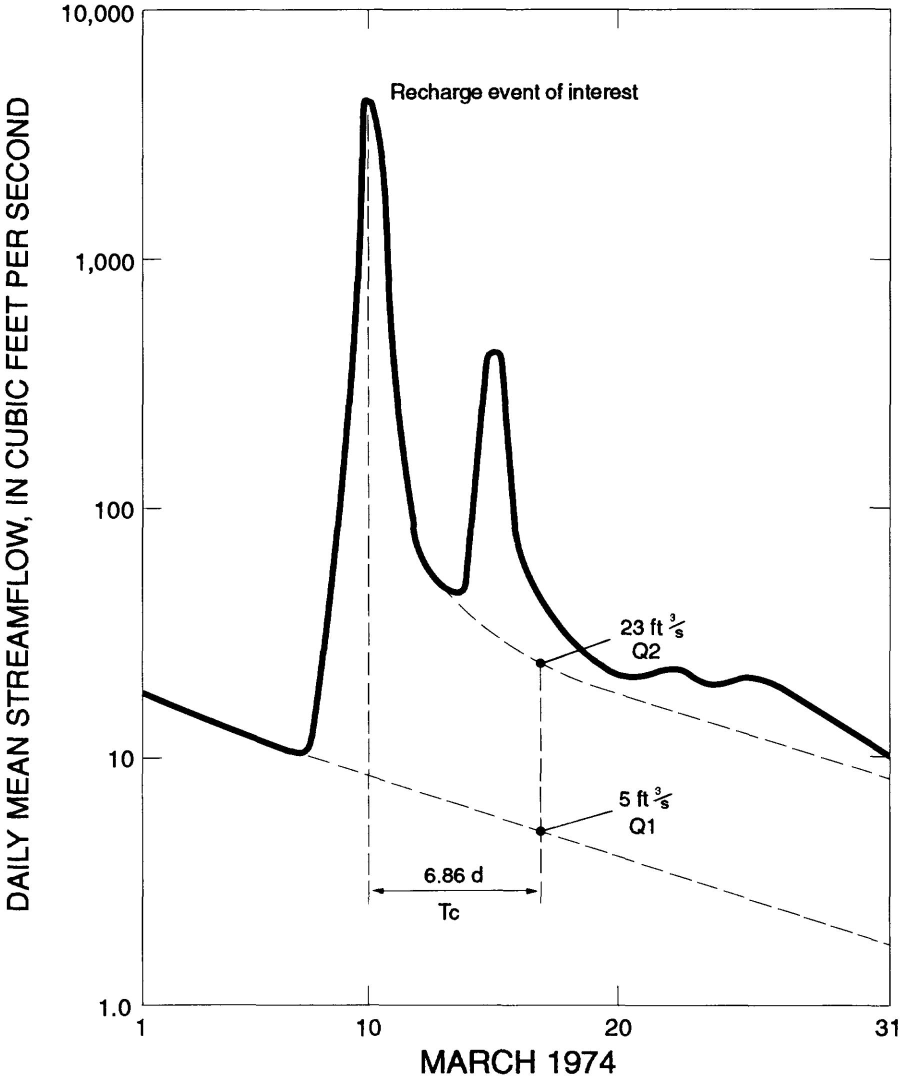
Q1 is ground-water discharge at critical time as extrapolated from the pre-event streamflow ression (L^3/T), and

Q2 is ground-water discharge at critical time as extrapolated from the post-event streamflow recession (L^3/T).

The recession-curve-displacement method consists of the following steps, most of which are shown in figure 6 (Bevans, 1986): (1) determination of the recession index (K) from the hydrograph during prolonged periods of negligible recharge, (2) calculation of critical time (Tc) from equation 4, (3) use of critical time to determine the time on the hydrograph to which streamflow recessions will be extrapolated, (4) determination of the hypothetical ground-water discharge to the stream at critical time by extrapolation of the pre-event recession curve, (5) determination of the hypothetical ground-water discharge to the stream at critical time by extrapolation of the post-event recession curve, and (6) application of equation 7. Steps 1 and 2 need only be executed once for a given streamflow gaging station--other steps are executed once for each peak. In practice, the user identifies the position of the post-event recession curve soon after surface runoff ceases so that the effects of riparian evapotranspiration are minimized; thus, the result is an estimate of total ground-water recharge. The recession-curve-displacement method, often referred to as the "Rorabaugh Method" (Rorabaugh, 1964; Daniel, 1976), has been applied manually by several investigators (Wilder and Simmons, 1978; Daniel and Sharpless, 1983; Evaldi and Lewis, 1983; Bevans, 1986; Gerhart and Lazorchick, 1988; Faye and Mayer, 1990; Hoos, 1990).

Program RORA

Program RORA executes the recession-curve-displacement method to estimate ground-water recharge for each peak in streamflow using a set of procedures that includes the identification of periods of ground-water-flow recession, the identification of peaks, and the extrapolation of data from the periods of recession to critical time after peaks. The method was first described by Rutledge (1992).



EXPLANATION

DAILY STREAMFLOW

EXTRAPOLATED GROUND-WATER DISCHARGE

PROCEDURE

1. Compute recession index, K (32 d/ log cycle)
2. Compute critical time, Tc (0.2144xK, or 6.86 d)
3. Locate time that is 6.86 days after peak
4. Extrapolate pre-event recession to Q1 (5 ft^3/s)
5. Extrapolate post-event recession to Q2 (23 ft^3/s)
6. Compute total recharge,

$$\frac{2\times(18\ ft^3/s)\times 32\ d}{2.3026} \times \frac{86400\ s}{1\ d} = 4.32\times10^{7}\ ft^{3}$$

Figure 6. Procedure for use of the recession-curve displacement method to estimate ground-water recharge in response to a recharge event. (Modified from Bevans, 1986, fig. 5.)

The Algorithm

The first procedure executed by program RORA locates days in the streamflow record that fit an antecedent recession requirement (eq. 1, rounded to the next larger integer). Then the program identifies periods of ground-water-flow recession, which can consist of one or more days that each fit this requirement. The program then defines a peak as the largest streamflow between two consecutive periods of ground-water-flow recession, and considers that peak to be a recharge event. The total recharge is calculated for each peak by use of procedures diagrammed in figure 7.

A crucial aspect of the method is the extrapolation (in time) of ground-water discharge from periods of ground-water-flow recession to points in time that are outside of these periods of recession. Before critical time, this equation is used:

$$dQ = \frac{C}{\sqrt{dT}} \qquad (8)$$

where

dQ is the difference between the ground-water discharge and the ground-water discharge that would have occurred at the same time in the absence of the recharge event (L^3/T),

c is a constant, the value of which is dependent on the magnitude of the recharge event ($L^3/T^{0.5}$), and

dT is the time since the recharge event (T).

Equation 8, a simplified version of Rorabaugh's (1964) equation 4, quantifies the margin of flow resulting from the recharge event that is superimposed on the flow that would have occurred in the absence of the event. Equation 8 is used to extrapolate the margin of flow at critical time by solving for C for each day of a period of ground-water-flow recession that occurs before critical time, obtaining the average, and substituting this C and critical time back into the equation.

After critical time, linear extrapolation is used:

$$Q = Qo \times 10^{(-dT/K)} \qquad (9)$$

where

Q is ground-water discharge extrapolated to a time after critical time(L^3/T),

Qo is ground-water discharge extrapolated to critical time after the peak, as derived from equation 8 and superposition (L^3/T), and

dT is the time period from critical time to the day of interest (T).

Equation 9 is mathematically the same as the graphical method of drawing a straight line through a known ground-water discharge at critical time and reading on this line the extrapolated ground-water discharge at a time after the critical time (the graph being ground-water discharge on a logarithmic scale as a function of time on a linear scale, and the inclination of the line being equal to K). One value for the recession index is used in calculations for an entire streamflow record. This is either the median recession index from the execution of program RECESS, or is a user-specified value.

Program Execution

Before the program is executed, one line of data must exist in file GAGING and one daily-values z-file must be prepared for each gaging station of interest. Because program RORA should be used to analyze periods of continuous record only, the user can execute program STREAM to locate such time periods (see "Preparation of Data Files"). File OUTROR, which is an output file for the program, must also exist (see "Overview of Programs and Files").

Before program RORA is executed, it is advisable, but not required, for program RECESS to be executed for each gaging station of interest so that RORA can read the median recession index from file OUTREC. Program RECESS can be executed expediently for this purpose only: the user can select a small number of recession segments (5 to 10 for example) that represent a range of different conditions. From file OUTREC, program RORA uses the median recession index only. Such an expedient use of program RECESS can be sufficient for obtaining the median recession index, but may not adequately define the MRC. Program RORA will search file OUTREC for the first line that includes the station name of interest and a "w" designating the season. Execution of RECESS for winter data exclusively is not required but it is advisable that the results represent recession during periods of small riparian evapotranspiration. If RECESS is not executed, the user has the option to enter the recession index during execution of RORA. It will be shown that the result of program RORA is only slightly sensitive to variation in the recession index.

