SWGW—A COMPUTER PROGRAM FOR ESTIMATING GROUND-WATER DISCHARGE TO A STREAM USING STREAMFLOW DATA

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CONVERSION FACTORS AND ABBREVIATIONS AND ACRONYMS

CONVERSION FACTORS

Multiply	*by*	*to obtain*
	Length	
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Area	
square mile (mi^2)	2.59	square kilometer
	Flow	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second

ABBREVIATIONS AND ACRONYMS

ACF	Apalachiacola-Chattahoochee-Flint
ACT	Alabama-Coosa-Tallapoosa
ADAPS	Automated Data Processing System, USGS internal
ASCII	American Standard Code Information Interchange
G2	A USGS-developed computer graphics application
QCCHEK	A subroutine of the computer program SWGW
RORA	A computer program (Rutledge, 1993) based on methods developed by Rorabaugh (1964)
SWGW	A computer program (this report) developed from RORA
TRANS	A computer program (Rutledge, 1993) used to format input data for the programs RORA and SWGW
UNIX	A computer operating system
USGS	U.S. Geological Survey

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ABSTRACT

The computer program SWGW automates the application of the recession-curve-displacement method for estimating ground-water discharge to streams (baseflow) from streamflow data. SWGW was developed from an existing U.S. Geological Survey computer program, RORA, and provides the user with four enhancements useful for the analysis of streamflow data. These enhancements (1) compute an adjustment factor to account for the apparent over-estimation of the recession curve by RORA; (2) produce data files for graphical output of hydrograph separation results; (3) incorporate two recession indices—one for the major rise period and one for the major recession period; and (4) consider streamflow data on a water-year basis. An adjustment factor is computed for each day following a streamflow peak that the computed recession discharge exceeds measured streamflow discharge. The adjustment factor equals the measured streamflow discharge divided by the computed recession discharge. For each peak, minimum adjustment factors are determined and are used to provide the user four choices for adjustment of the recession curve. The choices are (1) no adjustment (equivalent to RORA); (2) adjustment of the entire recession curve by the average of the minimum adjustment factors determined for each peak; (3) adjustment of the entire recession curve by the smallest of the minimum adjustment factors determined for each peak; or (4) adjustment of each segment of the recession curve by the minimum adjustment factor determined for the corresponding peak.

Computed results from RORA and SWGW are evaluated by comparing them to published estimates of baseflow derived manually using the recession-curve-displacement method. Differences between manually derived estimates and computed estimates from RORA and SWGW using different adjustment factors are computed for selected streams. A statistical analysis of the differences indicates that the closest comparison of the computed estimates from RORA and SWGW with the manually derived estimates is achieved by SWGW using two recession indices and an adjustment factor between the minimum and the average adjustment factors computed for each stream.

INTRODUCTION

Increasing and competing demands for water in the Apalachicola-Chattahoochee-Flint and the Alabama-Coosa-Tallapoosa (ACF-ACT) River basins (fig. 1) have created a need for evaluation of surface- and ground-water resources. In 1992, the Governors of Alabama, Florida, and Georgia and the Assistant Secretary of the Army for Civil Works signed a Memorandum of Agreement establishing a partnership to address interstate and intrastate water-resource issues, and promote coordinated system-wide management of water resources. These study partners subsequently requested the U.S. Geological Survey (USGS) to provide the ground-water-supply element of the Comprehensive Study of the ACF-ACT River basins (U.S. Army Corps of Engineers, 1991). This element addresses ground-water resources in each basin, particularly the ground-water contribution to major rivers. Based on hydrologic and physiographic boundaries, the two basins were further divided into eight subareas. Individual reports describing the ground-water resources of each of the subareas are planned by USGS staff in the Alabama and Georgia District Offices.

The surface- and ground-water resources of the ACF-ACT River basins are major components of a dynamic hydrologic system comprised of a network of aquifers, streams, reservoirs, control structures, floodplains, and estuaries. To manage this system effectively, hydrologic relations between the surface- and ground-water resources should be described and quantitatively evaluated. Streamflow hydrograph separation was identified as a useful methodology to estimate the ground-water contribution to streamflow. This contrbution is commonly termed *baseflow*. In this report, the term baseflow refers to ground-water discharge to a stream, which is the end result of the streamflow hydrograph separation procedures discussed.

Problem

One of the primary objectives of the ACF-ACT study is to determine ground-water discharge to streams (baseflow) under drought conditions. To support that objective, estimates of baseflow under average annual conditions are needed to provide a point of reference for the drought condition analysis. The FORTRAN computer program RORA (Rutledge, 1993) separates streamflow hydrographs using the recession-curve-displacement procedure developed by Rorabaugh (1964). Only by using a computer-automated, hydrograph separation procedure like RORA could average baseflows be determined for a large number of streams. However, RORA, when applied to hydrographs typical of streams in the ACF-ACT study area, does not always provide completely satisfactory results. In particular, estimates of baseflow computed by RORA commonly exceed corresponding published estimates determined by manual hydrograph separation (Faye and Mayer, 1990; Hoos, 1990). Differences range from about 4 to 200 percent. Also, inspection of numerous streamflow hydrographs from the ACF-ACT study area for various water years, plotted with the corresponding ground-water recession curves computed by RORA, reveals that the computed recession curves commonly exceed measured streamflow. Subsequently, RORA is used to compute recession curves over a wide range of streamflow conditions and locations within the ACF-ACT study area. Results from this evaluation are similar to comparisons made between manually derived and RORA computed estimates of baseflow, in that computed recession curves exceed streamflow for many locations, particularly during summer and early fall.

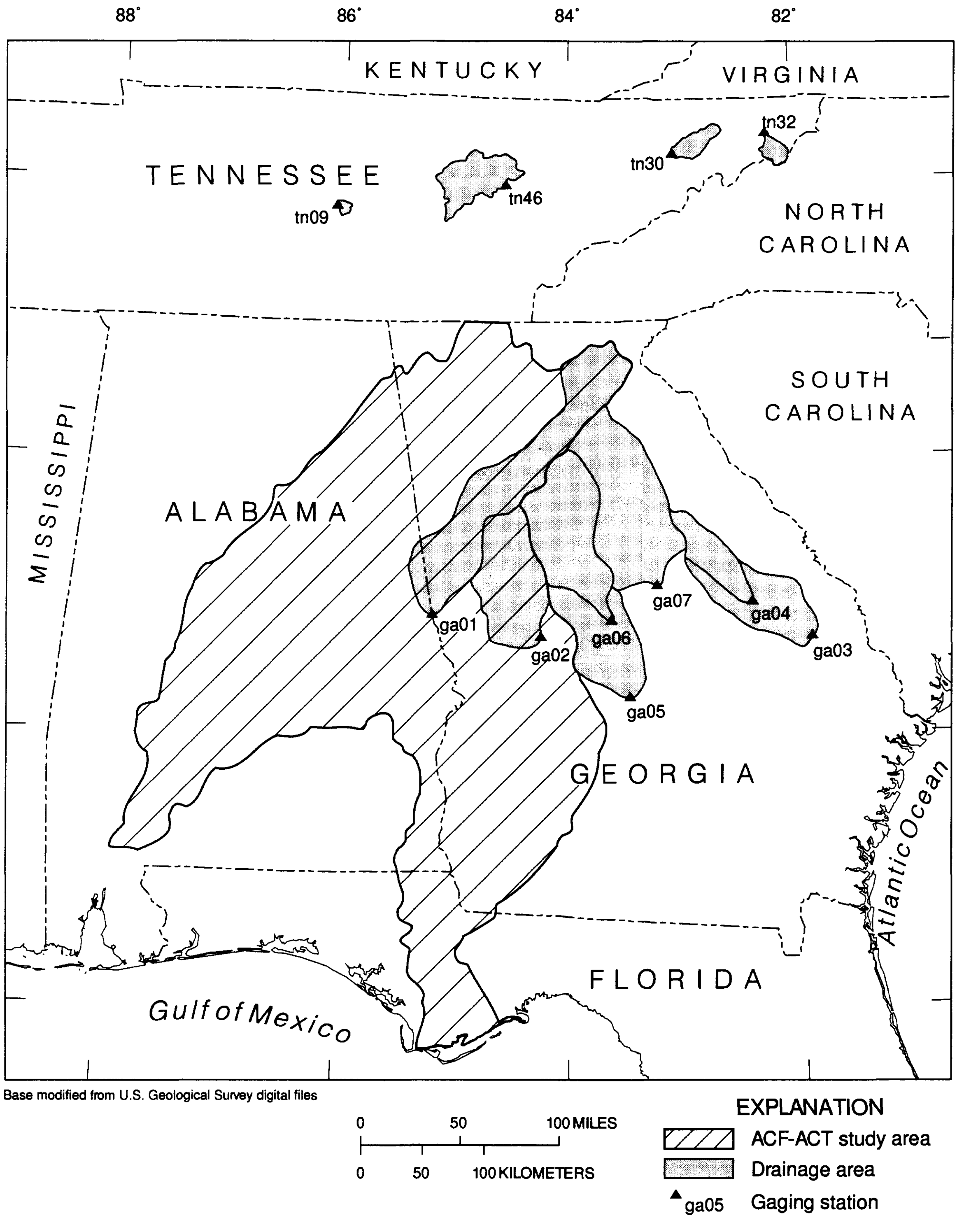

Figure 1. Location of streamflow gaging stations and respective drainage areas used in this report, and the Apalachicola-Chattahoochee-Flint and Alabama-Coosa-Tallapoosa River basins (ACF-ACT) study area.

