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Model-Estimated Ground-Water Recharge and Hydrograph of Ground-Water Discharge to a Stream

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Water Resources Investigations Report 97-4253

science for a changing world

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By A.T. Rutledge

U.S. GEOLOGICAL SURVEY

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PREFACE

The code for this model will be available for downloading over the Internet from a USGS software repository. The public anonymous FTP site is on a Water Resources server (ftprvares.er.usgs.gov or 130.11.51.209) in the/pub/arutledg/sf.programs directory.

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FIGURES

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)	2.590	square kilometer
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
	Hydraulic gradient	
foot per mile (ft/mi)	0.1894	meter per kilometer
	Transmissivity*	
foot squared per day (ft^2/d)	0.09290	meter squared per day

***Transmissivity**: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness $[(ft^3/d)/ft^2]ft$. In this report, the mathematically reduced form, foot squared per day (ft^2/d), is used for convenience.

Model-Estimated Ground-Water Recharge and Hydrograph of Ground-Water Discharge to a Stream

By A.T. Rutledge

Abstract

The computer model PULSE, described in this report, can be used to construct a hydrograph of ground-water discharge to a stream. The model is applicable to a ground-water flow system that is driven by areally uniform recharge to the water table, and in which ground water discharges to a gaining stream. One of the two formulations used by the model allows for an instantaneous recharge pulse and subsequent ground-water discharge to the stream. The other formulation, which allows for a gradual hydrologic gain or loss term in addition to the instantaneous pulse, can be used to simulate the effects of gradual recharge to the water table, ground-water evapotranspiration, or downward leakage to a deeper aquifer.

INTRODUCTION

Historically, hydrologists have used various methods to estimate the ground-water discharge component of streamflow. The typical methods consist of identifying those parts of the streamflow hydrograph that consist completely of ground-water discharge (base flow), followed by some form of interpolation of the ground-water discharge portion for the remainder of the hydrograph. Several of these methods for estimating base flow have been applied manually (Horton, 1933; Barnes,1939; Snyder, 1939; Chow, 1964), but computer techniques also have been used (Hewlett and Hibbert, 1967; Pettyjohn and Henning, 1979; Institute of Hydrology, 1980; Knisel and Sheridan, 1983; Shirmohammadi and others, 1984; Rutledge, 1993; Wahl and Wahl, 1995; Sloto and Crouse, 1996). These computerized methods, which are fully automated (no calibration process is required), can give estimates of base flow that are useful for regional hydrologic studies, but they are not based on flow models and should be used only to estimate the total or mean ground-water discharge over a long period.

This report describes use of a computer program, designated PULSE, which is based upon two analytical equations that describe the ground-water discharge to a stream following an instantaneous pulse of recharge to the water table. One equation (Rorabaugh, 1964) allows for flow to the stream only, without any other gain or loss term. The other equation (Daniel, 1976) allows for flow to the stream but also approximates the effects of ground-water evapotranspiration (GWET) during summer months, gradual recharge to the water table, or the effects of downward leakage to deeper flow systems. This report emphasizes determination of ground-water discharge following recharge that is considered to occur as instantaneous pulses, with GWET affecting some parts of the hydrograph.

The main purpose of this computer model is to provide estimates of ground-water recharge or discharge at a time scale that is smaller than the time scale typically used for the fully automated methods. For example, PULSE might be used to generate useful estimates of monthly ground-water discharge. This model also could be used as an educational tool for describing the processes of ground-water recharge and discharge and to evaluate results from the fully automated methods.

The procedure requires a calibration process in which the user makes initial estimates of recharge and GWET and then experiments with model input data until a reasonable match is obtained between simulated and measured streamflow during periods of ground-water discharge. PULSE can be useful for hydrograph analysis in some basin studies, but does not replace the fully automated methods. The latter are more appropriate for use in regional studies that involve analysis of large data sets, and for obtaining an objective estimate of the long-term rate of ground-water recharge or discharge.

MATHEMATICAL MODEL

The computer program PULSE applies a mathematical model of time-varying recharge to and discharge from a ground-water flow system. The input to the program includes recharge and GWET, which can vary over time, and program output includes ground-water discharge, which can be represented as a hydrograph.

Model Applicability

The mathematical model applies to a ground-water flow system characterized by diffuse areal recharge to the water table, and in which ground water discharges to a gaining stream. Recharge events are considered to occur as uniform pulses. All or most ground water in the basin should discharge to the stream, except for a relatively small amount that might be lost by evapotranspiration or leakage to a deeper flow system. Regulation and diversion of streamflow should be negligible. The model may not be reliable for flow systems dominated by the effects of snowmelt runoff, prolonged periods of surface runoff through wetlands, recharge from losing streams, ground-water withdrawals, or ground-water evapotranspiration. These limitations may not negate the utility of the model but instead may require that it be used judiciously. For example, the model could be used for analysis of a stream that goes dry in summer when ground-water levels decline below the stream channel, as long as results are qualified as not being reliable for summertime recharge.

The use of this model requires an estimate of the recession index. Because this estimate requires data for at least one, and preferably several, long periods of continuous recession, and because such periods may occur infrequently, the streamflow record must be of considerable duration. In many cases, this may require at least a year, and preferably several years, of streamflow record. Indirect methods for estimating the recession index may be required if the streamflow record is short or if the hydraulic properties of the aquifer preclude the opportunity to measure the recession index from the streamflow record (for example if the hydraulic diffusivity of the aquifer is very small). Considerable error is associated with these indirect methods.

Because most of the calibration process involves data from periods of low flow, the application of the model for analysis of streamflow records from very small basins may result in unreliable results. The small flow rates reported for stations that drain small areas may be subject to considerable uncertainty. For example, underflow may be proportionally large relative to the reported streamflow. The author suggests that the drainage area should be at least 1 square mile, although this limit may vary according to the judgment of the program user.

This model should be applied with caution to streamflow data for large drainage basins for two reasons. In such basins, storm events will often be nonuniform, resulting in deviations from the model assumption of uniform instantaneous pulse recharge over the basin area. Also, in large basins, streamflow may be affected by direct runoff much of the time, so that only a small part of the stream hydrograph is suitable for calibration. The upper limit of drainage area that might be analyzed by this technique will vary depending on climate and hydrologic setting. The author suggests an upper limit of 500 square miles, although in some circumstances a smaller upper limit should be used.

Basin slope also may limit the use of the model. Basins of extremely small slope will be characterized by long periods during which streamflow is attributed largely to direct surface runoff. This will mean that few or no parts of the streamflow hydrograph can be considered to represent solely ground-water discharge. The upper limit of drainage area may have to be much smaller than recommended above for such basins. The upper limit suggested above (500 square miles) may apply to most of the eastern United States, with the possible exception of the Coastal Plain, where the upper limit might be only 20 square miles. This limitation may apply to other regions of small relief. Another possible limitation associated with small slope is that ground-water evapotranspiration may be significant. In some cases, this will mean that the recession index, a quantity that must be known for model use, becomes difficult to determine. In some areas of extremely small slope, particularly in the Coastal Plain, the model probably should not be used.

The hydrologist might make judgments about the upper and lower limits of basin size and the lower limit of channel slope from the appearance of streamflow hydrographs. Most of the semilog streamflow hydrograph should be easily mimicked using the model.

Ground-Water Discharge Resulting from a Pulse Recharge to the Aquifer

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

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

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

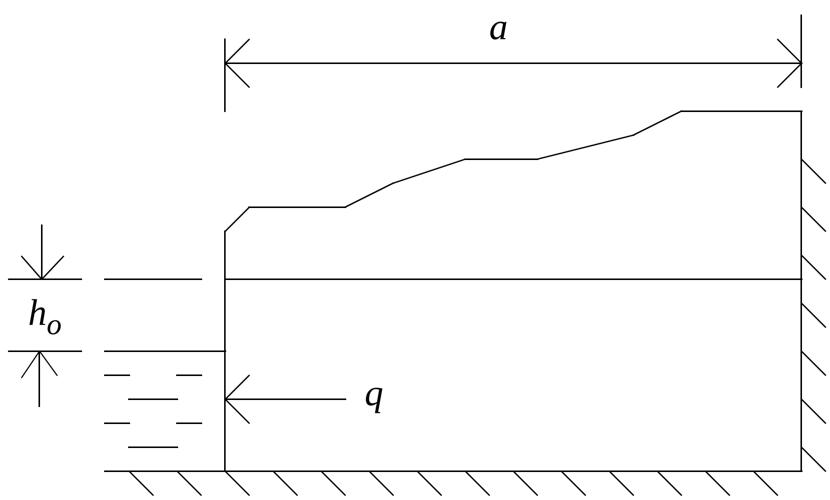


Figure 1. Definition sketch for Rorabaugh's equation (from Rorabaugh, 1964).

The above equation describes ground-water discharge per unit length of stream for one side of the channel. The mathematical model calculates the total ground-water discharge to a stream throughout the basin. For this purpose, q must be multiplied by $2L$, where L is the total length of perennial streams in the basin. The total ground-water discharge in the basin (Q), in units of volume per time, is:

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

The quantity L is approximated using the following equation (Daniel, 1976, page 362; Johnston, 1976, page 19; Stricker, 1983, page 14):

$$L = \frac{A}{2a} \tag{3}$$

where A= drainage area of the basin.

The formulations above require designation of T, S, a, and h_0. A more practical formulation involves the use of the recession index K. The recession index is determined as the time required for the ground-water discharge to recede by one log cycle beginning after a specified time interval after the last recharge event. This time interval is referred to as critical time, which is calculated as $0.2a^2S / T$ (Rorabaugh, 1964, p. 434). After rearranging the following equation (Rorabaugh and Simons, 1966, page 12):

$$\frac{T}{a^2S} = \frac{0.933}{K} \tag{4}$$

the recession index is

$$K = \frac{0.933a^2S}{T} \tag{5}$$

The computer model uses the recharge depth R_i in place of h_0. These two variables are related as follows:

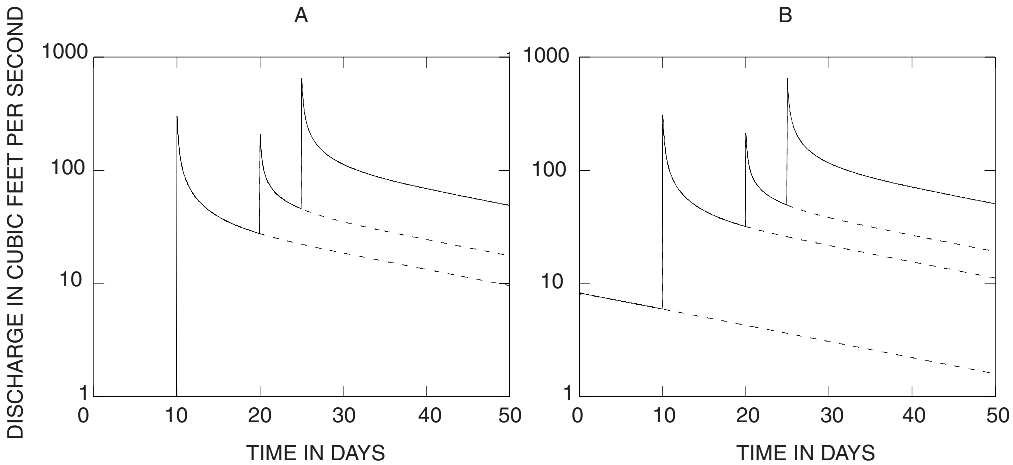
$$h_0 = \frac{R_i}{S_y} \tag{6}$$

where R_i = instantaneous recharge in units of length and S_y = the specific yield of the aquifer.