When the program is executed, it will ask for the name of the daily-values file of interest. The user should enter the name of the original data file that was obtained from the data base (the file name without the "z" at the beginning). The program actually reads the z-file. Next, the program will find the single-line entry in file GAGING that represents the station of interest to obtain the drainage area. The program uses the result of equation 1, rounded to the next larger integer, to determine the default antecedent recession requirement. In effect, this is the minimum time after each peak at which the position of the ground-water recession curve is measured. The user is given the option of modifying this value for testing only, and should consider the default value to be required for yielding the best estimate of recharge. The program then obtains the recession index from file OUTREC (or directly from the user). From the recession index, the program calculates the default value for critical time (eq. 4), which becomes the maximum time after each peak at which the position of the ground-water recession curve is measured. As is the case for the antecedent recession requirement, the option of modifying this variable is for testing only. The last day used for a given period of ground-water-flow recession may actually occur before critical time (or the day specified by user) if there is another period of increasing streamflow (fig. 7).

A

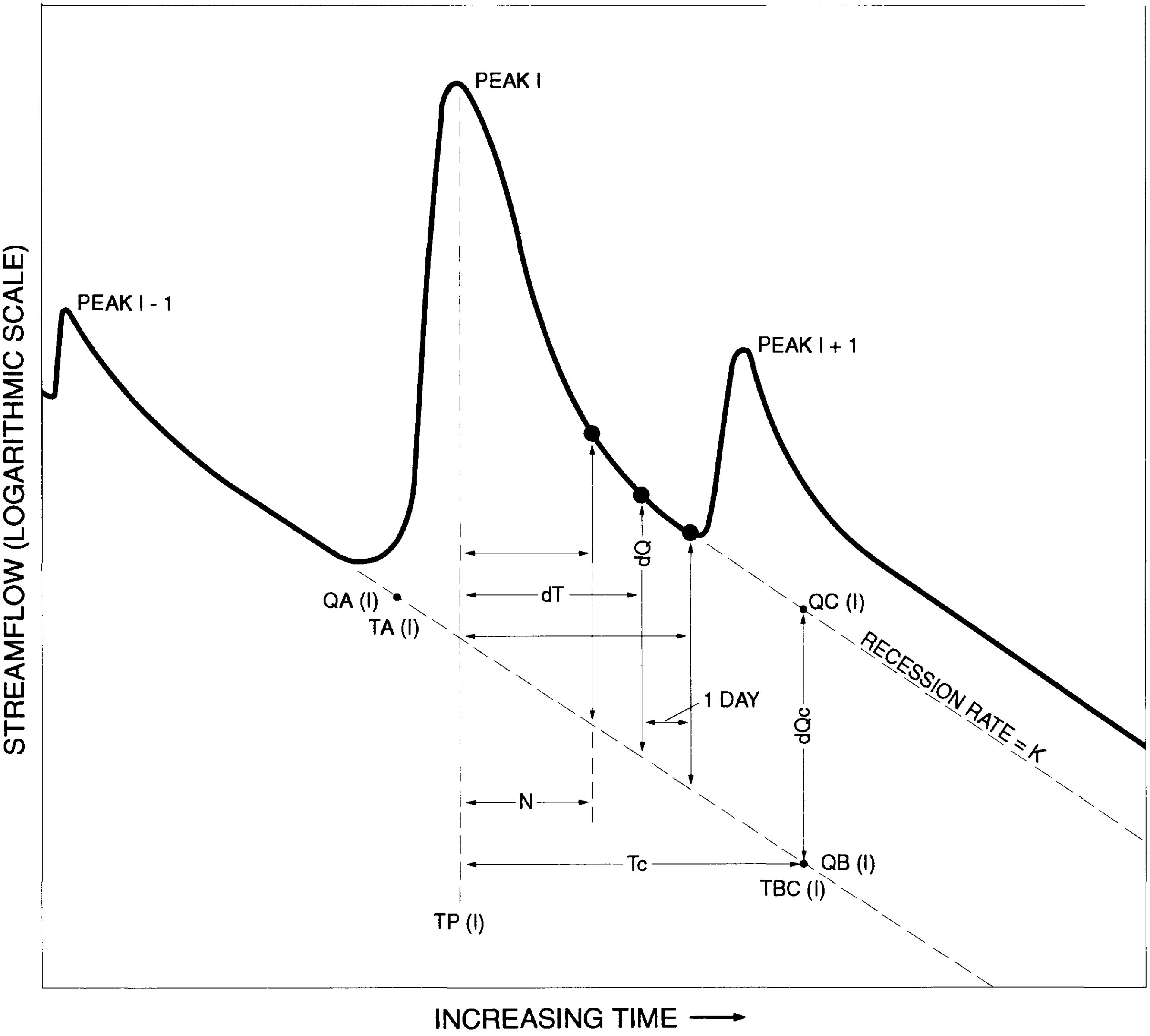
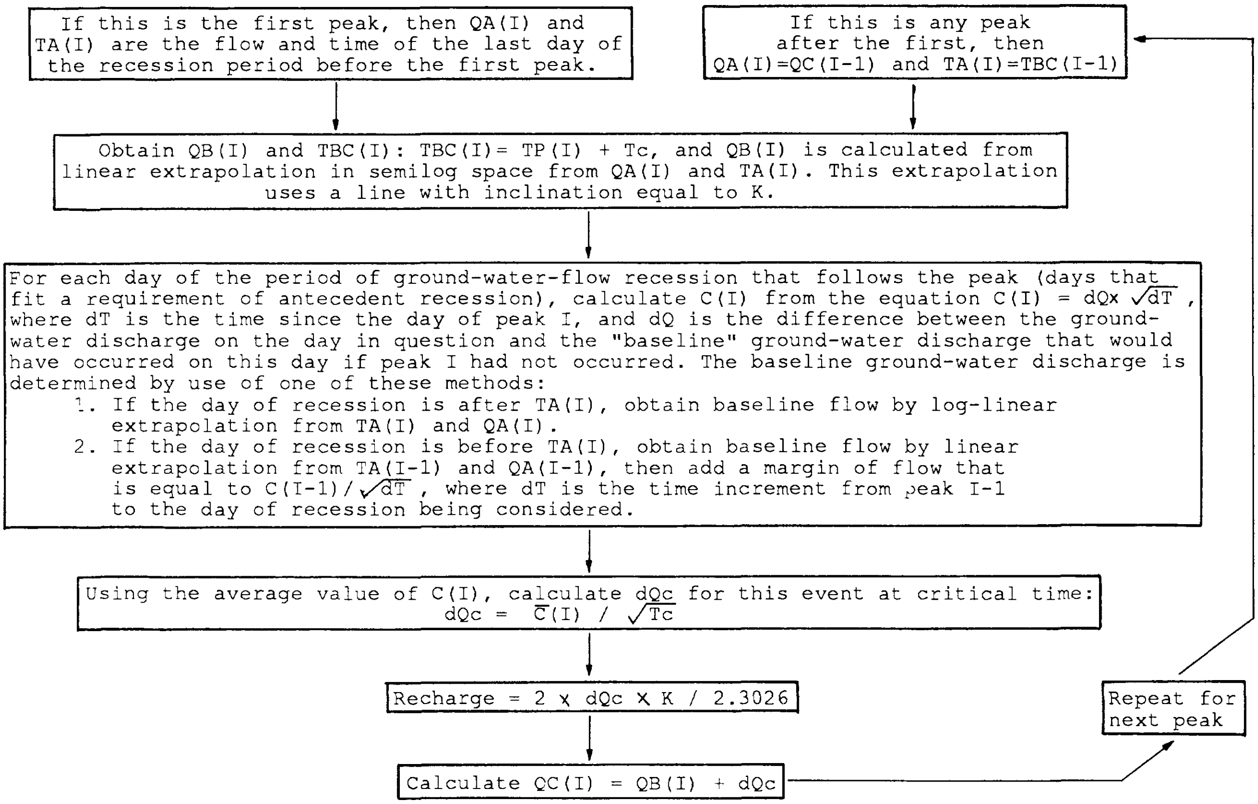


Figure 7. Schematic of hydrograph (above) and flow diagram (right) showing the procedures executed for each peak in the recession-curve displacement method.