Although RORA employs an automated procedure to determine the displacement of the recession curve for selected streamflow peaks, it does not provide graphical output for visual inspection and evaluation of the computed results. Such inspection is particularly critical for a gaging station on a stream that has widely varying flow characteristics, and for a regional investigation that includes compar-isons of hydrograph separations from several gaging stations. Consequently, plots of streamflow hydrographs and computed recession curves are considered essential to evaluate computed results for various streams and streamflow conditions.

In the southeastern United States, increased riparian evapotranspiration during summer and early fall ncreases the rate of streamflow recession. The effect of increased evapotranspiration can be accounted for in a recession-curve-displacement analysis by decreasing the value of the recession index, *K*. This index is inversely proportional to the slope of the recession curve; thus, a lower value of *K* corresponds to a greater slope of the recession curve, which would be expected during a period of high evapotranspiration. RORA allows specification of only a single, constant value of the recession index, which may not accurately represent conditions in the ACF-ACT study area during periods of riparian evapotranspiration. For the ACF-ACT study area, the ability to employ two recession indices, one for periods of lower riparian evapotranspiration and one for periods of higher riparian evapotranspiration, is considered necessary to appropriately apply the recession-curve-displacement procedure.

The ACF-ACT study requires water-year-period analyses. However, RORA determines a single, average annual value of baseflow for a user-defined, sequential, calendar-year period.

Purpose and Scope

This report describes modifications to the existing computer program RORA (Rutledge, 1993). RORA uses the recession-curve-displacement method originally described by Rorabaugh (1964) to estimate the recharge for each peak in a streamflow hydrograph record. RORA is modified to accommodate specific requirements of the ACF-ACT ground-water study. The resulting program, SWGW, is documented in this report. Several examples and comparisons of computed hydrograph separation results to published manual separations for streams within and near the ACF-ACT study area are provided to illustrate the application and utility of the modifications.

Hydrograph Separation

A streamflow hydrograph is a representation of the volumetric rate of streamflow, usually plotted on a logarithmic scale, at a specific stream location for a specified period of time. It can be regarded as an integrated expression of the physical characteristics that govern the relations among rainfall, infiltration, evapotranspiration, runoff, and ground-water discharge for a particular drainage area. The rate of streamflow generally depends upon factors such as the magnitude and duration of rainfall, the seasonal distribution of rainfall, the vegetative cover, the infiltration capacity of the soil, the topography of the basin, and the characteristics of the ground-water flow system of the basin.

The streamflow hydrograph typical of rivers in the southeastern Piedmont and Coastal Plain is characterized by a sequence of runoff events and evapotranspiration periods that subdivide the hydrograph into several distinct intervals (Faye and Mayer, 1990, fig. 2). During the initial part of a water year, generally October to December, stream discharge characteristically increases following the first substantial frost and the consequent reduction of evapotranspiration in late November or December. Throughout most of the winter and early spring, weather fronts producing rainfall cross the study area regularly and in relatively rapid succession. The runoff and aquifer recharge generated by these storms initially caused streamflow to increase rapidly and remain at a relatively high level through March or the early part of April. This period of recharge and relatively high streamflow is characteristically termed the *major rise period* (fig. 2). Following the cessation of winter rainfall and the onset of spring evapotranspiration, the streamflow normally undergoes a period of attenuated recession that periodically is interrupted by runoff generated by frequently intense, convective, summer rainstorms. A general recession in streamflow typically characterizes the hydrograph for most of the spring and summer months, and is termed the *major recession period* (fig. 2).

The objective of hydrograph separation usually is to estimate the quantity of ground water discharged from an aquifer or aquifer system to a stream. The range in scale of such investigations is large, from examinations of small site-specific watersheds (Daniel, 1976) to large regional studies (Faye and Mayer, 1990). Similarly, the scope of studies employing hydrograph separation is broad, ranging from investigations of precise physical processes to evaluations of regional water resources.

A major disadvantage of most hydrograph separation analyses is the lack of independent field measurements available for direct comparison of results. Consequently, the results of most hydrograph separation analyses are difficult to confirm and often are presented as estimates of unknown quality and confidence. hydrograph separation analyses are perhaps most useful when accompanied by results of independent analyses of baseflow, even if the other results also are estimates.

PROGRAM SWGW

The hydrograph separation program SWGW is a modified version of RORA (Rutledge, 1993) developed to meet the requirements of the ACF-ACT project. Modifications address the period of analysis, graphical output, evapotranspiration effects, and the apparent high estimation of baseflow. Results of automated hydrograph separation analyses using both RORA and SWGW are compared to published results of manual applications of the recession-curve-displacement method of Rorabaugh (1964) for several streams in the southeastern United States in and near the ACF-ACT study area. The discussion and descriptions of the results in this report are based on the assumption that the reader is familiar with the works of Rorabaugh (1964) and Rutledge (1993).

Design and Features

To calculate baseflow for an individual water year, the interactive routine in RORA that defines the time period of analysis is revised. Where RORA originally allows user specification of a beginning and an ending year, SWGW allows specification of a single water year. The beginning and ending years originally specified in RORA then are set to the two calendar years spanning the desired water year in SWGW, minimizing code revision. Performing the recession-curve-displacement analysis over this two-year period allows calculation of the recession curve at the beginning of the water year, generally before the first major hydrograph peak for the water year has occurred. To avoid problems caused by missing data, SWGW assumes a complete, daily data record for the specified two-year period. The analysis terminates if any data are missing for that period. An option also is added to SWGW to analyze data for additional water years from the same gaging station, thus avoiding repeated specification of input parameters.

For each execution of SWGW at a particular streamflow gaging station for a specified water year, SWGW creates two, uniquely named, data output files. One, ending with the suffix '.gra', contains data for graphical output, and the other, ending with the suffix '.out', contains tabulated data and results. The two output file names begin with an eight-digit prefix, 'ssssyyrr', that is defined as follows:

'ssss', a four-digit station identifier;

'yy', a two-digit water year; and

'rr', a two-digit run code.