The combination of equations 1-6 and the substitution of specific yield for storage coefficient results in the following formulation for the total basin ground-water discharge at time t after recharge occurred:

$$Q = \frac{1.866AR_i}{K} \times \sum_{m = 1, 3, 5}^{\infty} e^{(-0.933m^2\pi^2t)/(4K)} \tag{7}$$

This formulation is a function of drainage area, the instantaneous recharge depth, and the recession index. The ground-water-discharge hydrograph is generated by superposition using a “baseline” upon which the ground-water discharge resulting from each recharge event is added. The baseline can be either zero flow or a linear recession of ground-water discharge (on the semilog hydrograph) that results from recharge events that occur prior to the period of interest. The use of the baseline, and calculations for three successive recharge events, are shown in figure 2.



EXPLANATION

Time (days)	Instantaneous Recharge (inches)
10	0.50
20	0.30
25	1.00

Figure 2. Calculated ground-water discharge resulting from the first three pulse recharge events, showing total ground-water discharge as a solid line, for two conditions: (A) Baseline equal to zero flow, and (B) Baseline starting at 8 cubic feet per second and receding according to the recession index. (Recession index= 70 days per log cycle; Drainage area= 100 square miles.)

Ground-Water Discharge Resulting from a Pulse Recharge to the Aquifer and a Gradual Gain or Loss Applied Areally

Daniel (1976) described another equation developed by Rorabaugh for the system described above with the addition of a constant loss, $C = dh/dt$, to GWET or to constant leakage through a semipervious boundary under the aquifer of interest (Daniel, 1976, pages 360 - 361). The resulting formulation is (Daniel, 1976, equation 7):

$$q = \left(\frac{h_0 T}{a}\right)\left(\frac{Ca^2 S}{h_0 T}\right)\left[1 + 2\sum_{m\,=\,1,\,3,\,5}^{\infty}\left(\frac{h_0 T}{Ca^2 S} - \frac{4}{\pi^2 m^2}\right)\cdot e^{(-m^2\pi^2 Tt)/(4a^2 S)}\right] \tag{8}$$

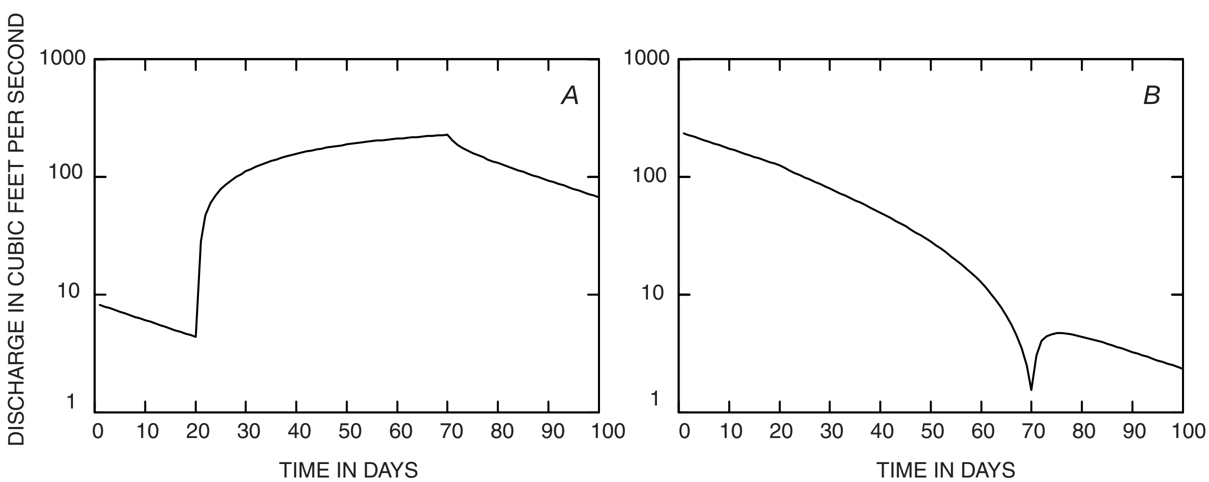
The combination of this equation with equations 2, 3, 5, and 6, and the substitution of specific yield for storage coefficient, results in the following equation for the total ground-water discharge as a function of drainage area, specific yield, the gradual gain or loss term, the instantaneous recharge amount, and the recession index:

$$Q = CAS_y + 2CAS_y \times \sum_{m\,=\,1,\,3,\,5}^{\infty}\left(\frac{0.933R_i}{CKS_y} - \frac{4}{\pi^2 m^2}\right)\cdot e^{(-0.933m^2\pi^2 t)/(4K)} \tag{9}$$

The rate of gradual gain or loss in units of volume per time is CAS_y (Daniel, 1976, page 362), which can also be expressed in units of volume per area per time, or length per time, as $R_g = CS_y$. The equation can then be rewritten as

$$Q = R_g A + 2R_g A \times \sum_{m = 1, 3, 5}^{\infty} \left[\frac{(0.933R_i)}{R_g K} - \frac{4}{\pi^2 m^2}\right] \cdot e^{(-0.933m^2\pi^2 t)/(4K)} \tag{10}$$

The use of equation 10 to simulate the effect of a finite period of gradual recharge requires that the principle of superposition be used to terminate the gradual recharge. For example, figure 3A illustrates the ground-water-discharge hydrograph resulting from a 50-day period of gradual recharge at 0.1 inch per day that starts on day 21 and ends on day 71. To accomplish this, the model is executed in such a way that day 21 is followed by a gradual recharge of +0.1 inch per day and that day 71 is followed by a gradual recharge of -0.1 inch per day. A similar method is used to approximate the effects of GWET, as shown in figure 3B. In this case, the period of GWET is initiated with a “recharge rate” of -0.01 inches per day, then is terminated 50 days later with a recharge rate of +0.01 inches per day. In both of these examples, recharge or GWET is a gradual process, so that instantaneous recharge amounts are zero (note explanation in figure 3). A hydrograph consisting of ground-water discharge during a period of GWET between two instantaneous recharge pulses is shown in figure 4.



EXPLANATION

Time (days)	Instantaneous Recharge (Inches)	Gradual recharge (inch/day)
21	0.00	0.10
71	0.00	-0.10

Time (days)	Instantaneous Recharge (Inches)	Gradual recharge (inch/day)
21	0.00	-0.0100
71	0.00	0.0100

Figure 3. Two applications of the model for hypothetical data showing (A) the effects of a 50-day period of gradual recharge and (B) the effects of a 50-day period of ground-water evapotranspiration. (Recession index= 70 days per log cycle; Drainage area= 100 square miles.)

The model can be used to compare ground-water discharge resulting from pulse recharge with ground-water discharge resulting from gradual recharge. Recharge that is distributed over time can be modeled either as multiple pulse recharge events or as a gradual recharge event (figure 5). The series of 8 pulse recharge events occurs over a 30-day period and the corresponding gradual recharge period is 30 days in duration. The total recharge is the same in both simulations. It is worthy of note that the ground-water discharge in each of the two situations becomes the same very soon after all recharge has taken place.

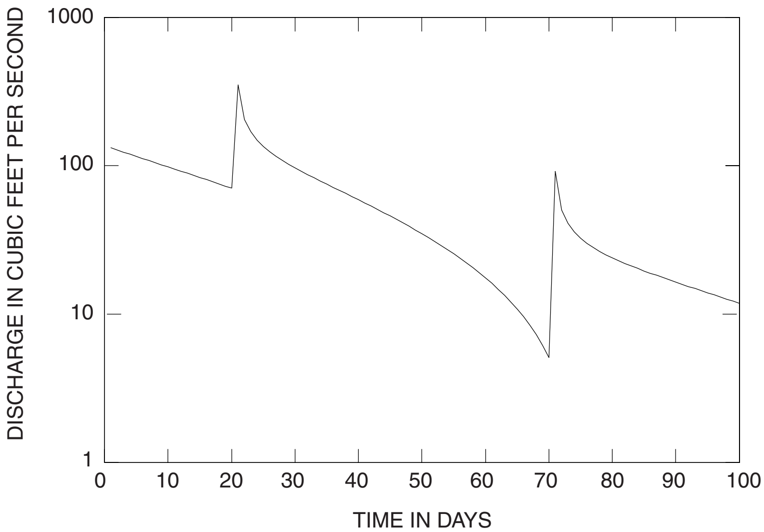


Figure 4. An application of the model for hypothetical data showing the effects of a period of ground-water evapotranspiration between two instantaneous pulse recharge events. (Recession index = 70 days per log cycle; Drainage area = 100 square miles)

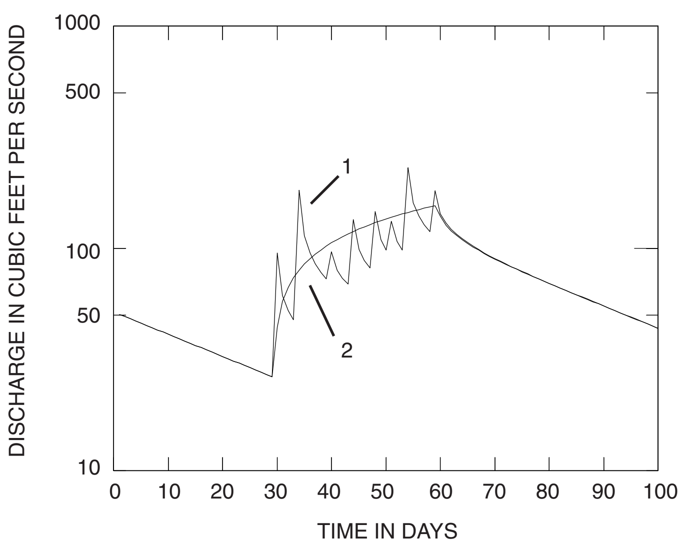


Figure 5. Applications of the model for hypothetical data showing the effect of a period of recharge that is simulated in two different ways with the same total recharge: (1) recharge occurring as eight pulse recharge events, and (2) recharge occurring gradually.

In some hydrologic evaluations, a long period of frequent recharge caused by multiple pulses can be conceptualized as gradual recharge over the same period. An example showing gradual recharge and pulse recharge applied at the same average rate results in two ground-water discharge hydrographs that have similar general trends (fig. 6). Another example (fig. 7) shows the effect of a period of pulse recharge at a given rate, followed by a period of pulse recharge at a lesser rate. A general decline in flow (ground-water discharge) begins at the start of the period of lesser recharge rate.