EXPLANATION

- N — Result of equation 1 (time base of surface runoff), rounded to next larger integer.
- K — Recession index (days per log cycle of recession after critical time).
- Tc — Critical time.
- I — Peak counter-- The above calculations pertain to the "present peak," which is peak I.
- TP(I) — The time of occurrence of peak I.
- C(I) — A value (for peak I) that is calculated in the equation for the difference between the flow during a period of ground-water flow recession and the ground-water flow that would have occurred in the absence of the peak, up to the critical time after the peak.
- $\overline{C}$(I) — The average value of C(I) for all days in the period of ground-water flow recession following peak I.
- QA(I), TA(I) — The flow and time at critical time after the last peak (I-1) that would have occurred in the absence of all peaks subsequent to the last peak; one exception is that if I=1, then QA(I) and TA(I) are the flow and time on the last day of the recession period before the first peak.
- QB(I), TBC(I) — The flow and time at critical time after the present peak (I) that would have occurred in the absence of the present peak and all subsequent peaks.
- QC(I), TBC(I) — The flow and time at critical time after the present peak (I) that would have occurred in the absence of all peaks subsequent to the present peak.
- dT — Time increment between the peak and a day during the ground-water flow recession period after the peak.
- dQ — Difference between the measured flow during the period of ground-water flow recession after peak I and the flow that would have occurred in the absence of peak I.
- dQc — Difference between the hypothetical ground-water discharge at critical time after peak I as extrapolated from the ground-water flow recession period after the peak and the hypothetical ground-water discharge at critical time after peak I as extrapolated from the ground-water flow recession period that precedes the peak.
- ● — On the hydrograph, the flow on a day during the period of ground-water flow recession that follows peak I.

Figure 7.--Continued.

When the program requests the time period of interest, the user should enter the beginning and the ending calendar years as four-digit integers. If the streamflow record includes zeros, the program will request that the user designate a value to be substituted for extrapolation on a log scale. A small value such as 0.01 cubic foot per second is suggested. The program will then complete all calculations and write results to the monitor and to output files.

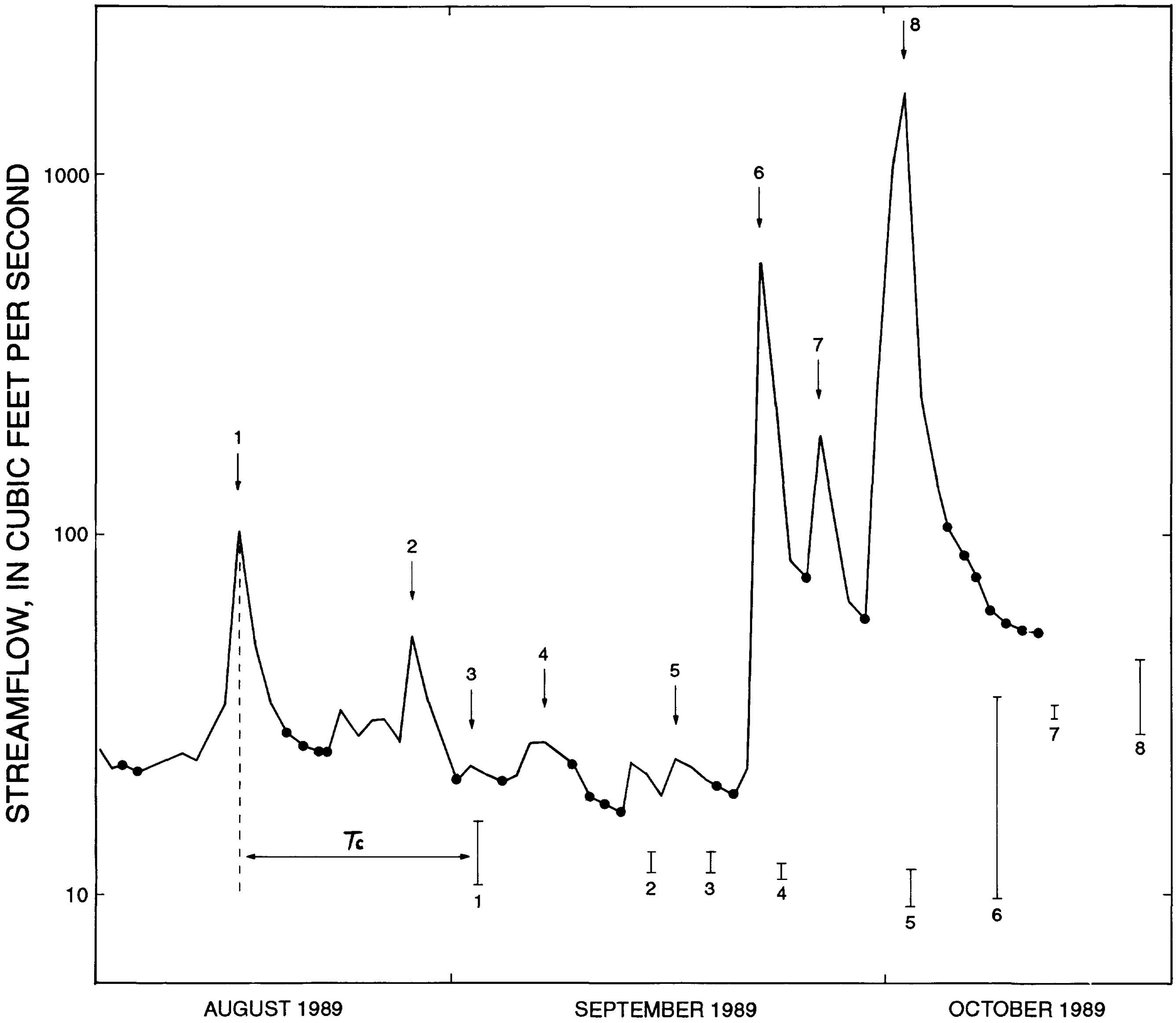
Output Files

Results of program RORA are written to two output files:

OUTROR One new line is written to the bottom of file OUTROR each time the program is executed, giving a summary of the results. Included are the name of the daily-values file, the gaging-station number, the drainage area of the station, the time period analyzed, the minimum and maximum days after a peak for the measurement of the period of ground-water-flow recession, the recession index, and the mean recharge rate.

OUTROR2 File OUTROR2 gives details about calculations of recharge for each peak. One line is written to OUTROR2 for each peak, giving most of the variables defined in figure 7. Time is reported in days since the beginning of the analysis, and flow is reported in cubic feet per second. Recharge is reported in inches. Variables not defined in figure 7 include TS, TE, and QP, which are the time of the beginning and the ending of the period of ground-water flow recession after the peak, and the streamflow for the day of the peak, respectively.

In most program applications, the output file OUTROR will be used the most. File OUTROR2 may be useful for determining the distribution of recharge over time on a monthly or seasonal basis. A hydrograph of results tabulated in OUTROR2 is shown in figure 8. 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 (fig. 7) 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. Riparian evapotranspiration, which is the loss of water to the atmosphere from ground water and from the channel, may also affect the accuracy of the method when it is applied at a small time scale. Estimates of recharge for individual events that occur during the summer may be suspect because of the change in slope of the ground-water-discharge recession curve that is caused by riparian evapotranspiration (Daniel, 1976). Results seem to be most reliable when the method is applied at a time scale of at least a year.



EXPLANATION

● Indicates that this day meets the requirement of antecedant recession--this day is thus considered to be during a period of ground-water-flow recession. A period of ground-water-flow recession can be one isolated day that meets the requirement, or it can be multiple days that all meet the requirement.

2 ↓ Indicates a day that is considered a peak in streamflow--the largest streamflow between two subsequent periods of ground-water-flow recession. The number identifies the peak for cross-reference with items explained below.

Top of bar indicates, for the peak identified below the bar, the flow at critical time after the peak that would have occured in the absence of all peaks subsequent to the peak (Q2 in equation 7).

Bottom of bar indicates, for the peak identified below the bar, the flow at critical time after the peak that would have occured in the absence of the peak and all subsequent peaks (Q1 in equation 7).

5

Figure 8. Example hydrograph of streamflow graphically showing decisions and calculations performed by program RORA, (streamflow-gaging station is Indian Creek near Laboratory, N.C.).

Comparison of Results of Manual and Computerized Methods

Results from program RORA were tested by comparing them with results from a corresponding manual method. For purposes of this investigation, results from Daniel (1990) were used for the comparison. Daniel's evaluation of an automated base-flow-record estimation method resulted in an extensive data set giving results of manual application of the recession-curve-displacement method for 16 streamflow-gaging stations in the eastern United States. For the purpose of this investigation, one station was eliminated from analysis because its small drainage area results in a time base of surface runoff (eq. 1) that is less than 1 day. Although some of the stations have drainage areas that exceed the limits suggested earlier (see "Applicability of Methods"), they were used because the purpose here is to simply compare annual recharge values calculated by RORA with values calculated by Daniel's manual method. For the 15 streamflow-gaging stations used, a period of 10 consecutive years is used, except for 1 station where 16 years is used (table 1).