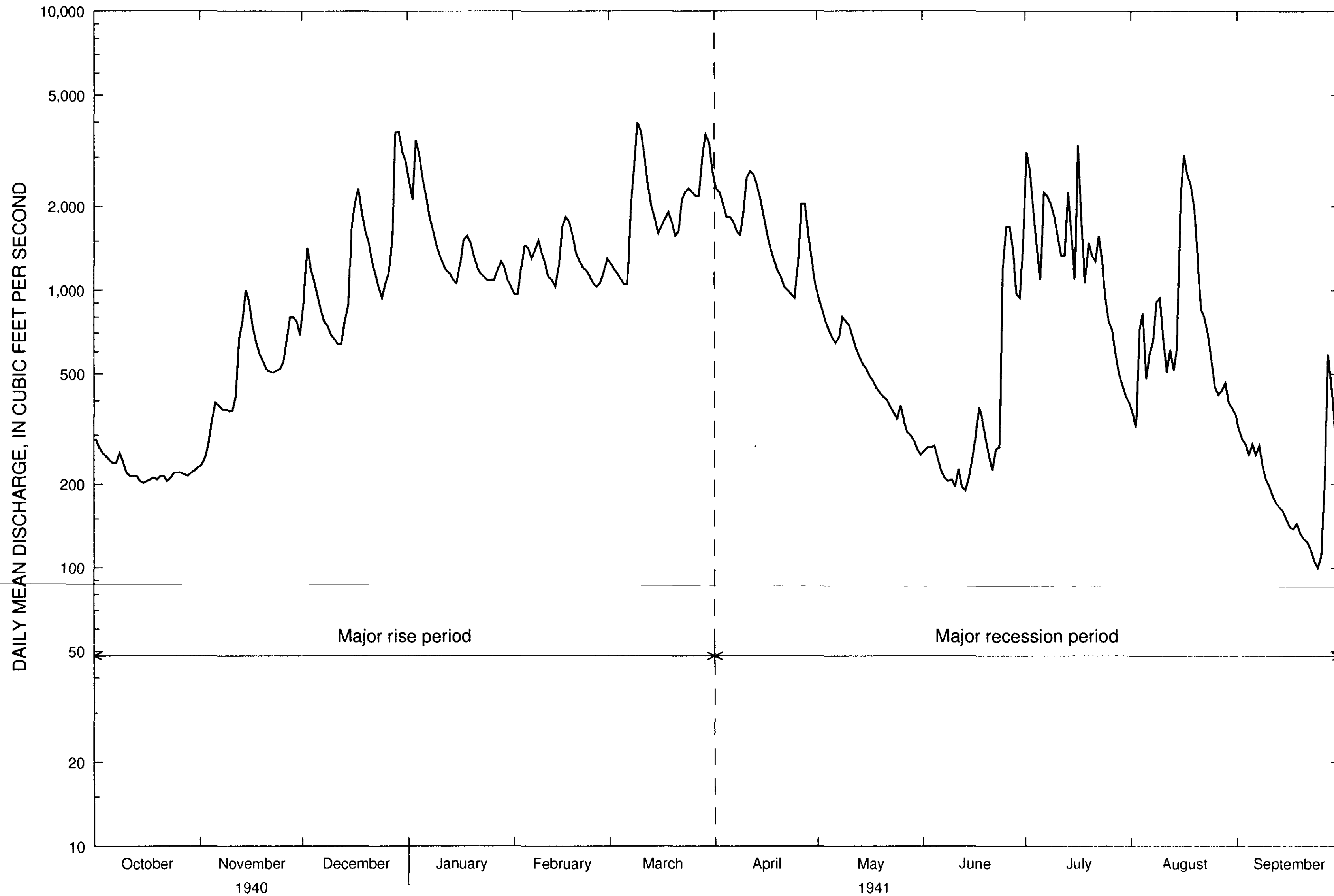

Figure 2. Streamflow hydrograph of the Flint River near Culloden, Georgia (station 02347500), for water year 1941, showing the major rise and the major recession periods.

The four-digit alphanumeric station identifier is defined by the user and also must be used to name the file of daily mean streamflow data from ADAPS (the Automated DAta Processing System for retrieving data from a USGS data base). RORA and SWGW do not use the daily values file directly from ADAPS; the program TRANS (Rutledge, 1993) must first be used to transform the streamflow data from ADAPS to the format used by RORA and SWGW. TRANS writes the transformed data to an input file used by RORA and SWGW, which has a five-digit name consisting of a 'z' and the four-digit station identifier. The station identifier also must be specified in another input file, 'gaging', which contains information on each streamflow gaging station. The water year and run code are specified interactively during execution of SWGW. Thus, for the station designated 'tn09', the input file containing the transformed data is 'ztn09; and for water year 1959, and the run specified as 'a1', the output file containing the graphical data is named 'tn0959a1.gra'.

The graphics package, G2, chosen for displaying results of RORA and SWGW, is an internal product of the USGS (James L. Fulton, U.S. Geological Survey, written commun., 1993). The data in the graphical output file created by SWGW are in standard comma-separated ASCII format, and can be easily adapted to other graphics packages. The graphical output file (ending with '.gra') consists of two title lines followed by columns of each of the three data types to be graphed—daily streamflow values, computed streamflow peaks, and endpoints of the computed streamflow recession curves. Plots of the separated hydrographs are produced by a UNIX script shell (called 'g2plot'), which creates an executable '.g2' program file from a template file by inserting the water year, the name of the '.gra' file, and the two titles. The UNIX script shell executes the G2 program, directing the output plot to a printer, and then deletes the '.g2' program file. The other output file (ending with '.out') is a modified version of the output file from RORA ('outror2'), and contains input parameters, variable definitions, tabulated results of the computations for each peak considered, and values of baseflow to the stream for the major rise period and the major recession period of the water year.

Another modification to RORA employed by SWGW is the specification of two recession indices, one for the summer evapotranspiration period (K_{et}), and another for the rest of the year (K_{mr}). After specification of the two recession indices, the user is prompted for the months corresponding to the beginning and end of the summer evapotranspiration period (usually April, and September or October, respectively, for the ACF-ACT study area). The appropriate recession index then is assigned by SWGW to each streamflow peak, depending on the month of its occurrence.

As noted previously, inspection of the graphical output for numerous water-year analyses from several streamflow gaging stations indicates that the recession-curve-displacement procedure employed by RORA often positions the computed ground-water recession curve above the streamflow hydrograph. Baseflow cannot be greater than the streamflow discharge and estimates of baseflow based on such an analysis would be unreasonable. A part of the RORA separated streamflow hydrograph for Big Hill Creek near Cherryvale, Kansas, is shown in figure 3. Several instances of the RORA computed ground-water recession curve (long dashed line) that exceed streamflow are evident. These data and separation results are presented to complement the descriptions of Rutledge (1993, fig. 6) and Bevans (1986, fig. 5).

QCCHEK, a subroutine written for SWGW, addresses the apparent over-estimation of baseflow by RORA. For each computed streamflow peak, QCCHEK compares each daily discharge of the computed recession curve, Q_r, to daily streamflow discharge, Q, for the period from the peak of interest to the critical time, $t_c = 0.2144 \times K$ (Rutledge, 1993) of the next peak (fig. 3). For the peak of interest in figure 3, Q_r exceeds Q on three days. An adjustment factor, $F=Q/Q_r$, is computed for each of these days. QCCHEK finds all occurrences of Q_r greater than Q and displays the date of the peak, the date of the