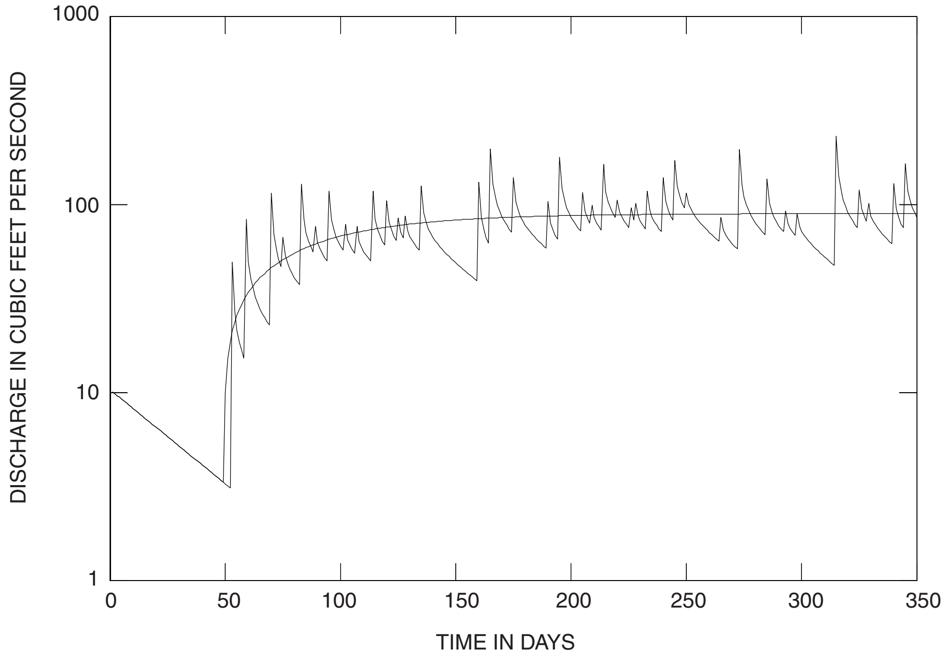


Figure 6. Applications of the model for hypothetical data showing a prolonged period of recharge occurring as (1) a gradual process and (2) a series of pulse recharge events. (In both cases the rate of recharge over time is the same, 1 inch per month.)

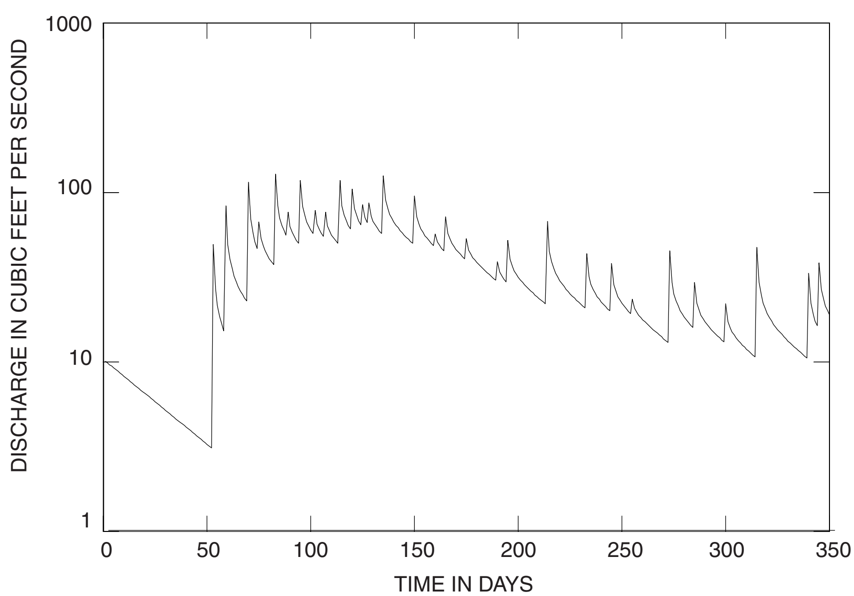


Figure 7. An application of the model for hypothetical data showing a prolonged period of recharge applied as instantaneous pulses at the average rate of 1.0 inch per month (from day 50 to day 150), followed by a prolonged period of recharge applied as instantaneous pulses at the average rate of 0.2 inch per month (from day 150 to day 350).

The effect of GWET on the shape of the semilog hydrograph may vary considerably depending on the timing of GWET and the rate of ground-water discharge at the beginning of GWET. Two hydrographs (fig. 8) are generated using the same recharge amounts but the GWET, which is quantitatively the same in the two instances, occurs from day 150 to day 200 in figure 8A and from day 200 to day 250 in figure 8B. This example demonstrates that the amount of convexity in a semilog hydrograph that is caused by GWET may not be so much a function of the amount of GWET as it is a function of other factors, such as the amount of recharge that occurred before the period of GWET.

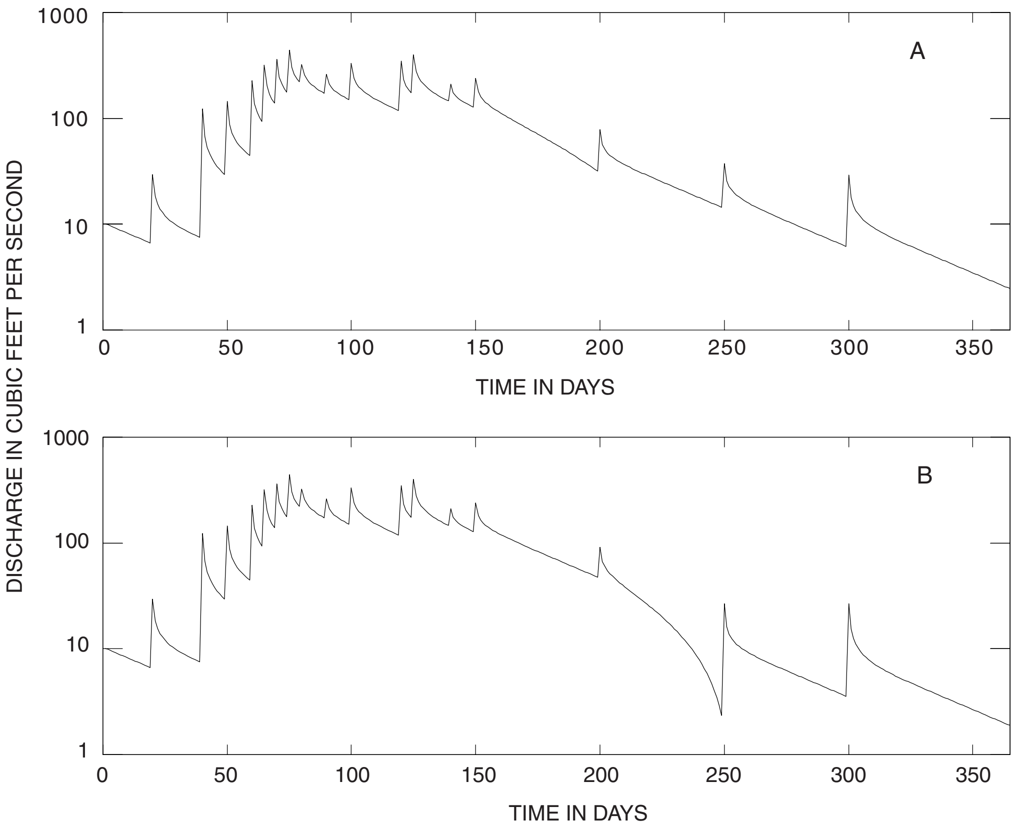


Figure 8. Applications of the model for hypothetical data, caused by the same amount of recharge and the same amount of ground-water evapotranspiration but with ground-water evapotranspiration occurring from day 150 to day 200 in one application (A) and from day 200 to day 250 in the other application (B).

PROCEDURE FOR ESTIMATION OF GROUND-WATER DISCHARGE FOR A STREAM-FLOW HYDROGRAPH

The program PULSE can be used in such a way that recharge and GWET (the input data to the model) are modified in a trial and error calibration process until a reasonable match is obtained between the measured stream-flow hydrograph and the simulated hydrograph of ground-water discharge (the output from the model). The end product of this process includes estimates of ground-water recharge, GWET, and ground-water discharge.

Model Input Variables

The use of the program for the analysis of a streamflow hydrograph requires specification of (1) the drainage area, (2) the initial ground-water discharge, (3) the recession index, (4) the time of surface runoff, and (5) estimates of recharge and GWET. Item 1 is available from streamflow-gaging-station records. The following text explains the methods for obtaining items 2-5. The calibration process, which consists largely of estimating recharge and GWET (item 5), may also include adjustments of items 2-4, as shown in an example.

Initial Ground-Water Discharge

The initial ground-water discharge often can be obtained directly from the hydrograph; the user specifies it to be equal to the streamflow on the first day of the period of interest. Some judgment is required if a storm occurs on or near that day. The starting date can be any day of the year, and is specified in the input file. Most applications shown in this report specify the starting day to be January 1. The initial flow might be zero in some applications (figure 2A).

The Recession Index

To obtain the recession index, the hydrologist usually must scan a considerable amount of streamflow record to find periods of continuous recession that are of sufficient duration. Such periods may occur infrequently. For example, Bevans (1986) evaluated a fifteen-year period of record for a stream in Kansas and evaluated base-flow recession curves for five different periods of continuous recession. For that study, the resulting recession index was 32 days per log cycle, as shown for three periods of continuous recession (fig. 9). Automated methods can be used to calculate the recession index, such as the computer program RECESS (Rutledge, 1993). Analysis of recession characteristics of 157 basins in a large part of the eastern United States consisted of extracting roughly 5 to 10 continuous recession segments per decade of streamflow record (Rutledge and Mesko, 1996, table 2). Another automated method for obtaining the recession index was used by Arnold and others (1995).

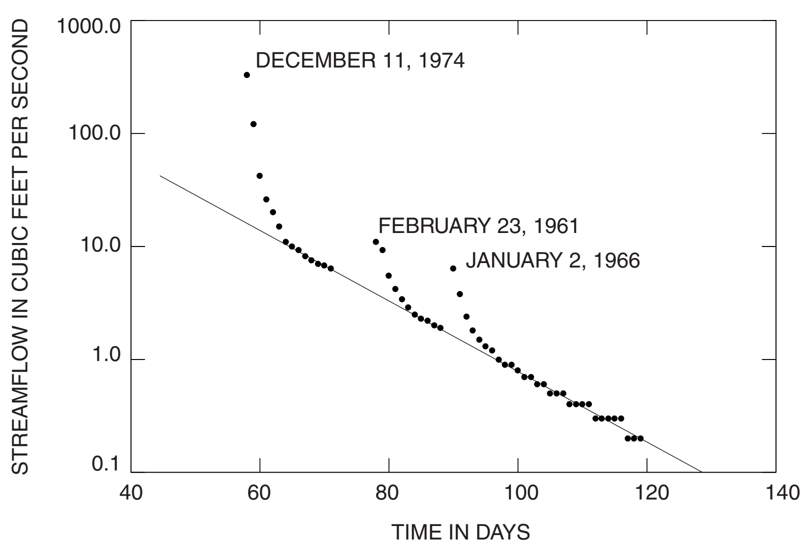


Figure 9. Determination of the recession index for Big Hill Creek near Cherryvale, Kansas. (U.S. Geological Survey station number 07170700. Each solid circle represents a daily mean streamflow, and dates represent the time of a hydrograph peak. The straight line is the extrapolated slope of the base-flow recession curve, 32 days per log cycle. Modified from Bevans, 1986.)

Even under nonideal conditions in which periods of continuous recession are short, the error in the estimate of the recession index from such periods can be relatively small. For example, most of the hydrograph in figure 7 shows the effects of frequent recharge events after day 50. This time period may seem problematic for estimation of the recession index. However, the inclination of the segment from day 207 to 212 is roughly 90 days per log cycle, and the inclination of the segment from day 265 to day 272 is roughly 95 days per log cycle. The actual recession index is 100 days per log cycle. These errors might be small compared to errors associated with alternative methods. For example, connection of low points during the general period of recession in the latter half of the hydrograph would result in much larger errors.