Table 1. Streamflow gaging stations used for comparisons between results of program RORA and results of the manual application of the recession-curve displacement method

Station sequence number	U.S. Geological Survey station number	Station name	Drainage area (square miles)	Recession index (days per log cycle)	Time period analyzed (water years)
1	01452500	Monocacy Creek at Bethlehem, Pa.	44.5	37.4	1965-74
2	01459500	Tohickon Creek near Pipersville, Pa.	97.4	28.3	1960-69
3	01465500	Neshaminy Creek near Langhorne, Pa.	210	46	1935-44
4	01555000	Penns Creek at Penns Creek, Pa.	301	39	1934-43
5	02080500	Roanoke River at Roanoke Rapids, N.C.	8,384	49	1940-49
6	02083500	Tar River at Tarboro, N.C.	2,183	45	1978-87
7	02089500	Neuse River at Kinston, N.C.	2,692	41	1978-87
8	02093800	Reedy Fork near Oak Ridge, N.C.	20.5	65	1971-80
9	02096700	Big Alamance Creek near Elon College, N.C.	116	45	1971-80
10	02099000	East Fork Deep River near High Point, N.C.	14.8	43	1971-80
11	02126000	Rocky River near Norwood, N.C.	1,372	35	1979-88
12	02339500	Chattahoochee River at West Point, Ga.	3,550	59	1940-55
13	03453500	French Broad River at Marshall, N.C.	1,332	49	1958-67
14	03538225	Poplar Creek near Oak Ridge, Tenn.	82.5	32	1975-84
15	03565300	South Chestuee Creek near Benton, Tenn.	31.8	45.8	1969-78

For this comparison test, 156 estimates of annual recharge from the manual method are paired with the corresponding results of program RORA. For the execution of RORA, the recession indexes were set equal to the value used in the manual method (table 1), and the number of days from the peak to the beginning and the ending of the period of ground-water-flow recession are set to their default values (see "Execution of Program"). For consistency with the results from the manual method, the output file OUTREC2 was processed to yield annual recharge on the basis of the water year.

Results of the manual and computerized methods are in reasonable agreement (fig. 9). The results of the comparison test can be expressed quantitatively by introducing a variable P that represents the percentage of difference between the two methods:

$$P = \frac{100 \times (Ra - Rm)}{Rm} \quad (10)$$

where

P is the percentage by which the computerized method exceeds that of the manual method,

Ra is the annual recharge estimated by the computerized method (L), and

Rm is the annual recharge estimated by the manual method for the same year (L).

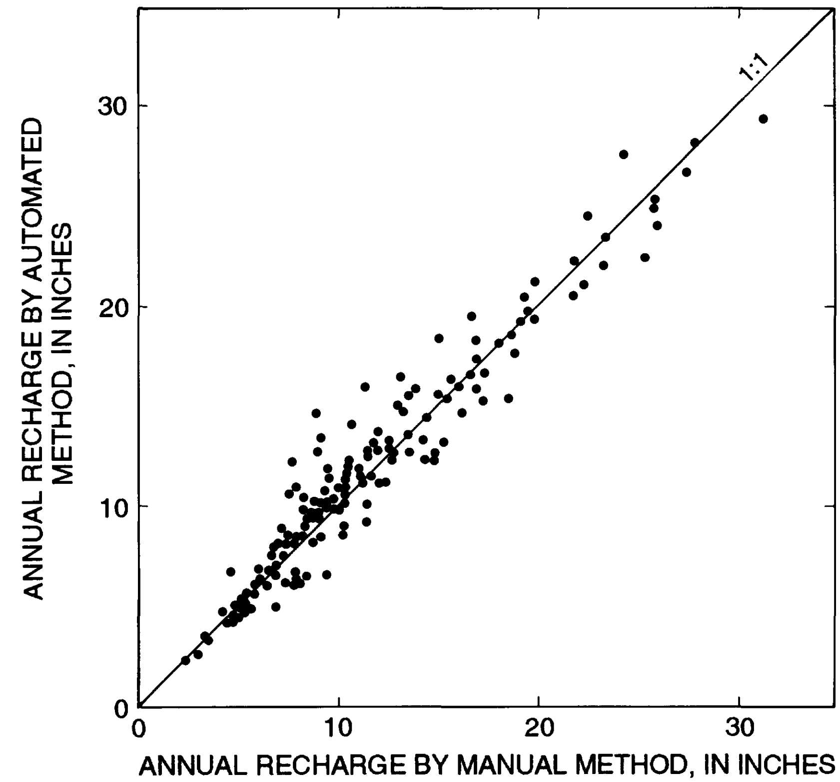


Figure 9. Relation between annual recharge estimated by program RORA and by the manual method for each year analyzed for each station. (See table 1.)

The distribution of P for the 156 samples is summarized below:

Percentile	P
90th	20.9
75th	12.3
50th	4.5
25th	-3.9
10th	-10.8

Sensitivity to Variations in Recession Index

Whether the recession-curve-displacement method is executed by manual or computerized techniques, it is preceded by the assignment of a value to the recession index. It is therefore reasonable to test the sensitivity of the result (the estimate of recharge) to the variation in the recession index. For this purpose, the recession index for each of the 15 stations described above was changed to a value that is 0.75 times, then 1.25 times the value shown in table 1. The resulting variation in the estimate of the recharge rate calculated by program RORA is shown in figure 10. This sensitivity test shows that changing the recession index by 25 percent causes a maximum variation in recharge of only 6 percent (for one station), whereas most estimates of recharge change by less than 3 percent.

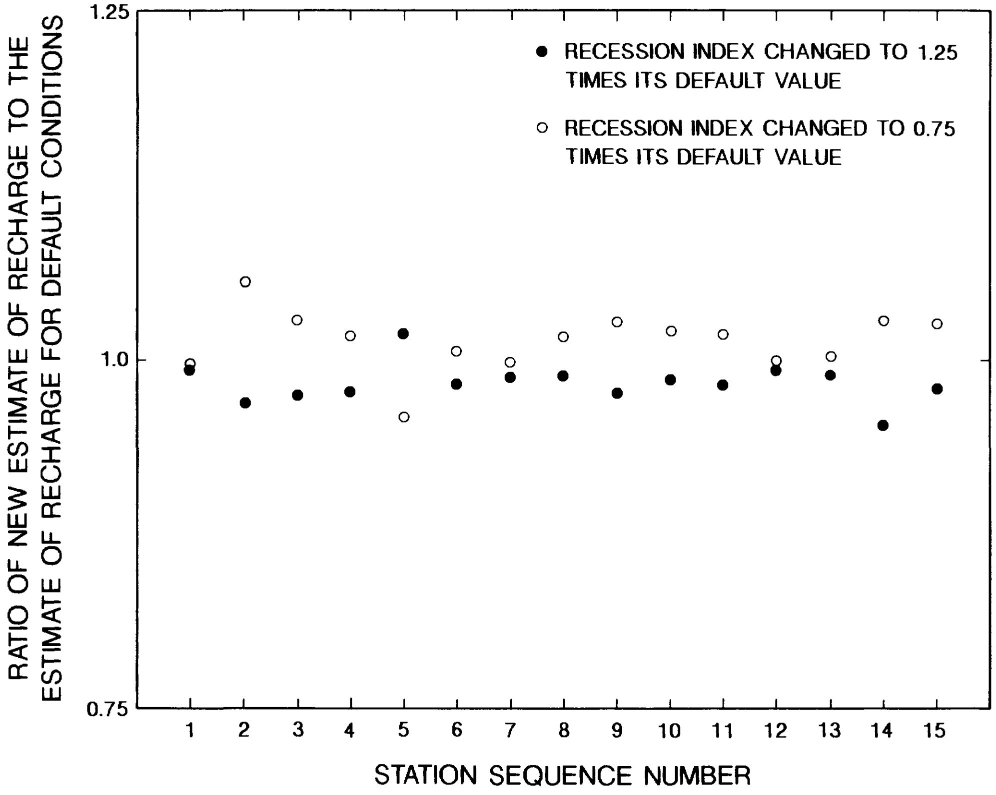


Figure 10. Change in the estimate of recharge from program RORA that results from changing the recession index to 0.75 times and 1.25 times its default value. (The default recession index for each station is in table 1. All calculations are based upon the time period analyzed for each station.)

COMPUTER PROGRAM FOR ESTIMATING MEAN GROUND-WATER DISCHARGE

The method of base-flow-record estimation is a relatively arbitrary procedure of estimating a continuous record of ground-water discharge, or base flow, under the streamflow hydrograph. If the streamflow record is incremental (such as daily) instead of continuous, estimates of ground-water discharge can be made on an incremental basis. The method should, in most cases, be applied over a long period of record (a year or more) to obtain an accurate estimate of the mean ground-water discharge. When the period of analysis is long enough that the effect on the water balance of changes in storage can be considered negligible, the mean ground-water discharge can be considered the effective recharge. The effective recharge should be less than total recharge by an amount equal to riparian evapotranspiration. Base-flow-record estimation should only be used if the conditions described in "Applicability of Methods" are met.