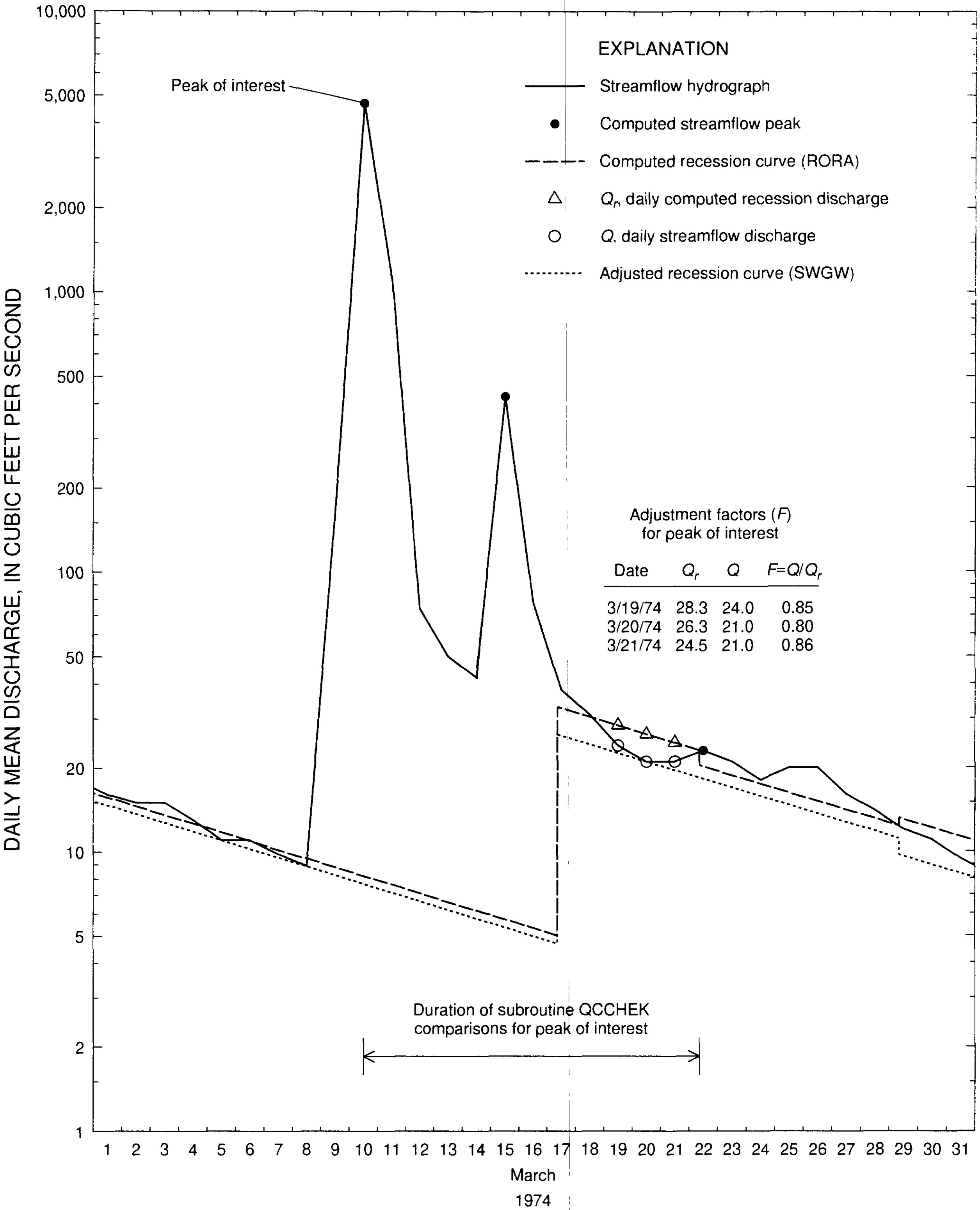

Figure 3. RORA hydrograph separation and SWGW adjusted recession based on streamflow data from Big Hill Creek near Cherryvale, Kansas (station 07170700), for March 1974.

occurrence, and the value of *F*. For the peak of interest, application of the smallest factor, *F*=0.80, repositions the recession curve (short dashed line) so that it does not exceed streamflow at any time during the QCCHEK period.

For each peak, QCCHEK selects the minimum *F* determined for that peak. After all peaks have been checked by QCCHEK, the average and smallest of the minimum *F*s determined for all peaks are displayed. The user then is given the option of: (1) making no adjustment at all (*F*=1.0, results equivalent to RORA results); (2) adjusting all recession curves by the average of the minimum *F*s; (3) adjusting all recession curves by the smallest of the minimum *F*s; (4) adjusting each segment of the recession curve by the minimum *F* computed for the corresponding peak; or (5) adjusting all recession curves by some other user-specified *F*. Option 4 is used for the adjusted recession curve in figure 3.

The ground-water recession curves from SWGW represent approximately the latter one-half of the total baseflow related to a particular recharge occurrence, the first half occurring prior to critical time (Rorabaugh, 1964; Glover, 1964). The graphical presentation of the SWGW recession curve also depicts approximately one-half of the total baseflow, and does not show baseflow that occurs between the peak of interest and critical time. The total volume of baseflow is determined by doubling the baseflow computed at the critical time of each peak (Rutledge, 1993, eqn. 7).

Results of automated streamflow hydrograph separation using the first four adjustment options of SWGW are shown in figures 4a and 4b. The streamflow data represent discharge at gaging stations on the Chattahoochee River at West Point, Georgia, for water-year 1952; and on the East Fork of Stones River at Woodbury, Tennessee, for water-year 1975. The drainage area of the station in Georgia is 3,550 square miles, and is in the Piedmont Province. The drainage area of the station in Tennessee is 39.1 square miles, and is in the Highland Rim Province. These two stations are selected to illustrate effects of different runoff characteristics and hydrograph separation results using SWGW adjustment options.

The four plots of each gaging station and water year in figures 4a and 4b differ by the options used to specify the adjustment of the ground-water recession curve. For the first plot, corresponding to option 1, no adjustment is made (*F*=1.0), and the computed recession curve (dashed line) is equivalent to results obtained using RORA, depicting occasional computed ground-water recession curve greater than streamflow discharge. The second plot shows results of option 2, which adjusts the entire ground-water recession curve downward by the average of the minimum factors computed for each peak in the two-calendar-year period. As shown in figures 4a and 4b, this option may produce results depicting occasional computed ground-water recession discharge greater than streamflow discharge, but the overages are smaller and less frequent than in option 1. The third plot of each station hydrograph depicts the use of the minimum adjustment factor determined for the two-year period (option 3). This option results in positioning the ground-water recession curve below streamflow throughout the entire period, and produces a relatively conservative baseflow estimate. Options 2 and 3 do not change the shape of the ground-water recession curve, but simply displace the original curve (*F*=1.0) downward uniformly throughout the analysis period. Results of option 4 are shown in the fourth plot of figures 4a and 4b. Using option 4, each individual segment of the ground-water recession curve, corresponding to each peak, is adjusted downward to less than streamflow if needed, based on the minimum *F* determined for that peak. Like option 3, option 4 results in positioning of the ground-water recession curve below streamflow throughout the entire period, but the resulting estimate of baseflow is less conservative than in option 3. Option 5 is not used for figures 4a and 4b.

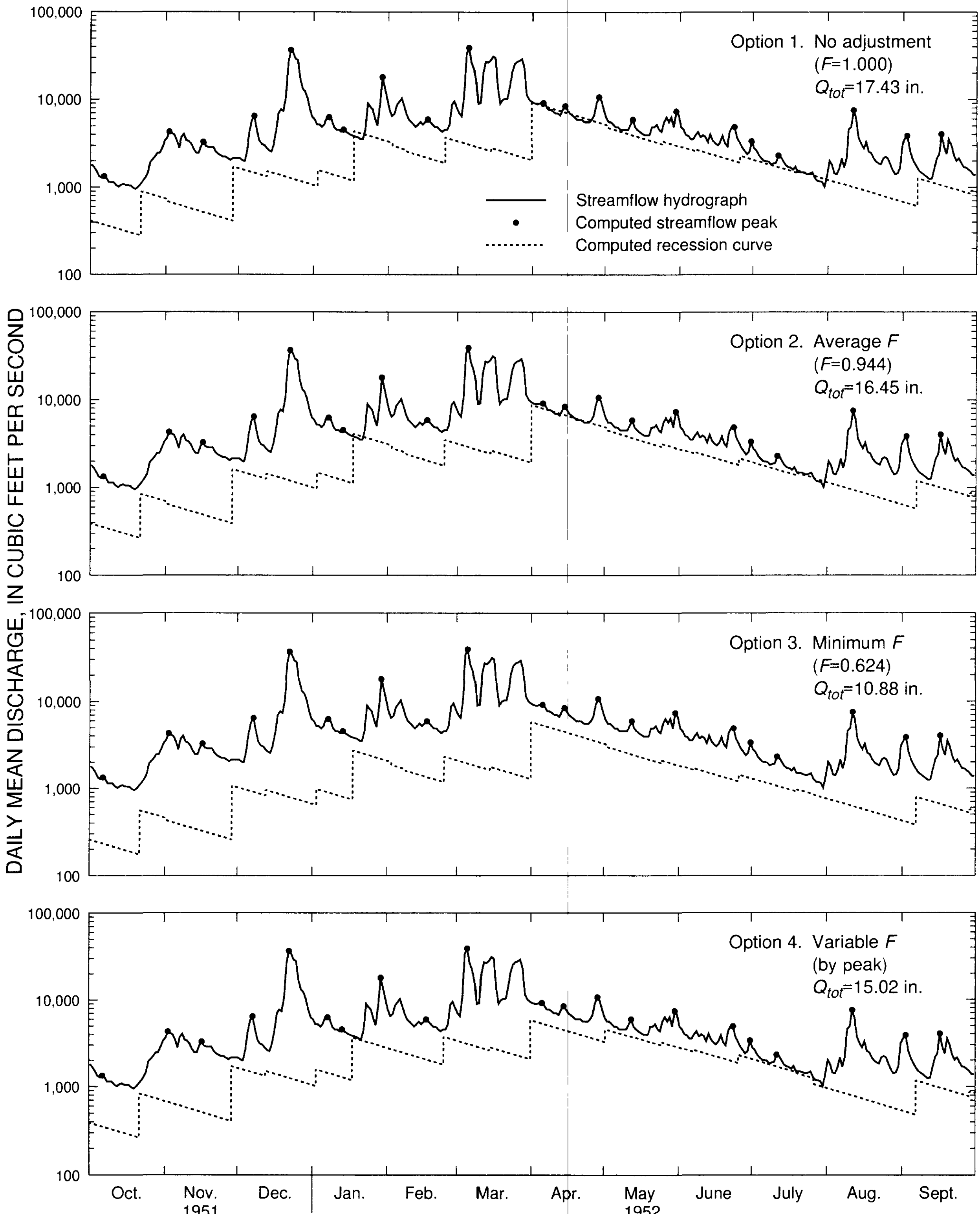

Figure 4a. Results of automated streamflow hydrograph separation using four adjustment options of SWGW, Chattahoochee River at West Point, Georgia (station 02339500), for water year 1952.