Recession indexes determined from different recession segments on a hydrograph may show considerable variation. This is because, unlike a hydrograph such as figure 7, that was generated from the Rorabaugh model, a hydrograph for a real stream will exhibit variations caused by heterogeneity of aquifer properties, nonuniformity of recharge prior to the various recession segments, and a variety of other complications (Rutledge and Mesko, 1996, pages 5-15). The author suggests that the median value among the range of recession indexes that may be obtained should be used in the input data file for program PULSE.

Testing might be done, using hydrographs such as figure 7, to determine the limitations of the method of determining the recession index from periods of continuous recession. It might be found, for example, that if a considerable number of recession segments for a stream exhibit recession indexes greater than 200 days, then the actual recession index may be considerably larger than the inclination of individual segments.

In some circumstances, the recession index K might be estimated indirectly using estimated or measured values of a, T, and S_y, along with equation 5, instead of obtaining K directly from the streamflow record. An estimate of a might be determined using a rearrangement of equation 3:

$$a = \frac{A}{2L} \qquad (11)$$

This equation can be solved by measuring (on topographic maps) the total length of all perennial streams (L) in the area (A). For some regions, generalizations about stream networks are available in the literature. Langbein (1947) found that stream density (L/A) averaged 1.65 miles per square mile for basins in the northeastern United States. Stream density averages 1.8 miles per square mile among 61 basins in Massachusetts (Ries, 1994, table 6). These stream densities correspond to a= 1,600 and 1,500 feet, respectively.

Estimation of the recession index from equation 5 is subject to substantial uncertainty under the best of circumstances. To illustrate the magnitude of such uncertainty, the finite-difference ground-water flow model MODFLOW (McDonald and Harbaugh, 1988) is used to generate a synthetic hydrograph for an aquifer of uniform hydraulic properties and simple stream geometry (fig. 10). Analysis of the synthetic hydrograph resulted in a recession index of 100 days. Had the recession index been estimated from known hydraulic properties using equation 5 and a value of a determined from equation 11, the recession index would be 75 days. This difference arises only from geometric factors, and might be even larger if T and S_y values also were uncertain. For example, if the uncertainty in each variable T, S_y, and a were 30 percent above and below some "central" value, then the range of possible values of the recession index would be roughly an order of magnitude. Consequently, the recession index should be determined directly from streamflow records whenever possible.

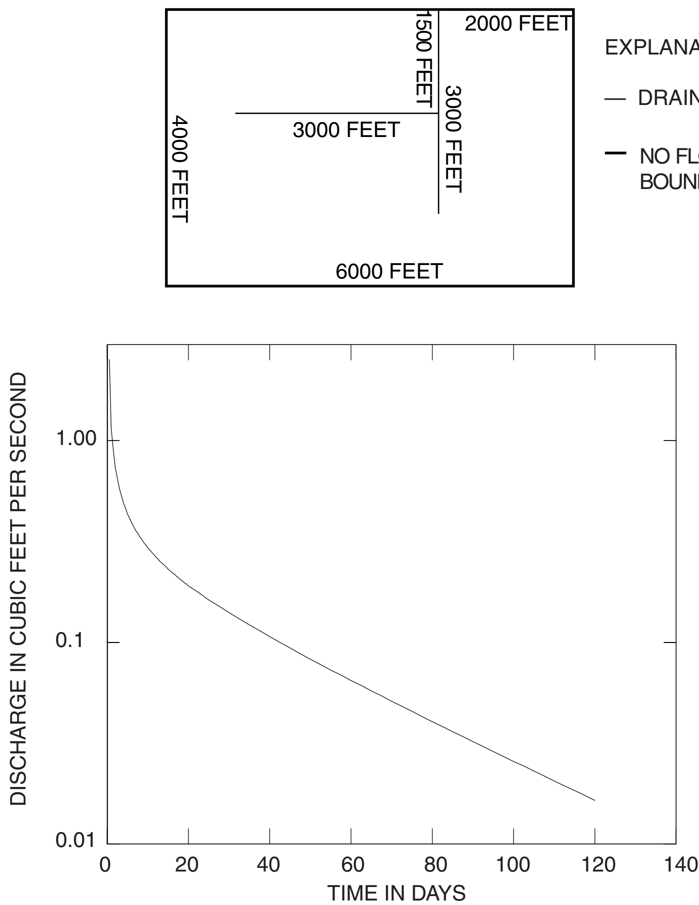


Figure 10. Results of a finite-difference simulation of the recession of ground-water discharge after a recharge event for a simple stream network. (Transmissivity= 5,000 feet squared per day; Storage coefficient= 0.1; Head in all drains= zero; Recharge at initial time= 1 inch. All finite-difference cells are 100 feet by 100 feet.)

The Time of Surface Runoff

To solve the problem of estimating model input (recharge and GWET) from the combined system that consists of surface runoff and ground-water discharge, the user must specify which periods of the streamflow hydrograph represent ground-water discharge only. The only streamflow data that are used in the calibration process are data from those periods. Such time periods can be determined using an estimate of the time of surface runoff, which is defined for the purposes of this report as the time from a peak in streamflow to a point in time after the peak when surface runoff ceases. After that point in time, all flow is attributed to ground-water discharge. An estimate of the time of surface runoff might be obtained using the following relation, from Linsley and others (1982):

$$N = A^{0.2} \tag{12}$$

where N = the number of days after the peak in streamflow and A = the drainage area in square miles.

Equation 12 is a simple relation that may not be reliable in all hydrologic systems. The time of surface runoff might involve other variables in addition to the drainage area, such as the channel slope and physiographic setting. Although little information on the time of surface runoff is available from the literature, the concept of lagtime might be useful because it has been related to various basin properties, including channel slope. From unit-hydrograph theory, lagtime is defined as the time from the centroid of the rainfall excess to the centroid of the run-off hydrograph. Lagtime is generally considered to be constant for a basin. An approximation might be made that the time of surface runoff is 2 or 3 times the lagtime, from dimensionless unit hydrographs (Inman, 1987, figure 7; U.S. Soil Conservation Service, 1972, figure 16.2). Formulations derived by Sauer and others (1983) express the lagtime of urban watersheds in the United States as a function of basin length, channel slope, and a basin development factor. Formulations derived by Inman (1987) express the lagtime of streams in Georgia as a function of drainage area and channel slope. One of the formulations used by Inman (1987, table 8) is for basins north of the fall line and the other for basins south of the fall line (figure 11). The fall line generally represents the northern boundary of the Coastal Plain in Georgia.

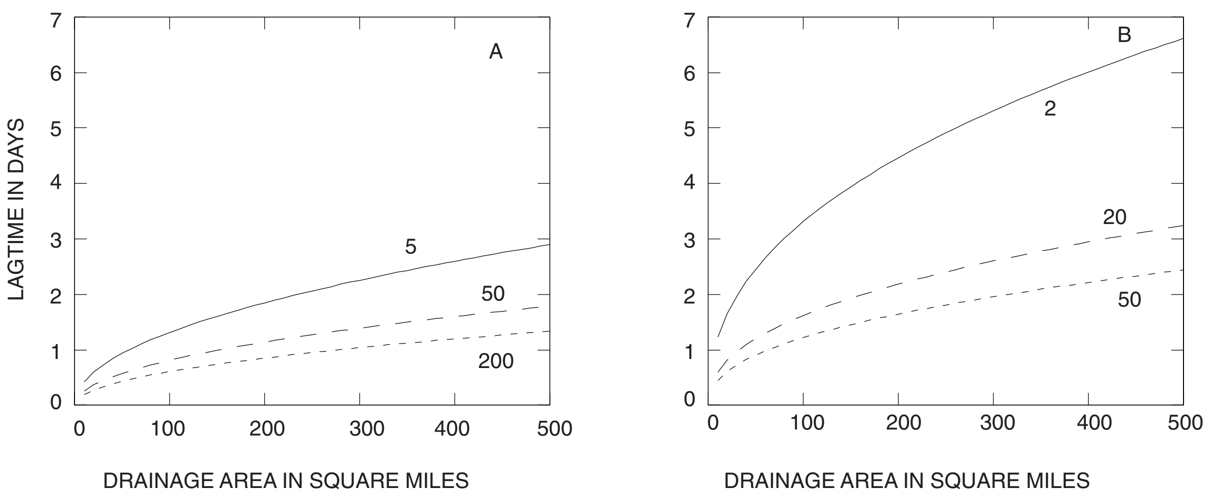


Figure 11. Generalized estimates of the lagtime of streams in Georgia shown for (A) streams north of the Fall Line and (B) streams south of the Fall Line, from Inman (1987, table 8). (The numbers on the curves represent stream-channel slope in feet per mile.)

The formula from Linsley (equation 12) and the concept of lagtime give best results for simple hydrographs caused by storm events of relatively short duration. In the calibration process for the program PULSE, the user must apply judgment because some parts of the streamflow hydrograph that occur a sufficient number of days after the last peak in streamflow may include effects of direct runoff. This can happen because occasionally a storm event will continue for a considerable time after the peak in streamflow. A more rigorous use of the model (not described in this report) might include the use of a precipitation record in addition to the streamflow record for determining which parts of the streamflow record to use in the calibration process. In this case, the designation of days when streamflow can be attributed solely to ground-water discharge might be determined on the basis of the number of days that have transpired since the last significant precipitation.

The results from Inman indicate that in some parts of the Georgia Coastal Plain, particularly areas of very small slope, the basin response can be extremely slow (figure 11B, the curve for slope= 2 feet per mile). Slow response time is also shown for a basin in the Coastal Plain of New Jersey (Langbein, 1947, figure 48). In these circumstances, the time of surface runoff might be large relative to the typical time between subsequent recharge events. This is problematic because ground-water discharge should then be considered undefined for large parts of the hydrograph. The problem is noted here for basins in the Coastal Plain, but may also occur in other regions of low relief. In some circumstances of extremely slow basin response time, the model should not be used.

Estimation of Recharge and GWET

After basin area, beginning ground-water discharge, the recession index, and the time of surface runoff are determined, the user begins a calibration procedure to determine recharge and GWET. This could be done entirely by trial and error, although a more efficient approach is to use the Rorabaugh Method for estimating recharge for each recharge pulse. This method, which has been described by Wilder and Simmons (1982, pages 8-12), Bevans (1986, pages 57-59), and Gerhart and Lazorchick (1988, pages 38-41), is actually the inverse problem of simply applying equation 7. In other words, the recharge is not an input variable, but is instead calculated. An auxiliary computer program, PREP, is provided with PULSE for the purpose of making initial estimates of recharge (see "Computer Implementation"). PREP is based on the Rorabaugh Method. Initial estimates generated by PREP will not include GWET.

The calibration process includes adjusting the estimates of recharge until there is reasonable agreement between the model-computed hydrograph of ground-water discharge and the streamflow record on parts of the hydrograph that are considered to represent solely ground-water discharge (figure 12). The process should be executed forward in time: from left to right on the hydrograph. An adjustment for the calculation of a given peak may have an effect on the model fit for the next peak, although this effect will diminish with time.