Method Development

Many different techniques, most of which involve considerable subjectivity in their application, have been used to estimate a record of ground-water discharge under the streamflow hydrograph. Horton (1933) described a method of shifting a "normal depletion-curve" horizontally across a hydrograph--noting that segments of the hydrograph that coincide with this curve represent periods during which streamflow is equal to ground-water discharge--then estimating ground-water discharge during periods of surface runoff by simply connecting the points where the hydrograph departs from the normal depletion curve. Barnes (1939) separated surface flow, storm seepage, and base flow by assigning a distinct "depletion factor" to each. Kulandaiswamy and Seetharaman (1969) pointed out that Barnes' method may not be reliable for separating streamflow into three parts but that the hydrograph can be separated into direct runoff and base flow. In some applications, investigators have used characteristic curves of ground-water discharge in combination with records of precipitation, snowfall, temperature, and ground-water levels (Olmsted and Hely, 1962).

In many cases, the method can be described as two steps: (1) locating periods of negligible surface runoff and designating that ground-water discharge equals streamflow, and (2) interpolating ground-water discharge between these periods. The decision that surface runoff is negligible can be based on antecedent recession. Linsley and others (1982) used the empirical relation of equation 1. For a given day, the antecedent recession requirement is met if recession has been continuous for N days or more preceding the day. Other investigators use linearity of recession, on the graph of logarithm of streamflow as a function of time, as the indicator that ground-water discharge equals streamflow (Ineson and Downing, 1964). There are many methods for executing step 2 (Snyder, 1939; Chow, 1964; Pettyjohn and Henning, 1979; and Nathan and McMahon, 1990): some are based on the assumption that the ground-water-discharge peak is concurrent with the streamflow peak, and others are based on the assumption that the recession of ground-water discharge continues after the time when surface runoff begins; that is, the response of ground-water discharge is delayed relative to surface runoff. Some methods involve simple linear interpolation to estimate ground-water discharge between the start and the end of surface runoff.

Computer techniques have been used for base-flow-record estimation and have allowed for increased speed of analysis and repeatability of results. Hewlett and Hibbert (1967) used a computer program for separating "quick flow" from "delayed flow" in streams of the eastern United States. Pettyjohn and Henning (1979) and Sloto (1991) used a method that involves searching for the minimum streamflow along an interval of record that is 2N days in duration and then assigning values of daily base flow by three different techniques (N is defined in equation 1). A method developed by the Institute of Hydrology (1980) includes searching for the minimum streamflow along 5-day, nonoverlapping periods, searching the series of minimums for values that are less than 0.9 times the two outer values, and defining such values as turning points. The base-flow hydrograph is constructed by connecting all the turning points. This method and a digital filter method used in signal analysis (Lyne and Hollick, 1979) are discussed by Nathan and McMahon (1990). A method called streamflow partitioning (Knisel and Sheridan, 1983; Shirmohammadi and others, 1984; Shirmohammadi and others, 1987) requires daily records of streamflow and precipitation and the designation of a threshold daily precipitation. For a given day, base flow equals streamflow if, on that day and all days that precede it by N days or less, precipitation is less than the threshold value. Base flow on all other days is estimated by linear interpolation.

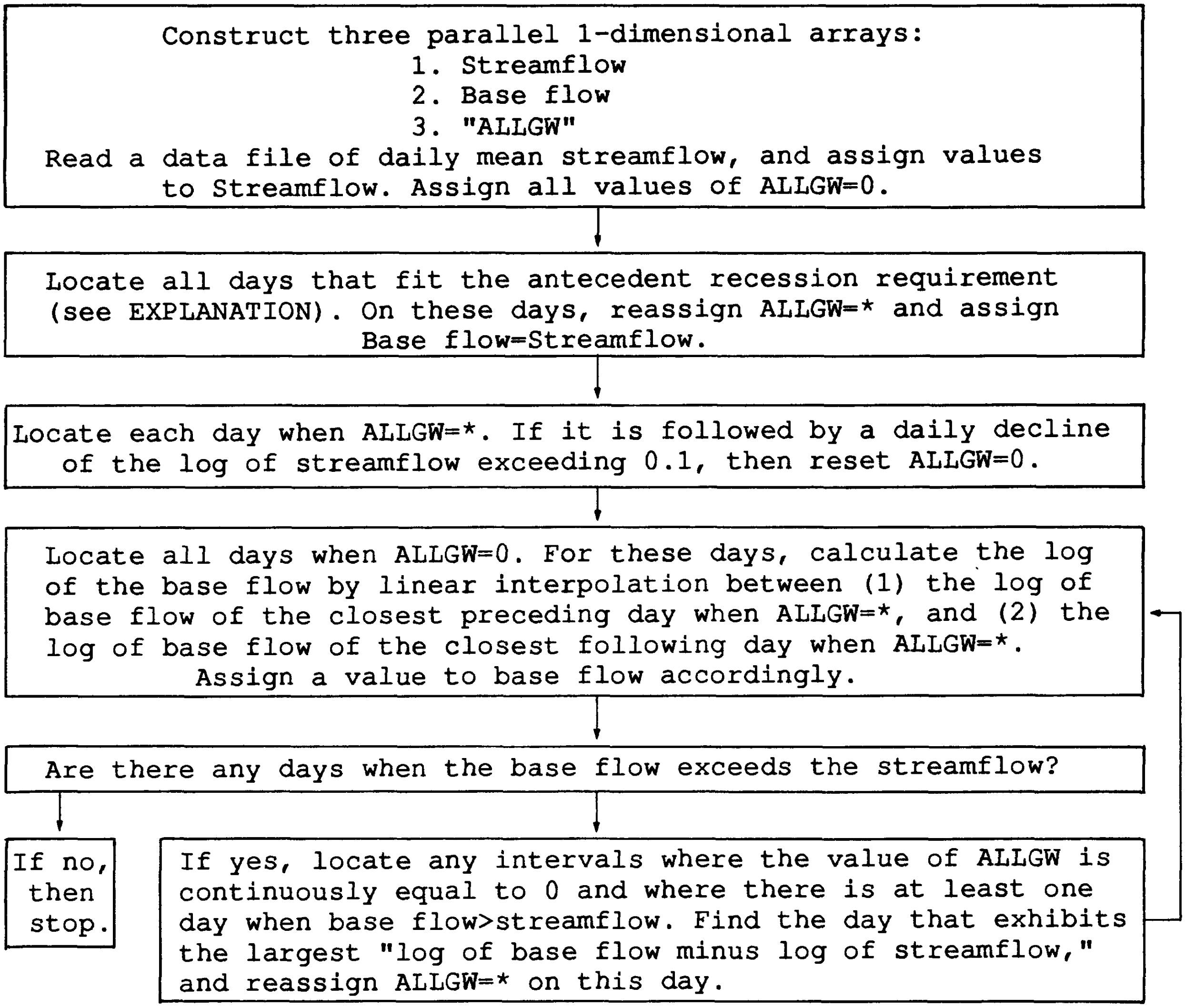
Program PART

The method of base-flow-record estimation that is described here is a form of streamflow partitioning that is similar to that of other investigators (Knisel and Sheridan, 1983; Shirmohammadi and others, 1984; Shirmohammadi and others, 1987) in that (1) daily values of streamflow are used and (2) linear interpolation is used to estimate ground-water discharge during periods of surface runoff. It differs in the method of designating days when ground-water discharge equals streamflow. Although previous methods are based on antecedent precipitation, this method, which was first described by Rutledge (1992), is based on antecedent streamflow recession.

The Algorithm

A flow diagram of the steps executed by program PART is shown in figure 11. The program fills a one-dimensional array of daily mean streamflow data then searches this array for days that fit an antecedent recession requirement. On each of these days, ground-water discharge is designated equal to stream-flow as long as it is not followed by a daily decline of more than 0.1 log cycle. It can be inferred from Barnes (1939) that a daily decline more than 0.1 log cycle could indicate interflow (stormflow) or surface flow. The program searches the array again, determining by linear interpolation the ground-water discharge on the remaining days. For some streamflow records, this interpolation can cause the calculated ground-water discharge to exceed streamflow for a few days in the record. The last step of the procedure corrects for this.

The entire procedure is executed three times: once considering the time base of surface runoff to be the largest integer that is less than the result of equation 1, and once for each of the next two larger integers. The program constructs a second-order polynomial expression for ground-water discharge as a function of time base of surface runoff, using the three data pairs of ground-water discharge and time base of surface runoff. Then the program calculates the ground-water discharge for the exact result of equation 1 using the polynomial expression.



EXPLANATION

The antecedent recession requirement is met for the day in question if, for the part of the daily mean streamflow record that includes all days that precede the day in question by N days or less, the streamflow on each of these days is greater than or equal to the streamflow on the day that follows it. (N= time base of surface runoff.)

The entire procedure is executed for three values of N: one is the next integer smaller then the result of equation 1, and the other two are the next two integers that are larger than the result of equation 1. Curvilinear interpolation gives the final estimate of base flow that corresponds to the precise result of equation 1.

Figure 11. Flow diagram showing the procedure of streamflow partitioning. (Base flow is considered to be ground-water discharge.)