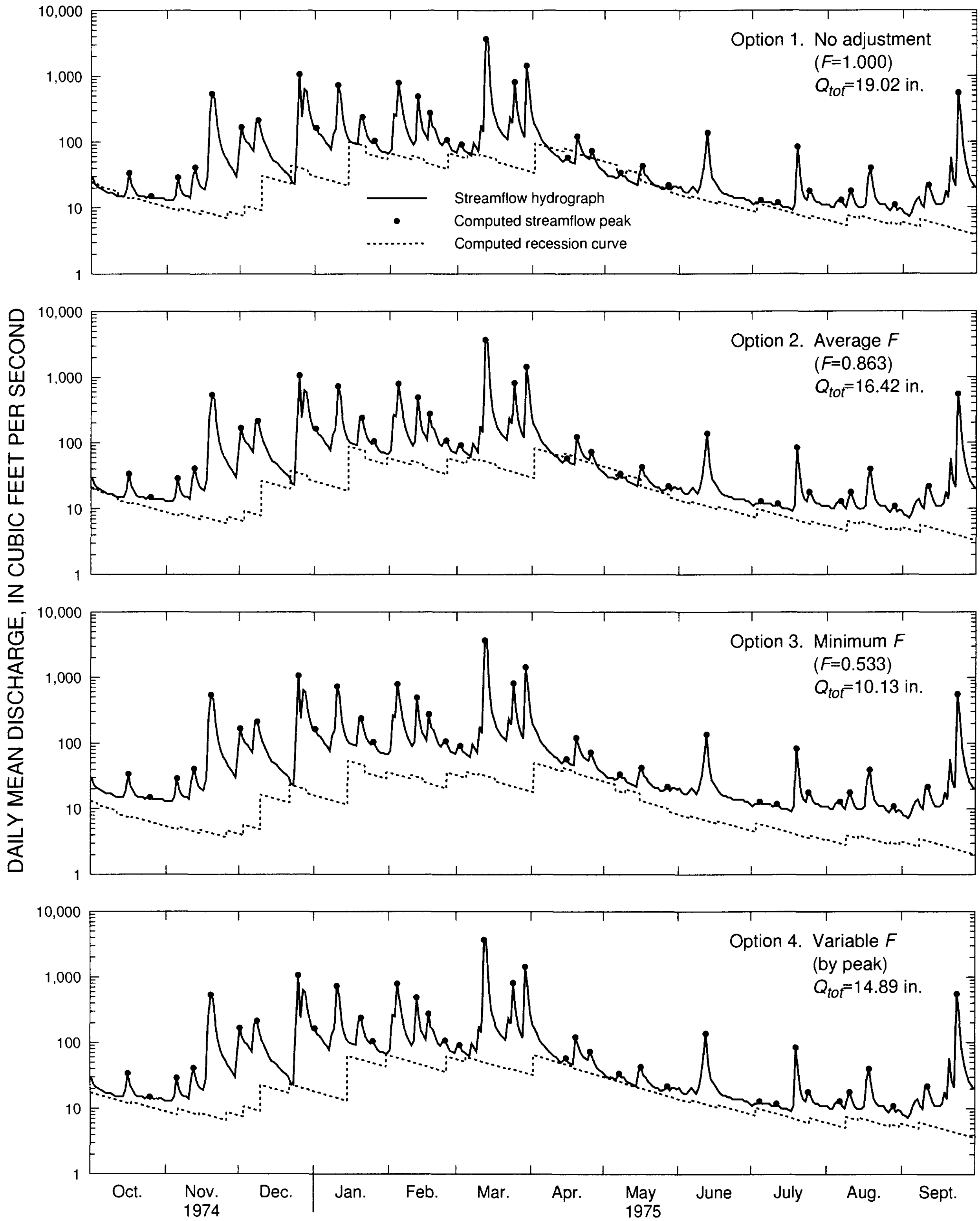

Figure 4b. Results of automated streamflow hydrograph separation using four adjustment options of SWGW, East Fork of Stones River at Woodbury, Tennessee (station 03426800), for water year 1975.

Adjustment of the ground-water recession curve is not intended to be arbitrary, but rather should be applied at the discretion and hydrologic judgment of the user, and with full consideration of the user's objectives. Options 1 through 4 are used throughout the following examples to illustrate available user options. Options 1 and 3 provide the user a complete range of possible adjustment alternatives, and option 2 gives the user an idea of the central tendency of that range. The SWGW user also is given a fifth option of applying another user-defined adjustment factor, which can be chosen based on the range and average values provided.

Examples of SWGW Analyses and Comparisons

Estimates of baseflow were computed manually using the recession-curve-displacement method for streamflow at gaging stations in the Piedmont and Coastal Plain of Georgia (Faye and Mayer, 1990), and in various physiographic provinces in middle and eastern Tennessee (Hoos, 1990). Faye and Mayer (1990) evaluated eight water years at seven stations. Hoos (1990) estimated baseflow for three water years representing high-, average-, and low-flow conditions for each of ten gaging stations. For comparison of manually derived results to results from automated procedures, hydrograph separation results at four stations and three water years for each station are chosen from Hoos (1990), and results from all eight water years are selected from Faye and Mayer (1990). In all, separation results at 11 stations for a total of 20 water years are compared. Two scenarios are considered: scenario (a)—constant recession index, K ($K_{mr}=K_{et}$), and scenario (b)—two values of K ($K_{mr}>K_{et}$). The names of the 11 gaging stations and characteristics of the

Table 1. Streamflow-gaging stations where separation results based on manual methods are compared to results from automated recession-curve-displacement procedures, and characteristics of the respective drainage basins

[K_{mr}, K_{et}, recession indices for the major rise and major recession periods, respectively; —, data not available, only one value of the recession index is used for these stations

Station ID (fig. 1)	Station name	Station number	Physiographic province	Drainage area, in square miles	K_{mr}, in days	K_{et}, in days	ET period, in months
ga01	Chattahoochee River at West Point, Ga.	02339500	Piedmont	3,550	122	80	Apr.-Sept.
ga02	Flint River near Culloden, Ga.	02347500	Piedmont	1,850	85	54	Apr.-Sept.
ga03	Ogeechee River at Scarboro, Ga.	02202000	Coastal Plain	1,940	80	—	—
ga04	Ogeechee River near Louisville, Ga.	02200500	Coastal Plain	800	94	—	—
ga05	Ocmulgee River at Hawkinsville, Ga.	02215000	Piedmont and Coastal Plain	3,800	150	—	—
ga06	Ocmulgee River at Macon, Ga.	02213000	Piedmont	2,240	117	—	—
ga07	Oconee River at Milledgeville, Ga.	02223000	Piedmont	2,950	62	—	—
tn09	East Fork Stones River at Woodbury, Tn.	03426800	Highland Rim	39.1	95	54	Apr.-Sept.
tn30	Lick Creek at Mohawk, Tn.	03467000	Valley and Ridge	220	65	56	Apr.-Sept.
tn32	Doe River at Elizabethton, Tn.	03485500	Blue Ridge	137	107	69	Apr.-Oct.
tn46	Emory River at Oakdale, Tn.	03540500	Cumberland Plateau	764	31	16	Apr.-Sept.

respective drainage basins are in table 1. The location and drainage basins of the 11 stations are shown in figure 1.

For scenario (a), a single value of the recession index is used for both the major rise period and the major recession period (K_{mr}=K_{et}). The recession index values are from Faye and Mayer (1990) and Hoos (1990). Four runs of SWGW are made for each of the 20 water years using different adjustment options 1 through 4. The first set of runs, designated 'a1', employs no adjustment (option 1, F=1.0), and produces results identical to those from RORA for the period of the chosen water year. The second and third sets of runs, 'a2' and 'a3', employ the average (option 2) and minimum (option 3) computed values of F, respectively, applied to each Q_c in the specified water year. The final set of runs, 'a4', adjusts each Q_c in the specified water year by the minimum F computed for the corresponding peak (option 4).