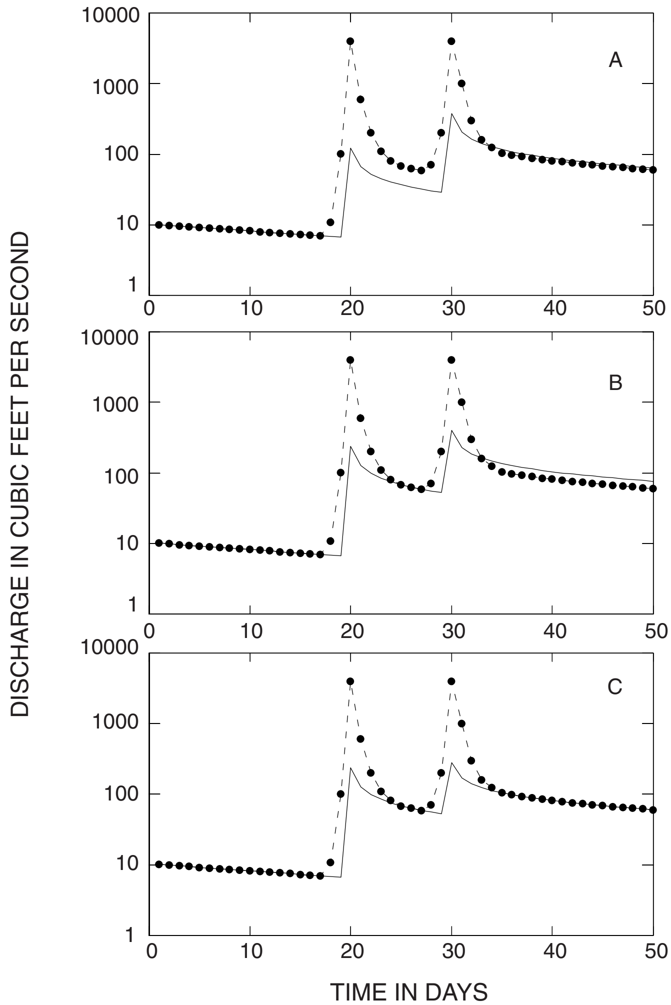


Figure 12. Example steps in the calibration process for two peaks in the streamflow hydrograph, showing (A) results given by initial estimates of recharge, (B) results after the recharge estimate for the first peak is increased to a more favorable amount, and (C) results after the recharge estimate for the second peak is decreased to a more favorable amount. (The solid curve is the model-estimated ground-water discharge and the solid circles are daily values of streamflow.)

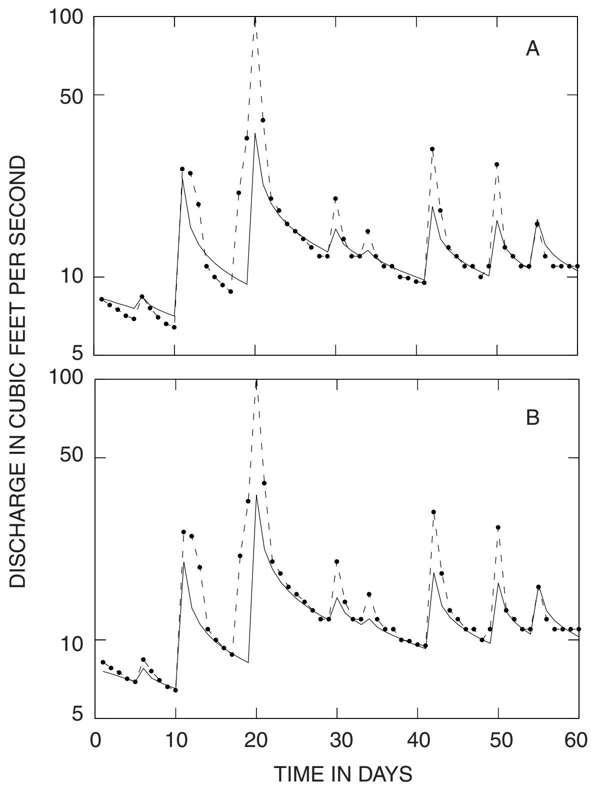
Ideally, if the calibration process has been effective, then the model-simulated ground-water discharge should closely match the streamflow record on days that are specified as representing solely ground-water discharge. However, various factors can cause the simulated ground-water-discharge hydrograph to depart from the streamflow hydrograph on such days. One such factor is that GWET is not specified in the model application at times when it may be occurring. Other factors can be described as noise in the observed “output signal,” and include (1) residual, direct-surface runoff on days that are specified to represent solely ground-water discharge; (2) a streamflow record that is not representative of basin output because of small undocumented diversions or underflow near the gaging station; and (3) errors in the streamflow record caused by such things as ice in the stream, rounding of numbers, and changes in the stream stage control (causing the stage/discharge rating to be unreliable).

If the vertical scale of the hydrograph is a log scale, the relative errors on the hydrograph will be distorted. In other words, an error at low flow may seem as large as an error at larger flows, although the latter may be a more quantitatively important error. The streamflow data may have substantial error during periods of low flow at some sites. These factors need to be considered so that marginally-accurate low-flow rates do not dominate the calibration process. The program user might display results of simulations using the linear scale along with the display using the log scale.

Example Applications

The program PULSE is applied to data for Indian Creek near Troy, Alabama as an example. The application uses the recession index for this basin (102 days per log cycle) determined by Daniel (1976). The parts of the streamflow record that can be used in the calibration process are those that occur after the last streamflow peak by an amount of time that is at least equal to the time of surface runoff. The time of surface runoff for the example basin (drainage area = 8.88 square miles), according to equation 12, is 1.5 days. This is rounded upward to 2 days because the streamflow record is available only on a daily basis. Another estimate of the time of surface runoff might be inferred from Inman’s generalized estimates of the lagtime (figure 11B). The channel slope for the example basin is roughly 20 feet per mile in the main channel and 50 feet per mile in tributary channels. If the main channel controls runoff characteristics, then the lagtime is 0.6 days (figure 11B). If the time of surface runoff is 3 times the lagtime, then it is roughly 1.8 days, which also is rounded upward to 2 days.

Figure 13A shows the measured streamflow hydrograph with the simulated ground-water-discharge hydrograph that results from the initial estimate of recharge given by the auxiliary program PREP (see Computer Implementation). Figure 13B shows the simulated ground-water discharge hydrograph after a calibration procedure to minimize the differences between modeled ground-water discharge and streamflow on days that are considered to represent solely ground-water discharge. The calibration process included a reduction in the estimate of recharge for the peak on day 11. Other adjustments in the estimates of recharge were made in the calibration process (tabulations in figure 13).



A

Time (days)	Recharge (inches)
6	0.05
11	0.83
20	1.31
30	0.16
34	0.05
42	0.45
50	0.33
55	0.31

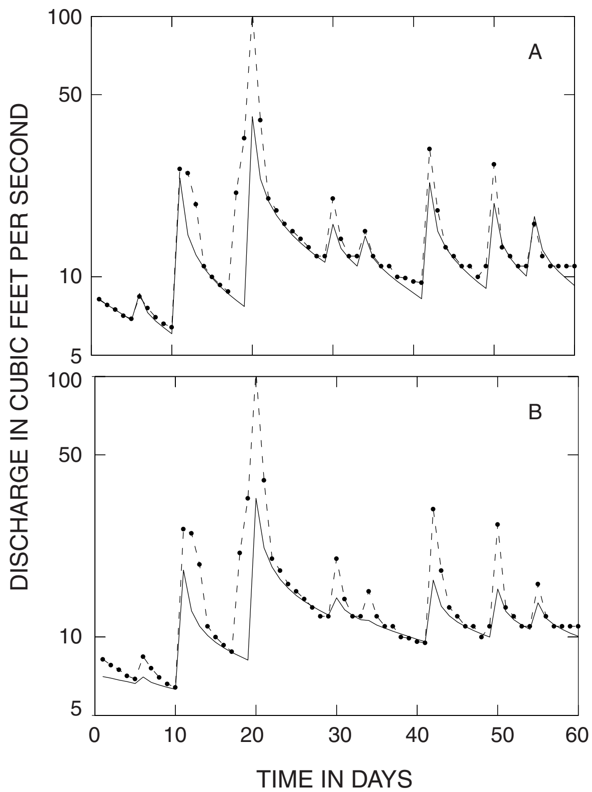
B

Time (days)	Recharge (inches)
6	0.05
11	0.67
20	1.38
30	0.15
34	0.05
42	0.45
50	0.35
55	0.30

Figure 13. Model-estimated ground-water discharge (solid curve) and measured streamflow (dotted curve with symbols representing daily values) for Indian Creek near Troy, Alabama, for the first 60 days of calendar year 1963, showing calculations for (A) initial estimates of recharge and (B) estimates of recharge after a calibration process. (U.S. Geological Survey station number 02371200; Recession index = 102.0 days per log cycle; Drainage area = 8.88 square miles.)

Although the calibration process consists largely of modification of recharge, it can also include adjustments in the initial ground-water discharge, the recession index, and the time of surface runoff. For example, the estimate of the initial ground-water discharge that is given by the auxiliary program PREP is apparently too large (figure 13A). This was adjusted in the calibration process (figure 13B). Adjustments might also be made because of uncertainty in the time of surface runoff. As explained earlier, the time of surface runoff might be estimated using a method such as equation 12, which is a general guideline based upon simple storm events caused by precipitation of short duration. Because many storm events do not occur in this way, user judgment is often required. Although day 13 is 2 days after the last peak, the streamflow on that day apparently reflects the effects of direct runoff and should not be used in the calibration process (figure 13). In order to minimize errors due to direct surface runoff, the program user might designate the time of surface runoff to be larger than the result of equation 12 for the entire analysis. For example, the time of surface runoff might be increased to 3 days for the example basin. This might result in a net reduction in errors, as long as the estimate of the time of surface runoff does not exceed the time between most consecutive recharge events. At some point when increasing the estimate of the time of surface runoff, other errors may result because ground-water discharge is considered to be undefined. The program user needs to achieve a balance between minimizing one type of error and another.

The recession index is a model-input variable, but the validity of its estimate can be evaluated as part of the calibration process. This evaluation is advisable because of variability of recession characteristics of a given basin. For example, the recession index for Indian Creek near Troy is 102 days per log cycle according to Daniel (1976), and is 90 days per log cycle according to Bingham (1982). The author analyzed the streamflow record for this station for the period 1958-1986 using the computer program RECESS (Rutledge, 1993). This analysis consisted of extracting only those periods of continuous recession that began in the six cooler months of the year in order to minimize errors resulting from GWET. The distribution of the recession index among 30 recession segments included a 25th percentile of 61 days per log cycle and a 75th percentile of 113 days per log cycle. An evaluation of recession characteristics for several streams in the southeastern sand aquifer (an area that includes Indian Creek near Troy) concluded that “in theory, each basin is associated with one recession slope but in actual practice the slopes may be different depending upon the interpreter” (Stricker, 1983, page 14). Another evaluation of base-flow recession characteristics that included a large part of the eastern United States noted several reasons for variation in the recession characteristics of any given basin (Rutledge and Mesko, 1996, page 6). A change in the model-input recession index for Indian Creek near Troy, from 102 days per log cycle to values that are 0.5 and 1.5 times this amount, followed by recalibration, causes slight variation in the appearance of the ground-water discharge hydrograph, and results in small changes in the estimate of recharge for the 60-day period (figure 14). The 60-day recharge is 3.2 inches for figure 14A and 3.6 inches for figure 14B.