Program Execution

Before the program is executed, one line must exist in file GAGING and one daily-values z-file must be prepared for each gaging station of interest. Because program PART should be used to analyze periods of continuous record only, the user may execute program STREAM to locate such time periods (see "Preparation of Data Files"). File OUTPART, which is an output file for the program, also must exist (see "Overview of Programs and Files").

When the program is executed, it will ask for the name of the daily-values file of interest. The user should enter the name of the original data file that was obtained from the data base (the file name without the "z" at the beginning). The program actually reads the z-file. Next, the program will find the single-line entry in file GAGING that represents the station of interest and obtain the drainage area. The program will then ask if the user chooses to keep the default value for the threshold for daily decline in the log of streamflow, which is 0.1 log cycle per day. The user is given the option of modifying this value for testing only and should consider the default value to be required for yielding the most accurate estimate of ground-water discharge.

When the program requests the time period of interest, the user should enter the beginning and the ending calendar years as four-digit integers. The user can then choose to finish the analysis, causing the program to complete all calculations and write results to the monitor and to output files (next section). Alternatively, the user can screen the daily results or write additional output before terminating the program and writing results. If this option is picked, the program will create a tabular display on the monitor of the first 16 days of the period of interest and will display options for user selection (shown below). At any given time during this data-display mode, the program shows the daily record of estimated base flow (ground-water discharge) that represents one of the three time bases of surface runoff.

Options are as follows:

- g Generate a graphical representation of streamflow and base flow where time is in the vertical (proceeding downward) and the flow is shown on a horizontal logarithmic scale.
- g1 Same as g except flow is on a linear scale.
- sc Change extremes for the graphical representation of the data (the minimum and maximum).
- t Generate a tabular display of streamflow and base flow
- n Move to the next 16-day period.
- b Move back to the last 16-day period.
- n1 Advance by 1 day.
- b1 Move back by 1 day.
- c Move to the beginning of a year to be specified.
- y Write daily tabulation of streamflow and base flow, for one or more years, to output file OUTP2.
- tb Allow the user to change the time base of surface runoff that is represented by the base-flow record displayed by any of the options above.
- e Exit the screening process, complete all calculations, write results to output file OUTPART, and terminate.

When the program completes all calculations, the coefficients of the equation for ground-water discharge as a function of time base of surface runoff are displayed to the monitor, along with the final calculation of ground-water discharge.

Output Files

Results of program PART are written to two output files:

OUTPART One new line is written to the bottom of file OUTPART each time the program is executed, giving a summary of the results. Included are the name of the daily-values file, the gaging-station number, the time period analyzed, the result of equation 1 (the time base of surface runoff that is solved for), the first of three integers representing the time bases that are used in calculations, the mean streamflow, the mean base flow (ground-water discharge), and the mean base-flow index (ratio of mean base flow to mean streamflow)

OUTP2 If the user specified the y option during the data-screening mode, file OUTP2 is created. A daily streamflow and base flow is written to each line in file OUTP2 for the period specified in the y option. The file can be used to generate hydrographs (fig. 12). The user should be aware that only one of three time bases is displayed at a time, so tabulations in file OUTP2 should not be used quantitatively. File OUTP2 is overwritten when the program is executed and the y option is invoked.

The hydrographs of figure 12 demonstrate why the results of base-flow-record estimation should only be applied at a large time scale. Base flow is shown to increase or decrease gradually from the beginning to the end of the period of surface runoff. Results of chemical analysis of stream water during peak discharge indicate that the record of base flow may increase and decline during the event in a manner that roughly mimics the peak in streamflow (Pinder and Jones, 1969). Analysis of changes in water levels in wells near a streamflow gaging station showed that the base flow record may actually decrease during the event because of the effects of bank storage (Daniel and others, 1970). Such variation in findings may be related to the specific method employed. As is the case for any method of base-flow-record estimation, the user should exercise caution when using the results of program PART at a small (daily) time scale, especially during periods of surface-water runoff. The suggested time scale for interpreting and reporting results of program PART is at least one year.

Comparison of Results of Manual and Computerized Methods

Program PART can be tested by comparison with published results of the manual execution of the base-flow-record estimation method. Results obtained (table 2) compare reasonably well. The result of the computerized method departs from that of the manual method by less than 10 percent, for 75 percent of the pairs of base-flow estimates.

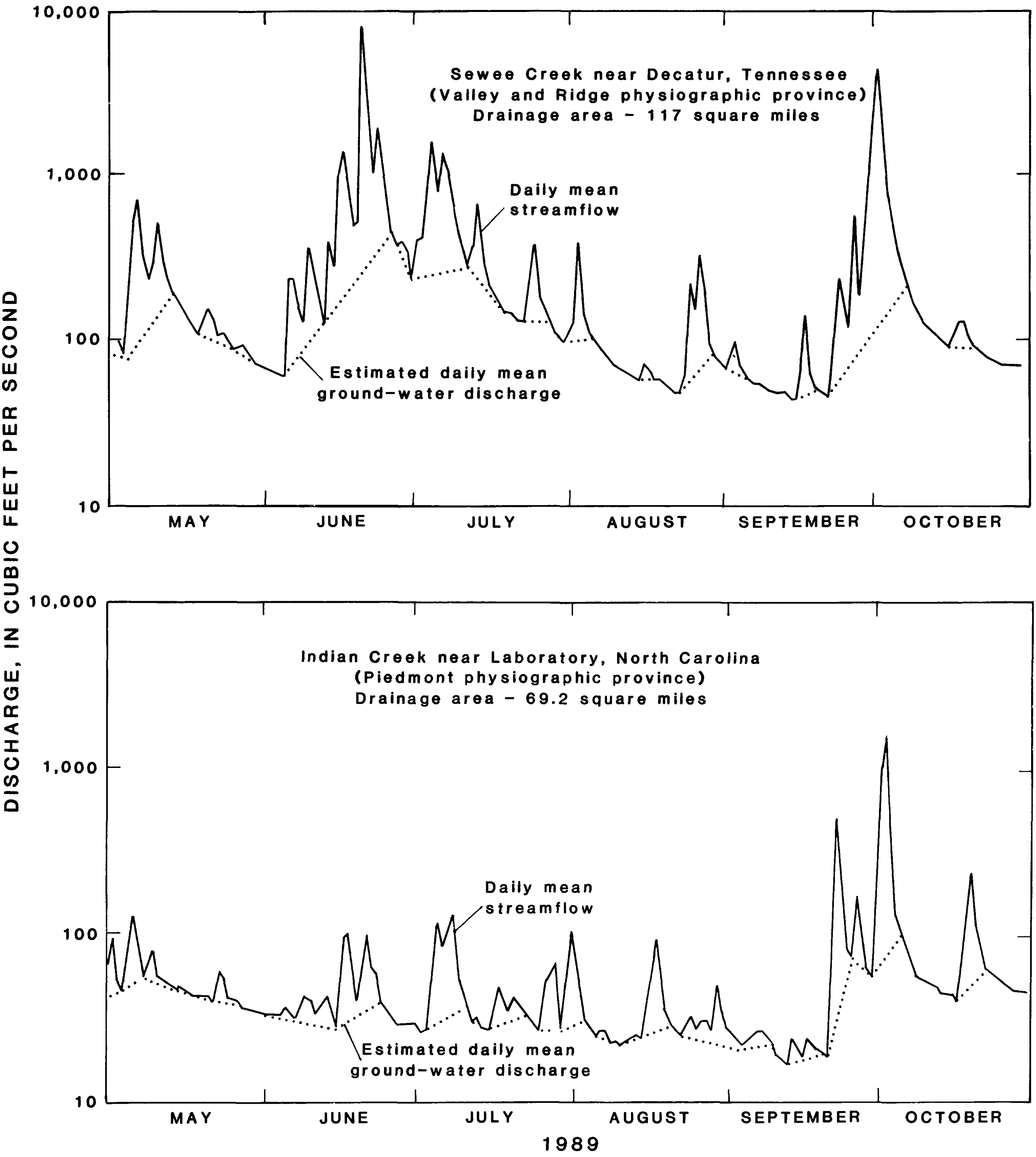


Figure 12. Hydrograph showing the results of streamflow partitioning. Where the curves coincide, ground-water discharge equals streamflow. For both hydrographs, the time base of surface runoff is 3 days.

Table 2. Published results of base-flow record estimation and results from program PART

Program PART uses calendar years only, except for comparison with publication 9, for which the data-input file was customized. Publications 1 and 8 used water years. All cited publications used base-flow record estimation for the entire period indicated, except publication 10 (in which the long-term mean base flow was estimated as the mean of base flow during a wet year and a dry year) and publication 2 (in which the long-term mean base flow was estimated as the mean of three separate years: one with above normal, one with normal, one with below normal precipitation). In publication 6, the drainage area is 103 square miles, but 107 square miles was used here.