Published, manually derived baseflow estimates and corresponding results from SWGW for scenario (a) are listed in table 2. In addition to estimates of total baseflow, estimates of baseflow components attributable to both the major rise and major recession periods also are listed in table 2 for both the manual and the automated procedures. Percent

Table 2. Summary of estimates of baseflow based on manual and automated recession-curve displacement procedures for scenario (a), K_{mr}=K_{et}

[Q_{mr}, Q_{et}, estimates of components of baseflow, in inches, attributable to the major rise period and the major recession period, respectively; **Qtot** (in bold), sum of Q_{mr} and Q_{et}, in inches; F, factor used to adjust recession curve; *Diff.*, difference, in percent, of the SWGW computed estimate from the manually derived estimate]

Station ID	Water year	Manually derived estimates			Runs, factors, SWGW computed estimates, and differences							
		Q_{mr}	Q_{et}	$\mathbf{Q_{tot}}$	Run	F	Q_{mr}	*Diff.*	Q_{et}	*Diff.*	$\mathbf{Q_{tot}}$	***Diff.***
ga01	1941	5.2	1.5	**6.7**	a1	1.00	6.9	32	1.8	23	**8.7**	**30**
					a2	0.92	6.3	21	1.7	13	**8.0**	**19**
					a3	0.74	5.0	-2.9	1.4	-10	**6.4**	**-4.5**
					a4	variable	7.0	35	1.6	3.1	**8.6**	**28**
ga01	1952	9.6	0.7	**10.3**	a1	1.00	16	64	1.7	140	**17**	**69**
					a2	0.94	15	55	1.6	130	**16**	**60**
					a3	0.64	10	4.2	1.1	55	**11**	**7.6**
					a4	variable	12	23	3.5	390	**15**	**48**
ga02	1941	4.0	0.4	**4.4**	a1	1.00	5.1	27	1.1	180	**6.2**	**41**
					a2	0.86	4.4	9.7	1.0	140	**5.4**	**22**
					a3	0.46	2.3	-42	0.52	29	**2.9**	**-35**
					a4	variable	5.0	24	0.56	40	**5.5**	**25**
ga03	1941	4.0	3.2	**7.2**	a1	1.00	4.9	22	2.7	-17	**7.5**	**4.5**
					a2	0.81	3.9	-1.7	2.2	-33	**6.1**	**-16**
					a3	0.36	1.8	-56	0.96	-70	**2.7**	**-62**
					a4	variable	4.9	23	1.6	-49	**6.5**	**-9.3**
ga04	1941	4.6	1.0	**5.6**	a1	1.00	6.3	37	2.7	170	**9.0**	**61**
					a2	0.79	5.0	8.7	2.2	120	**7.2**	**28**
					a3	0.48	6.0	-35	1.3	29	**4.3**	**-24**
					a4	variable	6.3	38	1.4	40	**7.7**	**38**
ga05	1931	3.9	0.9	**4.8**	a1	1.00	6.8	74	1.6	72	**8.3**	**74**
					a2	0.79	5.3	37	1.2	35	**6.6**	**37**
					a3	0.44	3.0	-24	0.68	-25	**3.6**	**-24**
					a4	variable	5.4	40	1.0	13	**6.5**	**35**
ga06	1905	3.4	0.5	**3.9**	a1	1.00	4.3	26	1.9	280	**6.2**	**59**
					a2	0.88	3.8	11	1.7	240	**5.4**	**40**
					a3	0.62	2.7	-22	1.2	140	**3.8**	**-1.5**
					a4	variable	4.1	20	1.6	220	**5.7**	**46**
ga07	1941	3.7	0.4	**4.1**	a1	1.00	5.4	47	1.7	310	**7.1**	**73**
					a2	0.95	5.2	40	1.6	290	**6.8**	**65**
					a3	0.78	4.3	15	1.3	220	**5.6**	**36**
					a4	variable	5.4	45	1.4	260	**6.8**	**66**

Table 2. Summary of estimates of baseflow based on manual and automated recession-curve displacement procedures for scenario (a), $K_{mr}=K_{et}$—Continued

[Q_{mr}, Q_{et}, estimates of components of baseflow, in inches, attributable to the major rise period and the major recession period, respectively; **Qtot** (in bold), sum of Q_{mr} and Q_{et}, in inches; *F*, factor used to adjust recession curve; *Diff.*, difference, in percent, of the SWGW computed estimate from the manually derived estimate]

Station ID	Water year	Manually derived estimates			Runs, factors, SWGW computed estimates, and differences							
		Q_{mr}	Q_{et}	Q_{tot}	Run	*F*	Q_{mr}	*Diff.*	Q_{et}	*Diff.*	Q_{tot}	*Diff.*
tn09	1975	12.1	1.6	**13.7**	a1	1.00	18	50	0.87	-46	**19**	**39**
					a2	0.86	16	30	0.75	-53	**16**	**20**
					a3	0.55	9.9	-18	0.47	-70	**10**	**-24**
					a4	variable	14	12	1.7	4.9	**15**	**11**
tn09	1971	7.7	1.2	**8.9**	a1	1.00	12	59	1.6	38	**14**	**56**
					a2	0.86	10	36	1.4	18	**12**	**34**
					a3	0.55	6.7	-13	0.90	-25	**7.6**	**-15**
					a4	variable	9.4	22	2.1	75	**11**	**29**
tn09	1981	3.0	0.9	**3.9**	a1	1.00	3.9	31	1.1	26	**5.1**	**30**
					a2	0.85	3.3	11	0.96	6.9	**4.3**	**10**
					a3	0.57	2.2	-26	0.64	-28	**2.9**	**-26**
					a4	variable	3.7	23	0.87	-3.7	**4.6**	**17**
tn30	1950	5.8	1.8	**7.2**	a1	1.00	8.1	39	2.8	58	**11**	**44**
					a2	0.86	6.9	19	2.4	35	**9.4**	**23**
					a3	0.40	3.2	-44	1.1	-37	**4.4**	**-42**
					a4	variable	6.2	6.5	2.3	26	**8.4**	**11**
tn30	1965	4.4	0.8	**5.2**	a1	1.00	7.0	59	1.0	30	**8.0**	**54**
					a2	0.94	6.5	48	0.97	22	**7.5**	**44**
					a3	0.55	3.8	-13	0.57	-29	**4.4**	**-16**
					a4	variable	6.2	40	1.1	42	**7.3**	**40**
tn30	1948	1.8	0.8	**2.6**	a1	1.00	4.8	160	0.84	4.4	**5.6**	**120**
					a2	0.93	4.4	150	0.78	-2.4	**5.2**	**100**
					a3	0.72	3.4	91	0.61	-24	**4.0**	**56**
					a4	variable	4.4	140	0.88	10	**5.3**	**100**
tn32	1975	12.3	3.8	**16.1**	a1	1.00	19	53	4.5	19	**23**	**45**
					a2	0.91	17	39	4.1	8.0	**21**	**32**
					a3	0.70	13	7.5	3.2	-16	**16**	**1.8**
					a4	variable	17	35	5.7	51	**22**	**39**
tn32	1959	9.4	1.3	**10.7**	a1	1.00	9.5	1.1	6.4	390	**16**	**48**
					a2	0.89	8.5	-9.9	5.7	340	**14**	**32**
					a3	0.63	6.0	-36	4.0	210	**10**	**-6.8**
					a4	variable	9.3	-1.3	5.3	310	**15**	**36**
tn32	1969	8.4	1.7	**10.1**	a1	1.00	11	26	3.2	88	**14**	**37**
					a2	0.90	9.6	14	2.9	70	**12**	**24**
					a3	0.67	7.1	-16	2.1	25	**9.2**	**-8.7**
					a4	variable	9.7	16	3.2	87	**13**	**28**
tn46	1973	10.3	-0.1	**10.2**	a1	1.00	17	62	7.2	—[1]	**24**	**130**
					a2	0.79	13	28	5.7	—[1]	**19**	**85**
					a3	0.41	6.8	-34	3.0	—[1]	**9.8**	**-4.2**
					a4	variable	15	42	5.6	—[1]	**20**	**98**
tn46	1970	8.2	0.7	**8.9**	a1	1.00	8.9	8.2	4.4	530	**13**	**49**
					a2	0.71	6.3	-23	3.1	350	**9.4**	**5.8**
					a3	0.20	1.8	-78	0.9	28	**2.7**	**-70**
					a4	variable	7.0	-14	2.3	230	**9.3**	**4.9**
tn46	1969	3.4	0.3	**3.7**	a1	1.00	7.3	120	3.9	1,200	**11**	**200**
					a2	0.75	5.5	62	2.9	870	**8.4**	**130**
					a3	0.20	1.5	-56	0.8	170	**2.3**	**-38**
					a4	variable	6.5	92	2.2	640	**8.7**	**140**

[1]Residual difference not calculated due to apparent negative value of manual estimate of Q_{et}.

differences, $Diff.=100*(Q_{comp}-Q_{man})/Q_{man}$, of the SWGW computed estimates, Q_{comp}, from the manually derived estimates, Q_{man}, also are listed in table 2.