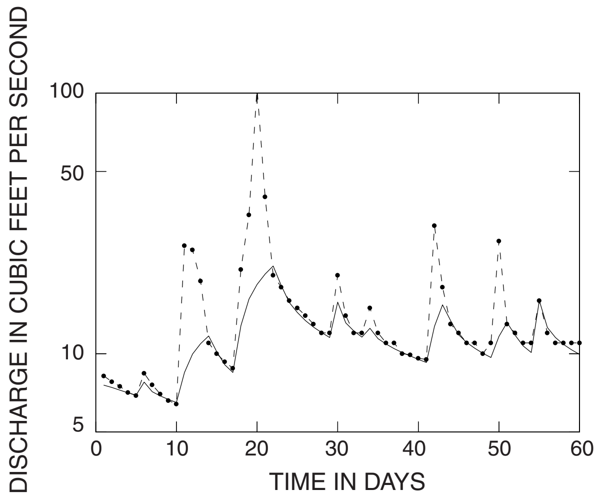


Time (days)	Recharge (inches)
6	0.07
11	0.60
20	1.12
30	0.17
34	0.13
42	0.50
50	0.35
55	0.25

Time (days)	Recharge (inches)
6	0.03
11	0.75
20	1.65
30	0.15
34	0.02
42	0.45
50	0.35
55	0.20

Figure 14. Model-estimated ground-water discharge (solid curve) and measured streamflow (dotted curve with symbols representing daily values) for Indian Creek near Troy, Alabama, for the first 60 days of calendar year 1963, showing calculations resulting from recharge applied as instantaneous pulses after a calibration process, using an experimental value of the recession index equal to (A) 51 days per log cycle, and (B) 153 days per log cycle. (U.S. Geological Survey station number 02371200; Drainage area = 8.88 square miles.)

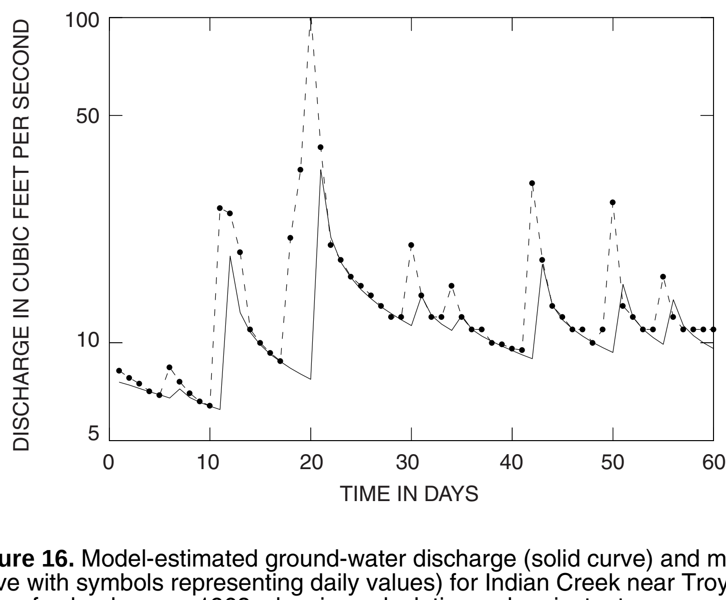
Because the conceptualization of recharge as an instantaneous pulse may not be realistic, the model can be evaluated by considering recharge as a gradual process that occurs during all or most of the period of direct surface runoff. The result of this process for the example basin (figure 15) is a total recharge amount that is reasonably close to the total recharge amount for instantaneous recharge (the total recharge for the 60-day period is 3.40 inches and 3.17 inches for the simulations of figures 13B and 15, respectively). The agreement between these estimates of total recharge is consistent with findings from the example illustrated in figure 5. That example showed that when the recharge is the same the position of the recession curve after recharge becomes the same in two very different conceptualizations of the recharge. Conversely, the example applications in figures 13B and 15 show that if the model is calibrated to minimize the differences between the simulated ground-water discharge and the measured streamflow during the periods of recession, then two very different conceptualizations of recharge can result in estimates of recharge that are very close.



Time (days)	Recharge (inches)
6	0.05
11-15	0.48
18-23	1.35
30	0.23
34	0.07
42-44	0.42
50-52	0.26
55	0.31

Figure 15. Model-estimated ground-water discharge (solid curve) and measured streamflow (dotted curve with symbols representing daily values) for Indian Creek near Troy, Alabama, for the first 60 days of calendar year 1963, showing results when recharge is applied as gradual and instantaneous pulses for various recharge events. (U.S. Geological Survey station number 02371200; Recession index = 102.0 days per log cycle; Drainage area = 8.88 square miles.)

Further experimentation shows the effect of changing the time of instantaneous recharge from concurrent with the peak in streamflow (figure 13) to one day after the peak (figure 16). After calibration, the new estimate of recharge is smaller than the estimate given when recharge is concurrent with the peak in streamflow (3.40 inches for figure 13B and 3.11 inches for figure 16). The conceptualization of recharge as a gradual process may result in a conservative estimate for this station because the centroid of recharge for most peaks is occurring after the time of the peak in streamflow. Adjustments in the time of instantaneous recharge might be made because the hydrologist believes that recharge occurs at a time other than the time of the peak in streamflow. The adjustment is a function of drainage area because the time of the streamflow peak can vary with drainage area.



Time (days)	Recharge (inches)
7	0.03
12	0.61
21	1.31
31	0.15
35	0.08
43	0.43
51	0.30
56	0.20

Figure 16. Model-estimated ground-water discharge (solid curve) and measured streamflow (dotted curve with symbols representing daily values) for Indian Creek near Troy, Alabama, for the first 60 days of calendar year 1963, showing calculations when instantaneous recharge events are considered to occur one day after the peaks in streamflow. (U.S. Geological Survey station number 02371200; Recession index = 102.0 days per log cycle; Drainage area = 8.88 square miles.)

The period of relatively high ground-water discharge in early 1963 was followed by a period of considerably less ground-water discharge, as shown on a hydrograph of the 1963 calendar year (figure 17). The total ground-water discharge for 1963 is 7.2 inches. The ground-water discharge in the first 3 months of 1963 is 4.6 inches. The simulation for calendar year 1963 includes a period of GWET represented by convex recession on the semilog scale (figure 17A). The rate of GWET was specified for model input to be the same as that estimated by Daniel (1976, pages 361-362). The rate of GWET might vary among the warm months of the year, according to variation in the depth to ground-water levels and rate of plant growth. The total GWET simulated (figure 17) is only 0.5 inch and occurs from early April (day 90) to mid-June (day 169). Considerable error is associated with the GWET component of the hydrologic budget; however, the resulting errors in the basin hydrologic budget are very small because GWET makes up a very small part of that budget. The program user should place considerably more reliance on the other estimates; for example, the total ground-water discharge calculated by the model. The analyst might use linear plots in addition to semilog plots in the calibration process (figure 17B) as a guide to determine the relative magnitudes of errors at various parts of the hydrograph.

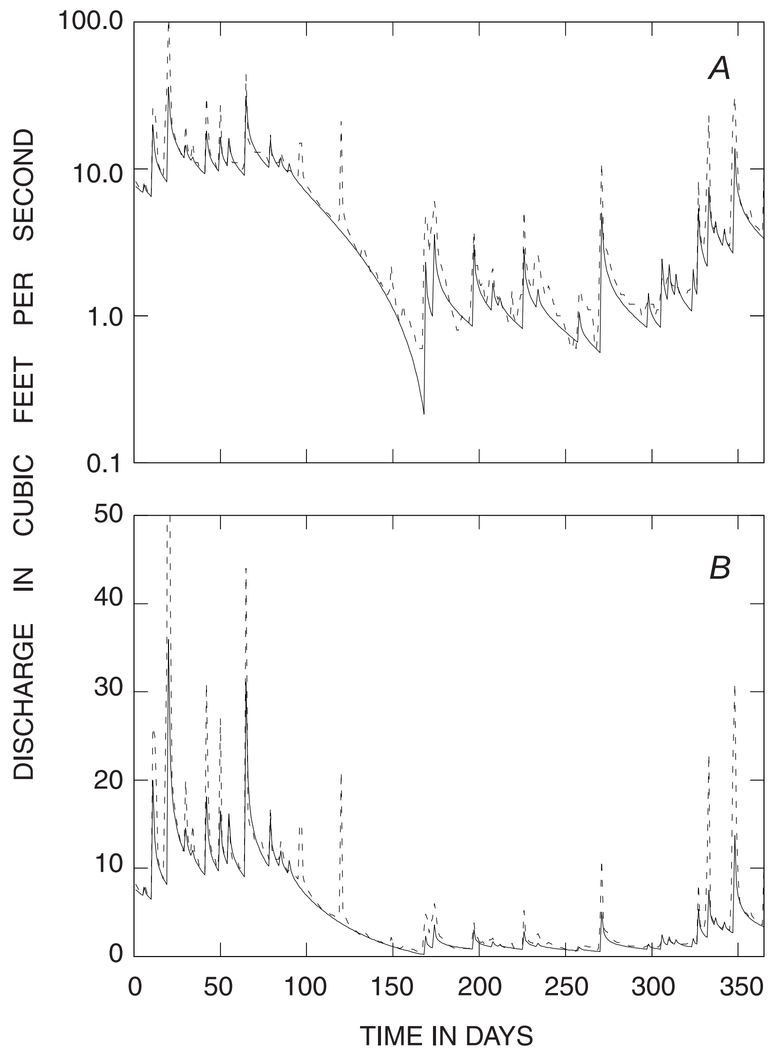


Figure 17. Model-estimated ground-water discharge (solid curve) and measured streamflow (dotted curve), for Indian Creek near Troy, Alabama, for calendar year 1963, shown using (A) logarithmic and (B) linear plots. (U.S. Geological Survey station number 02371200; Recession index = 102.0 days per log cycle; Drainage area = 8.88 square miles. Total streamflow is 9.0 inches and total ground-water discharge is 7.2 inches, for the time period shown.)

The program is designed primarily for analyzing a calendar year of record, but because it can work with two consecutive calendar years at a time, it can be used to simulate various multiple-month periods. This feature is useful for applications in which a recharge season begins in the fall of one year and continues through the spring of the next year. For example, the program can be used to simulate a buildup of ground-water discharge that began in late 1962 and continued into early 1963 for Indian Creek near Troy (figure 18). The simulated recharge for the period November 1 to March 31 is 7.3 inches. Other estimates were obtained previously using manual methods. These estimates were 6.7 inches using the gradual-recharge approximation, and 7.2 inches using the instantaneous-recharge approximation (T. Winter, U.S. Geological Survey, written commun., 1996). The analysis of records from the cooler months for this station and others (figs. 18-21) can be simpler than analysis of the entire year because GWET can be considered negligible. The x-axis in these illustrations begins with the 275th day of the first calendar year.

Illustrations in this report show examples of hydrographs of ground-water discharge that were generated for various streamflow hydrographs by a trial and error method. Considerable subjectivity is built into the calibration process. For example, it was assumed in these examples that recharge occurs as an instantaneous pulse that is concurrent with a streamflow peak. Additional judgments were made by the author in selecting parts of the streamflow record for consideration as representing only ground-water discharge, and deciding upon a general best-fit between the flow on those parts of the record and the flow calculated by the model. As indicated earlier, the gradual recharge concept is more realistic than that of instantaneous recharge, but as long as calibration is performed to address only those parts of the hydrograph that represent ground-water discharge, the recharge estimates over time tend to be similar. The instantaneous recharge method is advantageous, however, because it is less time-consuming. Instantaneous recharge requires only that equation 7 is implemented one time for each recharge event, yet gradual recharge events require that equation 10 is implemented twice for each recharge event. Another advantage of using the instantaneous recharge method is that the auxiliary program PREP will give estimates in this format.