Publication (number, authors, and year)	Station	Time period	Result from publication [1]	Result from PART [1]
1. Becher and Root, 1981	Conodoguinet Creek near Hogestown, Pa.	1968-74	13.0 66	12.9 65.6
	Yellow Breeches Creek near Camp Hill, Pa.	1968-74	16.8 80	16.9 80.4
2. Carswell and Lloyd, 1979	Brodhead Creek near Minisink Hill, Pa.	1963, 1969, and 1973	19.6 66	20.8 70
3. Dingman and Meyer, 1954	Rock Creek at Sherrill Dr., Md.	1933-49	8.5 67	8.4 66
4. Dingman and Ferguson, 1956	Little Gunpowder Falls near Laurel Brook, Md.	1927-49	11.3 66	12.3 71
5. Olmsted and Hely, 1962	Brandywine Creek at Chadds Ford, Pa.	1928-31	11.2 67.8	11.6 70.3
6. Stewart and others, 1964	Etowah River near Dawsonville, Ga.	1956	20.3 75	20.6 80.6
7. Stuart and others, 1967	Swatara Creek above Harper Tavern, Pa.	1919-60	11.3 49	14.3 62
8. Taylor and others, 1983	Spring Creek near Axemann, Pa.	1961-80	12.7 89	12.7 89
9. Waller, 1976	Roanoke River at Roanoke, Va.	April 1969 to March 1970	5.2 67	5.7 73
10. Wood, 1980	West Conewago Creek at Manchester, Pa.	1931-76	6.0 38.5	7.4 46.9

[1] The mean ground-water discharge (base flow) is expressed in two ways: top number is base flow in inches per year; bottom number is base-flow index, which is the ratio of mean base flow to mean streamflow, expressed in percent.

COMPARISON OF ESTIMATES OF RECHARGE AND DISCHARGE

In the preceding sections, results of the computerized methods used to estimate ground-water recharge and discharge compared reasonably with the corresponding manual methods. Further validation of the computerized methods can be achieved by direct comparison between results of programs PART and RORA. For this purpose, the mean rate of ground-water recharge and discharge at 166 streamflow-gaging stations was determined for the period 1981-90. All stations are within the APRASA study area. Results show a close correlation between recharge and discharge (fig. 13).

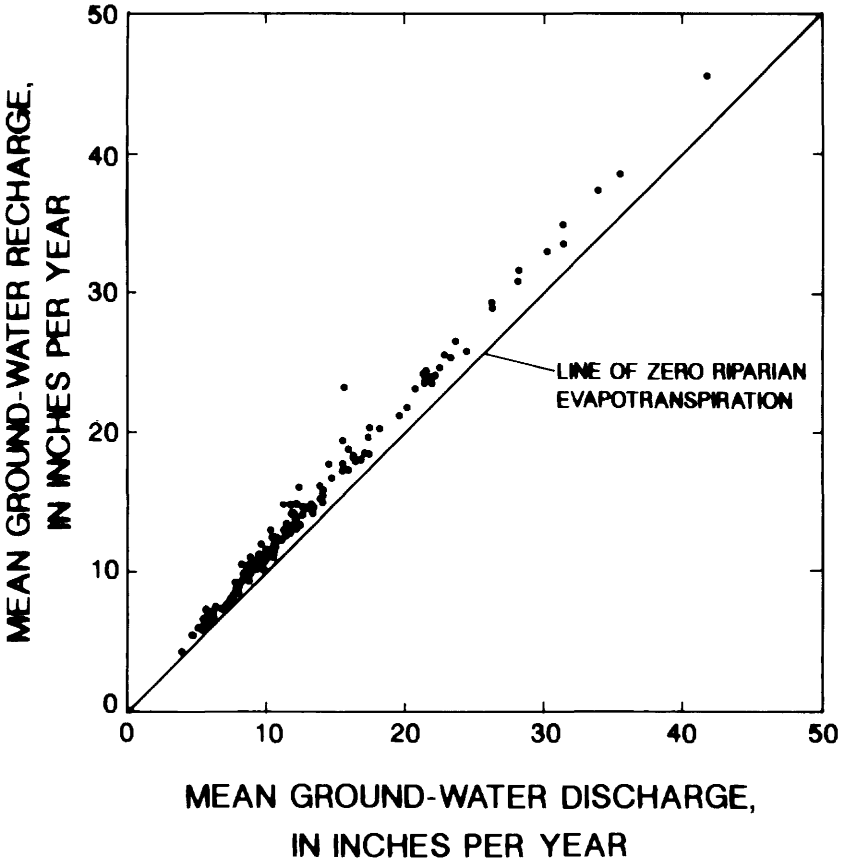


Figure 13. Relation between the mean ground-water recharge estimated by program RORA and the mean ground-water discharge estimated by program PART. (Each point represents one of the 166 streamflow stations in the Appalachian Valley and Ridge, Blue Ridge, and Piedmont physiographic provinces of the eastern United States, for the period 1981-90. Regulation and diversion of flow at all stations is negligible, and records are classified as "good" in U.S. Geological Survey data books.)

If ground-water withdrawals are negligible, the difference between mean rate of ground-water recharge and discharge is riparian evapotranspiration--the loss of water from stream channels and the saturated zone near stream channels to the atmosphere. On the basis of these results, the distribution of riparian evapotranspiration can be described as having a 25th percentile of approximately 1 inch per year and a 75th percentile of approximately 2 inches per year. Because the estimate of this variable (riparian evapotranspiration) is calculated as a small margin between two variables that are approximately an order of magnitude larger, the error in the estimate is considerable. These estimates of riparian evapotranspiration may not be representative of all hydrologic environments.

SUMMARY

The computer programs included here develop a mathematical expression for recession of ground-water discharge and estimate mean ground-water recharge and discharge. Because the programs read data files of daily mean streamflow, instructions are included for the assembly of data files from USGS records or from other sources before program execution. Use of the programs does not require separate computer software (other than the software that is required to compile, load, and execute Fortran-77 computer programs), but some output files can be read by separate graphics software for illustrating results.

The programs are intended for analysis of the streamflow record of a basin where one can reasonably assume that all, or nearly all ground-water discharges to the stream except for what is lost to riparian evapotranspiration, and where regulation and diversion of flow can be considered negligible. The methods for estimation of recharge or discharge are intended for the analysis of a flow system that is driven by areally diffuse recharge events that can be considered roughly concurrent with peaks in streamflow.

Program RECESS determines the master recession curve (MRC) of streamflow recession during times when all flow can be considered to be ground-water discharge and when the profile of the ground-water head distribution is nearly stable. The method uses a repetitive interactive procedure for selecting several periods of continuous recession, determines a best-fit equation for the rate of recession as a function of the logarithm of flow, and then uses the coefficients of this equation to derive the MRC, an equation of time as a function of the logarithm of flow. The method thus allows for the possibility of nonlinearity in the relation between time and the logarithm of flow. Output files generated by RECESS and by an auxiliary program can be read by separate graphics software for illustrating the MRC.

Program RORA uses the recession-curve-displacement method to estimate the recharge for each peak in the streamflow record. The procedure, also called the Rorabaugh Method, is based on the measurement of the change in the total potential ground-water discharge as estimated at critical time after the event by extrapolation from the pre-peak and the post-peak recession periods. The method is applied to a large period of record and gives an estimate of the mean rate of ground-water recharge. Results of RORA compare reasonably well with the results of manual execution of the recession-curve-displacement method that were obtained for 15 streamflow-gaging stations in the eastern United States. Sensitivity analysis indicates that the results of program RORA are not very sensitive to changes in the recession index.

Program PART uses streamflow partitioning to estimate a daily record of ground-water discharge under the streamflow record. The program scans the record for days that fit a requirement of antecedent recession, designates base flow to be equal to streamflow on these days, then linearly interpolates the daily record of base flow for days that do not fit the requirement of antecedent recession. The program is applied to a large period of record to give an estimate of the mean rate of ground-water discharge, or effective recharge. Results of PART compare reasonably well with published results of the manual execution of base-flow-record estimation in the eastern United States.

A test of the programs for 166 streamflow-gaging stations in the eastern United States shows that the result of program RORA (ground-water recharge) correlates well with the result of program PART (ground-water discharge). Recharge exceeds discharge by a small margin that can be considered riparian evapotranspiration.

REFERENCES CITED

Anderson, M.G., and Burt, T.P., 1980, Interpretation of recession flow: Journal of Hydrology, v. 46, p. 89-101.

Barnes, B.S., 1939, The structure of discharge recession curves: Transactions of American Geophysical Union 20, p. 721-725.

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

Carswell, L.D., and Lloyd, O.B., 1979, Geology and groundwater resources of Monroe County, Pennsylvania: Pennsylvania Geological Survey, 4th Series, Water Resources Report 47, 61 p.

Chow, V.T., 1964, Handbook of applied hydrology: New York, McGraw-Hill, [variously paged].