Scenario (b) is considered using a recession index, K_{et}, specified for the major recession period, that is smaller than the recession index, K_{mr}, for the major rise period. Estimates of K_{et} (table 1) are made for the four stations from Hoos (1990) and for stations ga01 and ga02 from Faye and Mayer (1990) by graphical inspection of numerous streamflow hydrographs, providing a total of 15 water years at 6 stations. The same four sets of runs of SWGW are completed as described for scenario (a), and are similarly designated 'b1', 'b2', 'b3', and 'b4'. Run 'b1' differs from RORA only by the specification of two values of K. Published estimates of the major rise and major recession components of baseflow and total baseflow are listed in table 3 with the corresponding results from SWGW. Percent differences, $Diff.=100*(Q_{comp}-Q_{man})/Q_{man}$, of

Table 3. Summary of estimates of baseflow based on manual and automated recession-curve displacement procedures for scenario (b), $K_{mr}>K_{et}$

[Q_{mr}, Q_{et}, estimates of components of baseflow, in inches, attributable to the major rise period and the major recession period, respectively; **Qtot** (in bold), sum of Q_{mr} and Q_{et}, in inches; F, factor used to adjust recession curve; *Diff.*, difference, in percent, of the SWGW computed estimate from the manually derived estimate]

Station ID	Water year	Manually derived estimates			Runs, factors, SWGW computed estimates, and differences							
		Q_{mr}	Q_{et}	Q_{tot}	Run	F	Q_{mr}	*Diff.*	Q_{et}	*Diff.*	Q_{tot}	*Diff.*
ga01	1941	5.2	1.5	6.7	b1	1.00	6.8	31	2.5	68	**9.4**	**40**
					b2	0.90	6.2	19	2.3	52	**8.4**	**26**
					b3	0.62	4.2	-19	1.6	4.3	**5.8**	**-14**
					b4	variable	7.1	36	2.4	60	**9.5**	**42**
ga01	1952	9.6	0.7	10.3	b1	1.00	16	64	3.5	400	**19**	**87**
					b2	0.94	15	54	3.3	370	**18**	**75**
					b3	0.64	10	4.1	2.2	220	**12**	**19**
					b4	variable	12	22	4.7	570	**16**	**59**
ga02	1941	4.0	0.4	4.4	b1	1.00	5.1	27	1.6	300	**6.7**	**52**
					b2	0.92	4.6	16	1.5	270	**6.1**	**39**
					b3	0.62	3.2	-21	1.0	150	**4.2**	**-5.2**
					b4	variable	5.0	24	1.2	200	**6.2**	**40**
tn09	1975	12.1	1.6	13.7	b1	1.00	18	50	2.0	23	**20**	**47**
					b2	0.88	16	33	1.7	8.7	**18**	**30**
					b3	0.55	9.9	-18	1.1	-33	**11**	**-20**
					b4	variable	14	14	2.3	44	**16**	**17**
tn09	1971	7.7	1.2	8.9	b1	1.00	12.3	59	2.8	140	**15**	**70**
					b2	0.87	10.7	39	2.5	110	**13**	**48**
					b3	0.56	6.9	-10	1.6	34	**8.5**	**-4.5**
					b4	variable	9.7	26	2.9	150	**13**	**42**
tn09	1981	3.0	0.9	3.9	b1	1.00	4.0	32	1.6	72	**5.5**	**41**
					b2	0.90	3.6	19	1.4	55	**5.0**	**27**
					b3	0.57	2.2	-25	0.88	-2.6	**3.1**	**-20**
					b4	variable	3.7	24	1.4	50	**5.1**	**30**

Table 3. Summary of estimates of baseflow based on manual and automated recession-curve-displacement procedures for scenario (b), $K_{mr}>K_{et}$—Continued

[Q_{mr}, Q_{et}, estimates of components of baseflow, in inches, attributable to the major rise period and the major recession period, respectively; **Qtot** (in bold), sum of Q_{mr} and Q_{et}, in inches; *F*, factor used to adjust recession curve; *Diff.*, difference, in percent, of the SWGW computed estimate from the manually derived estimate]

Station ID	Water year	Manually derived estimates			Runs, factors, SWGW computed estimates, and differences							
		Q_{mr}	Q_{et}	Q_{tot}	Run	*F*	Q_{mr}	*Diff.*	Q_{et}	*Diff.*	Q_{tot}	*Diff.*
tn30	1950	5.8	1.8	7.6	b1	1.00	8.1	39	2.9	63	**11**	**45**
					b2	0.84	6.8	17	2.5	37	**9.3**	**22**
					b3	0.40	3.2	-44	1.2	-34	**4.4**	**-42**
					b4	variable	6.2	6.5	2.4	31	**8.5**	**12**
tn30	1965	4.4	0.8	5.2	b1	1.00	7.0	59	1.2	55	**8.2**	**58**
					b2	0.94	6.6	49	1.2	46	**7.7**	**48**
					b3	0.55	3.8	-13	0.68	-15	**4.5**	**-14**
					b4	variable	6.2	40	1.3	66	**7.5**	**44**
tn30	1948	1.8	0.8	2.6	b1	1.00	4.8	160	0.95	18	**5.7**	**120**
					b2	0.93	4.4	150	0.88	11	**5.3**	**100**
					b3	0.72	3.4	92	0.69	-14	**4.1**	**59**
					b4	variable	4.4	150	0.98	22	**5.4**	**110**
tn32	1975	12.3	3.8	16.1	b1	1.00	19	54	5.8	53	**25**	**54**
					b2	0.92	18	43	5.4	42	**23**	**42**
					b3	0.76	14	16	4.4	16	**19**	**16**
					b4	variable	17	36	6.6	74	**23**	**45**
tn32	1959	9.4	1.3	10.7	b1	1.00	9.6	2.1	7.2	460	**17**	**57**
					b2	0.92	18	43	5.4	42	**23**	**42**
					b3	0.72	6.9	-27	5.2	300	**12**	**13**
					b4	variable	9.4	-0.3	6.4	390	**16**	**48**
tn32	1969	8.4	1.7	10.1	b1	1.00	11	27	3.8	130	**14**	**43**
					b2	0.91	9.7	15	3.5	100	**13**	**30**
					b3	0.71	7.6	-9.7	2.7	61	**10**	**2.2**
					b4	variable	9.7	16	3.9	130	**14**	**34**
tn46	1973	10.3	-0.1	10.2	b1	1.00	19	82	9.2	—[1]	**28**	**170**
					b2	0.83	16	51	7.6	—[1]	**23**	**130**
					b3	0.54	10	-2.6	4.9	—[1]	**15**	**47**
					b4	variable	16	54	7.4	—[1]	**23**	**130**
tn46	1970	8.2	0.7	8.9	b1	1.00	10	26	5.0	610	**15**	**72**
					b2	0.78	8.1	-1.1	3.9	450	**12**	**35**
					b3	0.19	2.0	-76	0.94	34	**2.9**	**-68**
					b4	variable	8.2	0.0	3.3	380	**12**	**30**
tn46	1969	3.4	0.3	3.7	b1	1.00	7.8	130	4.9	1,500	**13**	**240**
					b2	0.80	6.2	84	3.9	1,200	**10**	**170**
					b3	0.19	1.5	-57	0.92	210	**2.4**	**-36**
					b4	variable	6.7	98	3.1	940	**9.8**	**170**

[1]Residual difference not calculated due to apparent negative value of manual estimate of Q_{et}.

the SWGW computed estimates, Q_{comp}, from the manually derived estimates, Q_{man}, also are listed in table 3.

Statistical Analysis of Example Results

A statistical analysis of the differences of the SWGW computed estimates from the manually derived estimates of total baseflow is used to evaluate the performance of each of the four described options for adjusting the displacement of the recession curve. To evaluate results for gaging stations in Georgia and Tennessee independently, the differences are grouped into several data sets. For each of the two scenarios, (a) and (b), three data sets of differences are formed: (1) stations in Georgia (data sets 'Georgia-a' and 'Georgia-b'); (2) stations in Tennessee (data sets 'Tennessee-a' and 'Tennessee-b'); and (3) all stations (data sets 'total-a' and 'total-b'). Because estimates of K_{et} are available only for three of the eight water years at stations in Georgia used in scenario (a), data sets 'Georgia-b' and 'total-b' consist of five fewer data pairs than the corresponding data sets developed by scenario (a). To provide an appropriate comparison between the two scenarios, an additional data set (called 'total-a*') is formed using only residual differences from scenario (a) for the Georgia stations represented in data set 'total-b'. The minimum and maximum differences, and the mean, standard deviation, and skewness of the differences in each data set are summarized in table 4.