The PULSE model can be applied in cases of zero flow at the beginning and end of the period of interest. This is shown by an example hydrograph for a stream in Kansas that usually goes dry in the summer because of the effects of GWET (figure 22). The period shown includes the period shown in figure 21. The simulation is initiated using a baseline equal to zero, similar to the hypothetical example in figure 2A. Calculations are begun on day number 245 (September 2, 1973) at the beginning of a period of recharge that maintains ground-water discharge above zero until the next summer. The model is calibrated to simulate ground-water discharge until day number 558 (July 12, 1974), at which time the discharge becomes zero again. When this occurs, the model stops calculations because the stream is considered to be dry. The model specifies ground-water discharge to be zero for the remainder of the period shown. The user would need to re-start the model to simulate ground-water discharge later in 1974. Several of the model-input estimates used to simulate the ground-water discharge hydrograph in figures 21 and 22 are from Bevans (1986), including the recession index, the recharge for day number 434 and 439, and the rate of GWET from day 522 to the end of the simulation.

In this specific example (fig. 22), nonideal flow conditions prevail prior to day number 245 and after day number 558. These nonideal flow conditions include ground-water levels below the bottom of the stream channel, negligible ground-water discharge to the stream, and streamflow that consists solely of direct surface runoff. It is worthy of note that flow conditions in the first 50 days of the simulation may not be completely ideal, as is evident from the rapid rate of recession during this period. During this time the Rorabaugh Model may apply to some parts of the basin but not to others.

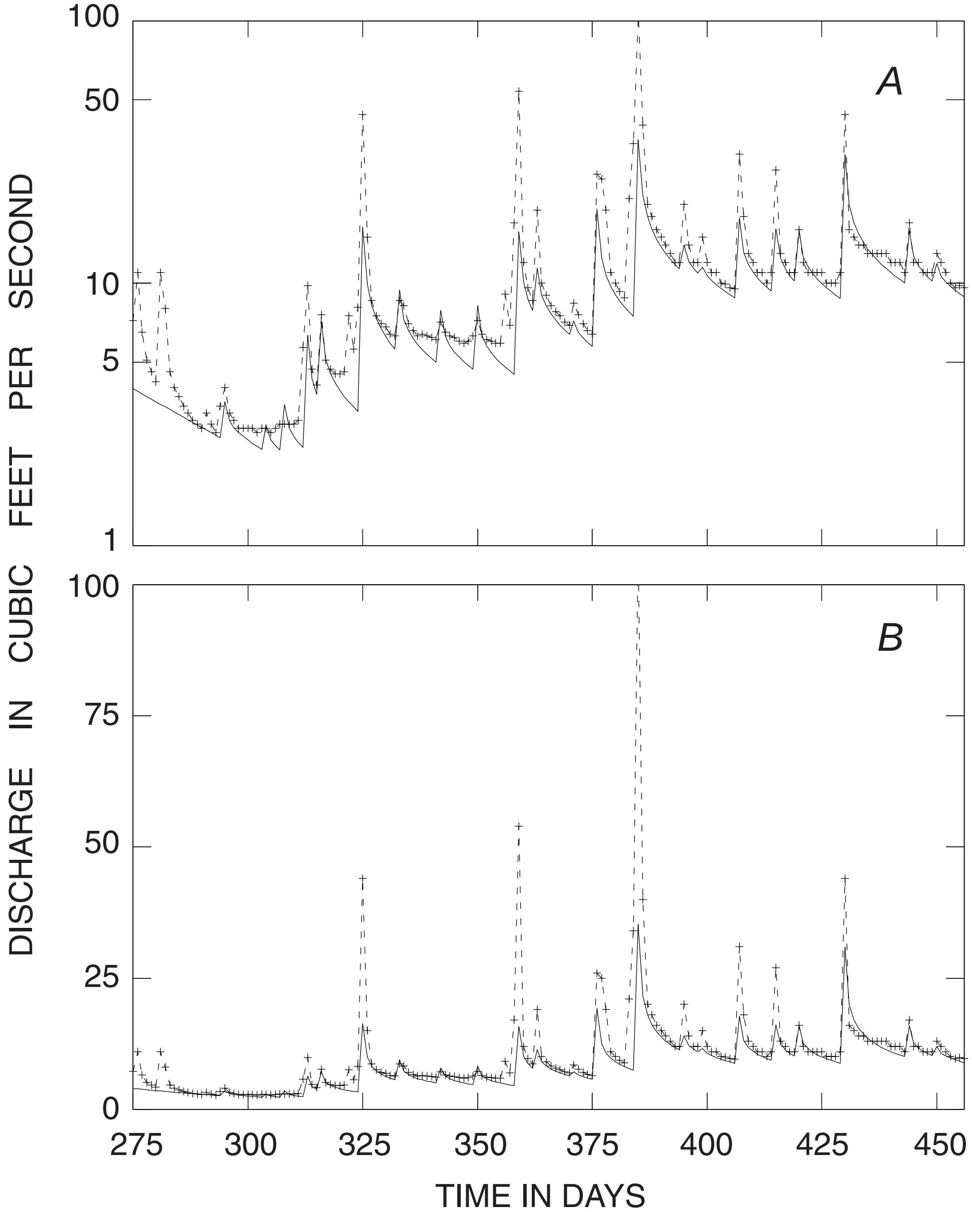


Figure 18.--Model-estimated ground-water discharge (solid curve) and measured streamflow (dotted curve with symbols representing daily values) for Indian Creek near Troy, Alabama, for the period October 2, 1962 (day 275) to March 31, 1963 (day 455), shown using (A) logarithmic and (B) linear plots. (U.S. Geological Survey station number 02371200; Recession index = 102.0 days per log cycle; Drainage area = 8.88 square miles. Total streamflow is 8.1 inches and total ground-water discharge is 6.3 inches, for the time period shown.)

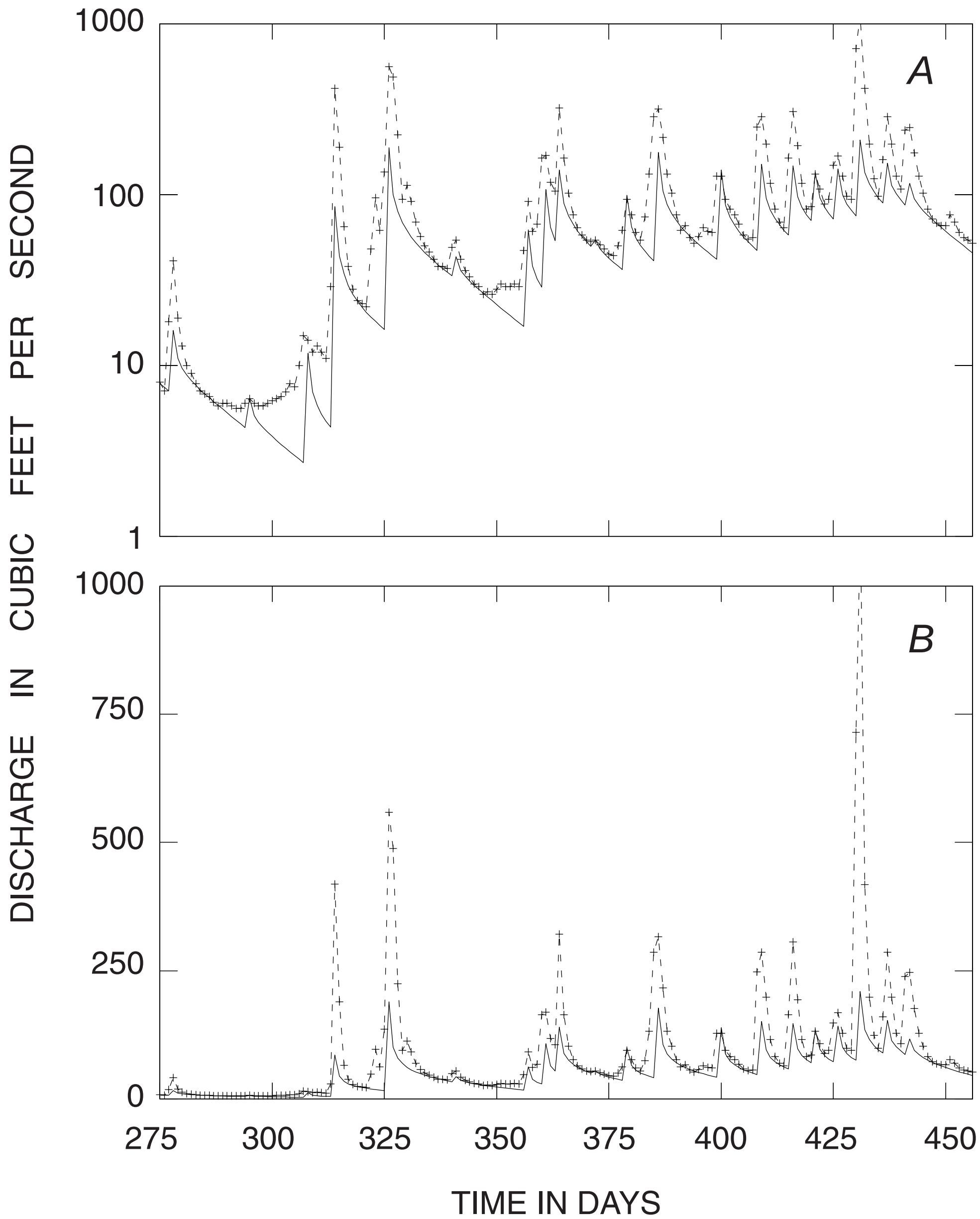


Figure 19. Model-estimated ground-water discharge (solid curve) and measured streamflow (dotted curve with symbols representing daily values) for Fountains Creek near Brink, Virginia, for the period October 2, 1962 (day 275) to March 31, 1963 (day 455), shown using (A) logarithmic and (B) linear plots. (U.S. Geological Survey station number 02052500; Recession index = 47.5 days per log cycle; Drainage area = 65.2 square miles. Total streamflow is 9.8 inches and total ground-water discharge is 5.4 inches, for the time period shown.)