Daniel, C.C., III, and Sharpless, N.B., 1983, Ground-water supply potential and procedures for well-site selection in the upper Cape Fear River Basin, North Carolina: North Carolina Department of Natural Resources and Community Development and U.S. Water Resources Council, 73 p.

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., Cable, L.W., and Wolf, R.J., 1970, Ground water-surface water relation during periods of overland flow, *in* Geological Survey Research 1970: U.S. Geological Survey Professional Paper 700-B, p. 219-223.

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

Dingman, R.J., and Meyer, Gerald, 1954, The ground-water resources, *in* The water resources of Howard and Montgomery Counties: Maryland Department of Geology, Mines, and Water Resources Bulletin 14, p. 1-139.

Dingman, R.J., and Ferguson, H.F., 1956, The ground-water resources of the Piedmont part, *in* The water resources of Baltimore and Harford Counties: Maryland Department of Geology, Mines, and Water Resources Bulletin 17, p. 1-128.

Evaldi, R.D., and Lewis, J.G., 1983, Base flow and ground water in Upper Sweetwater Valley, Tennessee: U.S. Geological Survey Water-Resources Investigations Report 83-4068, 30 p.

Faye, R.E., and Mayer, G.C., 1990, Ground-water flow and stream-aquifer relations in the northern coastal plain of Georgia and adjacent parts of Alabama and South Carolina: U.S. Geological Survey Water-Resources Investigations Report 88-4143, 83 p.

Gerhart, J.M. and Lazorchick, G.J., 1988, Evaluation of the ground-water resources of the lower Susquehanna River basin, Pennsylvania and Maryland: U.S. Geological Survey Water-Supply Paper 2284, 128 p.

Glover, R.E., 1964, Ground-water movement: U.S. Bureau of Reclamation Engineering Monograph Series, no. 31, p. 31-34.

Hewlett, J.D. and Hibbert, A.R., 1967, Factors affecting the response of small watersheds to precipitation in humid areas, *in* Sopper, W.E., and Lull, H.W., eds., International Symposium on Forest Hydrology: New York, Pergamon, p. 275-290.

Hoos, A.B., 1990, Recharge rates and aquifer hydraulic characteristics for selected drainage basins in middle and east Tennessee: U.S. Geological Survey Water-Resources Investigations Report 90-4015, 34 p.

Hornberger, G.M., Ebert, Janet, and Remson, Irwin, 1970, Numerical solution of the Boussinesq Equation for aquifer-stream interaction: Water Resources Research, v. 6, no. 2, p. 601-608.

Horton, R.E. 1933, The role of infiltration in the hydrologic cycle: Transactions of American Geophysical Union 14, p. 446-460.

Ibrahim, H.A. and Brutsaert, Wilfried, 1965, Inflow hydrographs from large unconfined aquifers: American Society of Civil Engineers, Journal of Irrigation and Drainage Division, v. 91, no. IR 2, p. 21-38.

Ineson, J. and Downing, R.A., 1964, The ground-water component of river discharge and its relationship to hydrogeology: Journal of the Institution of Water Engineers, v. 18, no. 7, p. 519-541.

Institute of Hydrology, 1980, Low flow studies: Wallingford, U.K., Institute of Hydrology, Research Report 1 [variously paged].

Knisel, W.G., and Sheridan, J.M., 1983, Procedure for characterizing hydrologic processes in the coastal plain of the southeastern United States, *in* Hydrology on Large Flatlands: UNESCO International Program on Hydrology, Buenos Aires, Argentina, April 1983, Proceedings, v. 1, p. 191-211.

Kulandaiswamy, V.C., and Seetharaman, S., 1969, A note on Barnes' method of hydrograph separation: Journal of Hydrology, v. 9, p. 222-229.

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

Lyne, V. and Hollick, M., 1979, Stochastic time-variable rainfall-runoff modelling, *in* Hydrology and Water Resources Symposium, Perth, Australia, September 10-12, 1979, Proceedings: Perth, Australia, National Committee on Hydrology and Water Resources of the Institution of Engineers, no. 79/10, p. 89-92.

Meyboom, P., 1961, Estimating ground-water recharge from stream hydrographs: Journal of Geophysical Research, v. 66, no. 4, p. 1,203-1,214.

Nathan, R.J., and McMahon, T.A., 1990, Evaluation of automated techniques for base flow and recession analysis: Water Resources Research, v. 26, no. 7, p. 1,465-1,473.

Nutbrown, D.A., and Downing, R.A., 1976, Normal-mode analysis of the structure of baseflow-recession curves: Journal of Hydrology, v. 30, p. 327-340.

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

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

Petras, Ivan, 1986, An approach to the mathematical expression of recession curves: Pretoria, South Africa, Hydrologic Research Institute, Water S.A., v. 12, no. 3, p. 145-150.

Pinder, G.F., and Jones, J.F., 1969, Determination of the ground-water component of peak discharge from the chemistry of total runoff: Water Resources Research, v. 5, no. 2, p. 438-445.

Riggs, H.C., 1964, The base-flow recession curve as an indicator of ground water: International Association of Scientific Hydrology, Publication 63, p. 352-363.

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., 1991, A new method for calculating a mathematical expression for streamflow recession, *in* Ritter, W.F., ed., Irrigation and Drainage: National Conference on Irrigation and Drainage, American Society of Civil Engineers, Irrigation and Drainage Division, Honolulu, Hawaii, 1991, Proceedings, p. 337-343.

Rutledge, A.T., 1992, Methods of using streamflow records for estimating total and effective recharge in the Appalachian Valley and Ridge, Piedmont, and Blue Ridge physiographic provinces, *in* Hotchkiss, W.R. and Johnson, A.I., eds., Regional aquifer systems of the United States, aquifers of the southern and eastern states: American Water Resources Association Monograph Series, no. 17, p. 59-73

Shirmohammadi, Adel, Knisel, W.G., and Sheridan, J.M., 1984, An approximate method for partitioning daily streamflow data: Journal of Hydrology, v. 74, p. 335-354.

Shirmohammadi, Adel, Sheridan, J.M., and Knisel, W.G., 1987, Regional application of an approximate streamflow partitioning method: Water Resources Bulletin, v. 23, no. 1, p. 103-111

Singh, K.P., 1969, Theoretical baseflow curves: American Society of Civil Engineers, Journal of Hydraulics, v. 95, no. HY 6, p. 2,029-2,048.

Singh, K.P. and Stall, J.B., 1971, Derivation of base flow recession curves and parameters: Water Resources Research, v. 7, no. 2, p. 292-303.

Sloto, R.A., 1991, A computer method for estimating ground-water contribution to streamflow using hydrograph-separation techniques, *in* Balthrop, B.H. and Terry, J.E., eds., U.S. Geological Survey National Computer Technology Meeting, Phoenix, Arizona., 1988, Proceedings: U.S. Geological Survey Water-Resources Investigations Report 90-4162, p. 101-110.

Snyder, F.F., 1939, A conception of runoff-phenomena: Transactions of American Geophysical Union 20: p. 725-738.

Stewart, J.W., Callahan, J.T., Carter, R.F., and others, 1964, Geologic and hydrologic investigation at the site of the Georgia Nuclear Laboratory, Dawson County, Georgia: U.S. Geological Survey Bulletin 1133-F, 90 p.

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

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 hydrogeology: U.S. Geological Survey Water-Resources Investigations Report 91-4066, 44 p.

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

Toebes, C., and Strang, D.D., 1964, On recession curves; 1, Recession equations: Journal of Hydrology (New Zealand), v. 3, no. 2, p. 2-14.

Trainer, F.W., and Watkins, F.W., 1974, Use of base-runoff recession curves to determine areal transmissivities in the upper Potomac River Basin: U.S. Geological Survey Journal of Research, v. 2, no. 1, p. 125-131.

Trainer, F.W., and Watkins, F.W., 1975, Geohydrologic reconnaissance of the upper Potomac River basin: U.S. Geological Survey Water Supply Paper 2035, 68 p.

Waller, J.O., 1976, Geohydrology of the upper Roanoke River basin, Virginia: Virginia State Water Control Board, Bureau of Water Control Management, Planning Bulletin 302, 148 p.

Werner, P.W., and Sundquist, K.J., 1951, On the groundwater recession curve for large water-sheds: International Association of Scientific Hydrology Publication 33, v. 2, p. 202-212.

Wilder, H.B., and Simmons, C.E., 1978, Program for evaluating stream quality in North Carolina: U.S. Geological Survey Circular 764, 16 p.

Wood, C.R., Flippo, H.N., Jr., Lescinsky, J.B., and Barker, J.L., 1972, Water resources of Lehigh County, Pennsylvania: Pennsylvania Geological Survey, 4th ser., Water Resources Report 31, 263 p.

Wood, C.R., 1980, Groundwater resources of the Gettysburg and Hammer Creek formations, southeastern Pensylvania: Pennsylvania Geological Survey, 4th ser., Water Resources Report 49, 87 p.