For data set 'total-a', estimates of total baseflow computed by SWGW are greater than those based on manual methods by an average of 63 percent for runs 'a1'; 40 percent for runs 'a2'; and 41 percent for runs 'a4'. SWGW computed estimates are less than manually derived estimates by an average of 15 percent for runs 'a3'. The mean differences computed for runs 'a1', which are equivalent to the estimates from RORA, are furthest from the published manually derived results for 18 of the 20 water years selected for comparison. The differences for runs using adjusted values of Q_c, runs 'a2', 'a3', and 'a4', are not only smaller on average than the differences from runs 'a1', but also are less scattered and more normally distributed. For runs 'a1', the standard deviation and skewness of the differences are 44 percent and 1.9, respectively. Corresponding values are 34 percent and 1.1 for runs 'a2', 29 percent and 0.4 for runs 'a3', and 35 percent and 1.2 for runs 'a4'. The value of F that would cause the annual baseflow estimates computed by SWGW to match exactly the corresponding manually derived estimates lay between the average F and the minimum F for 15 of the 20 water years considered.

The differences of data sets 'Georgia-a' and 'Tennessee-a' for scenario (a) display results similar to the data set 'total-a' (table 4). Runs 'a1' of each data set produced the highest mean residual, while runs 'a3' produced the lowest. The value of F that would cause the baseflow computed by SWGW to match exactly the manually derived estimate for the Georgia and Tennessee stations lay between the average F and the minimum F for 5 of the 8, and 10 of the 12 water years, respectively.

For the 15 water years considered for scenario (b), data set 'total-b', SWGW estimates of baseflow are greater, on average, than manually derived estimates by 80 percent for runs 'b1'; 58 percent for runs 'b2'; and 56 percent for runs 'b4'; and are less than manually derived estimates by 4.4 percent for runs 'b3'. For 14 of the 15 water years considered, the estimates of baseflow for runs 'b1', which most closely correspond to the estimates computed by RORA, are the furthest from the published manually derived results. Like scenario (a), the differences for the runs using adjusted values of Q_c, runs 'b2', 'b3', and 'b4', are not only smaller on average than the differences from runs 'b1', but also are less scattered and more normally distributed. For runs 'b1', the standard deviation and skewness of the differences are 57 percent and 1.9, respectively. Corresponding values are 44 percent and 1.6 for runs 'b2', 33 percent and 0.2 for runs 'b3', and 43 percent and 1.5 for runs 'b4'. The value of F that would cause the annual baseflow estimates computed by SWGW to match exactly the manually derived

Table 4. Summary of statistics for sets of differences of SWGW computed estimates of baseflow from manually derived estimates of baseflow

Sets of difference data	Number of station-years	Run	F	Difference, in percent					Skewness
				Minimum	Maximum	Mean	Standard deviation		
				Scenario (a) — K_{mr}=K_{et}					
Georgia-a	8	a1	1.0 (RORA)	4.5	74	51	25		-0.9
		a2	average	-16	65	32	25		-0.5
		a3	minimum	-62	36	-14	30		0.0
		a4	variable	-9.3	66	34	22		-0.7
Tennessee-a	12	a1	1.0 (RORA)	30	200	71	53		1.6
		a2	average	5.8	130	45	38		1.1
		a3	minimum	-70	56	-16	30		0.7
		a4	variable	4.9	140	46	43		1.1
Total-a	20	a1	1.0 (RORA)	4.5	200	63	44		1.9
		a2	average	-16	130	40	34		1.1
		a3	minimum	-70	56	-15	29		0.4
		a4	variable	-9.3	140	41	35		1.2
Total-a*[1]	15	a1	1.0 (RORA)	30	200	66	48		1.9
		a2	average	5.8	130	43	35		1.3
		a3	minimum	-70	56	-15	28		0.6
		a4	variable	4.9	140	44	38		1.3
				Scenario (b) — K_{mr}>K_{et}					
Georgia-b	3	b1	1.0	40	87	59	24		0.5
		b2	average	26	75	47	25		0.5
		b3	minimum	-14	19	0.0	17		0.5
		b4	variable	40	59	47	11		0.7
Tennessee-b	12	b1	1.0	41	240	85	63		1.6
		b2	average	22	170	61	48		1.4
		b3	minimum	-68	59	-5.5	36		0.2
		b4	variable	12	170	59	48		1.2
Total-b	15	b1	1.0	40	240	80	57		1.9
		b2	average	22	170	58	44		1.6
		b3	minimum	-68	59	-4.4	33		0.2
		b4	variable	12	170	56	43		1.5

[1]Stations considered under scenario (a) that are also considered under scenario (b).

estimate lay between the average *F* and the minimum *F* for 9 of the 15 water years considered. Comparing these results with those computed using the same water-year data under scenario (a), data set 'total-a*', the means and standard deviations are higher under scenario (b) for all four sets of runs.

Of the total sets of runs from both scenarios, the best set is 'b3' in data set 'total-b' of scenario (b), which has a mean difference of -4.4 percent, a standard deviation of 33 percent, and a skewness of 0.2. This set of runs has a mean value closest to the manually derived estimates and is the most normally distributed. Inspection of table 4 shows that of each set of water years analyzed, run '3' commonly has the mean difference closest to zero, and also the most normal distribution. These comparisons indicate that for streams in the ACF-ACT study area, the use of two recession indices and an adjustment factor (*F*) between the minimum and average values produces estimates of baseflow most consistent with estimates based on manual analysis of the same data.

DISCUSSION

This work describes results of streamflow hydrograph separation using recession-curve-displacement procedures performed on streamflow data from selected gaging stations in Georgia and Tennessee. The results indicate that adjustment of RORA computed recession curves and baseflow may be appropriate for the ACF-ACT study area. Results also indicate that evapotranspiration effects on ground-water discharge to streams may be accounted for in the ACF-ACT study area by the use of appropriate baseflow recession indices. Features of SWGW, including water-year analysis period, graphic output of computed ground-water recession curves, and optional adjustments of RORA results, substantially enhance analysis of ground-water/surface-water relations.

The effect of a number of hydrologic processes and basin characteristics probably are significant to the results of this or any recession-curve-displacement procedure, and have not been thoroughly investigated. Rainfall, runoff, and recharge processes are complex and dynamic, especially in large watersheds. For example, in a large watershed, the temporal and spatial distribution of a rainfall event may influence the temporal and spatial patterns of consequent streamflow, and affect the displacement of the recession curve. Similarly, the distribution of aquifer hydraulic characteristics and ground-water flow processes may not coincide with watershed boundaries, and the development of regional and intermediate ground-water flow systems may further complicate the relation between surface water and ground water within a particular watershed. Other factors may affect the results of a recession-curve-displacement procedure. These include, but are not limited to, basin size, basin topography, land use, soil type, aquifer properties, climate, and streamflow characteristics.

In addition to the uncertain effects of hydrologic processes on the scale of the drainage basin discussed in the previous paragraph, there also is uncertainty in the present understanding of small-scale processes such as the movement of water from the ground through a streambed into a flowing stream. The physical mechanisms of the recession-curve-displacement method basically assume that a stream is similar to a horizontal well, in which water in the well bore is in direct contact with the surrounding saturated soil medium. Streambed sediments, however, may have substantially different hydrologic properties than the underlying soil medium, complicating the physical process of ground-water discharge to a stream. Without additional work to gain a thorough understanding of this and related processes, field verification of the estimates of baseflow obtained through any hydrograph separation procedure will be difficult.

Additional work is needed to refine recession-curve-displacement and related method-ologies, and to evaluate the confidence of analytical results. The relation of surface-runoff processes to ground-water discharge during and immediately following a rainfall-runoff event is of particular interest and complexity. The methods used in SWGW and in RORA are somewhat to highly subjective regarding the separation of runoff components during periods of rising and peak streamflow. This discretization of streamflow into components of surface water and ground water is extraordinarily difficult to approach because of the lack of a theoretical description of the physical processes. Investigation of this phenomenon is difficult and rarely has been undertaken.

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