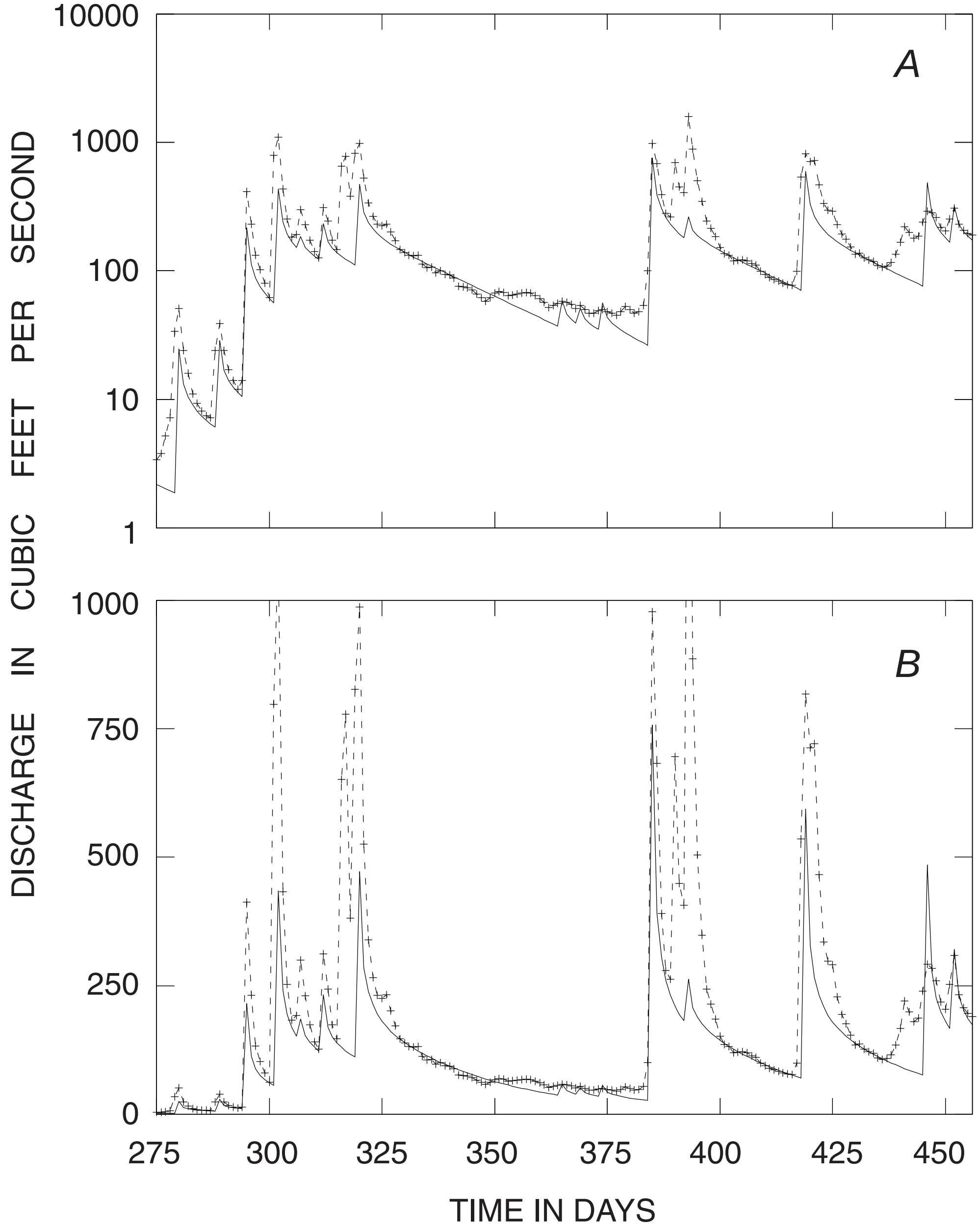


Figure 20. Model-estimated ground-water discharge (solid curve) and measured streamflow (dotted curve with symbols representing daily values) for Little Androscoggin River near South Paris, Maine, for the period October 2, 1995 (day 275) to March 31, 1996 (day 455), shown using (A) logarithmic and (B) linear plots. (U.S. Geological Survey station number 01057000; Recession index = 60.0 days per log cycle; Drainage area = 73.5 square miles. Total streamflow is 18.2 inches and total ground-water discharge is 11.3 inches, for the time period shown.)

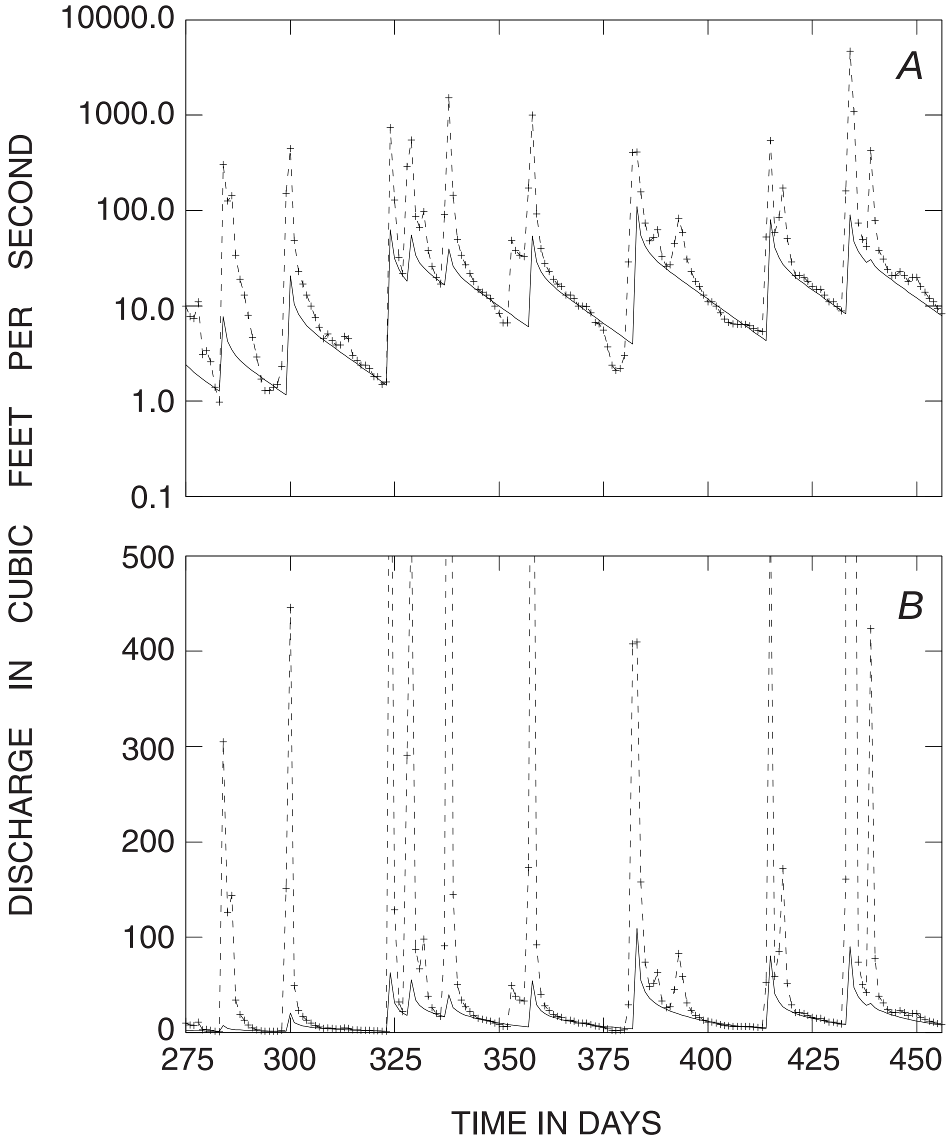


Figure 21. Model-estimated ground-water discharge (solid curve) and measured streamflow (dotted curve with symbols representing daily values) for Big Hill Creek near Cherryvale, Kansas, for the period October 2, 1973 to March 31, 1974, shown using (A) logarithmic and (B) linear plots. (U.S. Geological Survey station number 07170700; Recession index = 32.0 days per log cycle; Drainage area = 37 square miles. Total streamflow is 17.2 inches and total ground-water discharge is 2.7 inches, for the time period shown.)

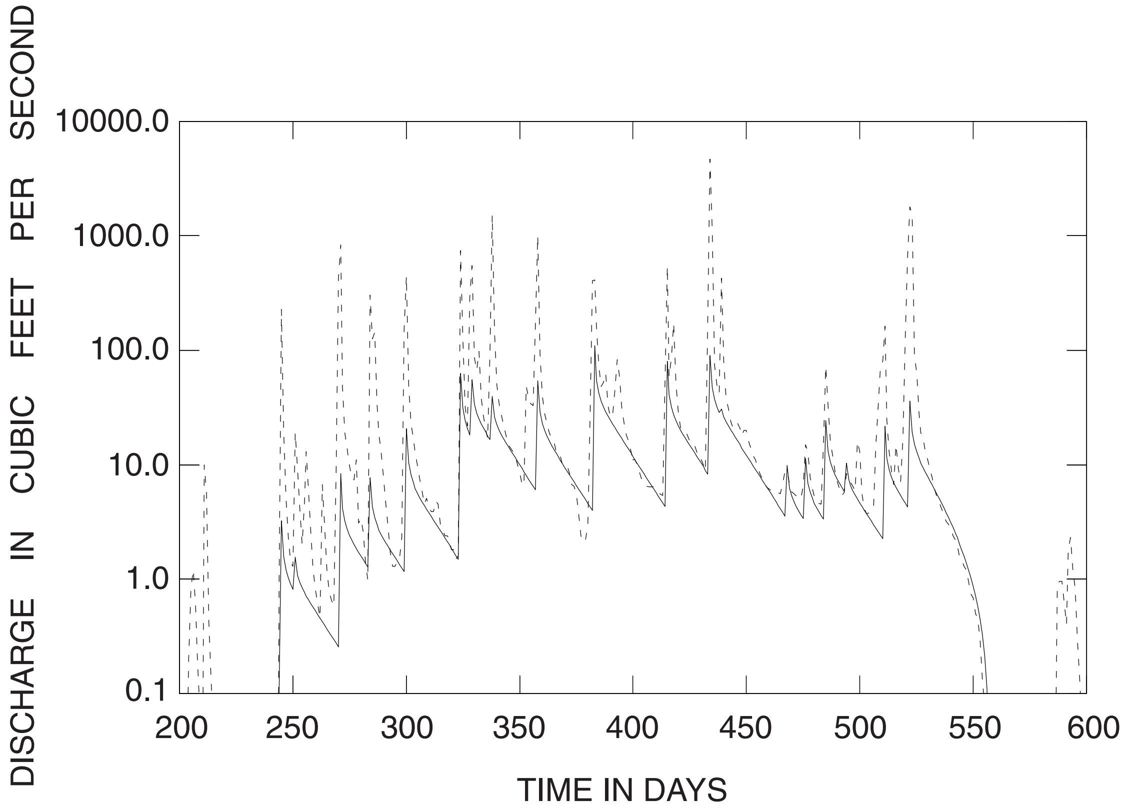


Figure 22. Model-estimated ground-water discharge (solid curve) and measured streamflow (dotted curve) for Big Hill Creek near Cherryvale, Kansas, for summer 1973 to summer 1974. (U.S. Geological Survey station number 07170700; Recession index = 32 days per log cycle; Drainage area = 37 square miles. The x-axis begins with day 200 of calendar year 1973, which is July 19. The initial ground-water discharge is specified to be zero, and model calculations are initiated on day number 245, which is September 2, 1973. Model calculations are stopped on day number 558, which is July 12, 1974, when the modeled ground-water discharge becomes zero. This model application does not give estimates prior to day number 245 or after day number 558. Total streamflow is 24.2 inches and total ground-water discharge is 3.4 inches, for the time period of the model simulation.)

TIME SCALES FOR REPORTING RESULTS

Although the hydrographs shown in this report depict ground-water discharge and streamflow on the basis of daily mean quantities, the recommended time scale for reporting results is larger than a day. During periods of recharge, when direct surface runoff can be occurring, simulation results are nonunique and might vary depending on whether instantaneous or gradual recharge is specified by the program user. During other periods, the model approximates ground-water discharge on the basis of the general agreement among several daily values of streamflow, so that ground-water discharge may not agree with individual streamflow values. The recommended time scale for reporting recharge or discharge quantities is a month (or more). A monthly tabulation of ground-water discharge is shown (figure 23) for the example basin Indian Creek near Troy for the period of record illustrated in figure 17.

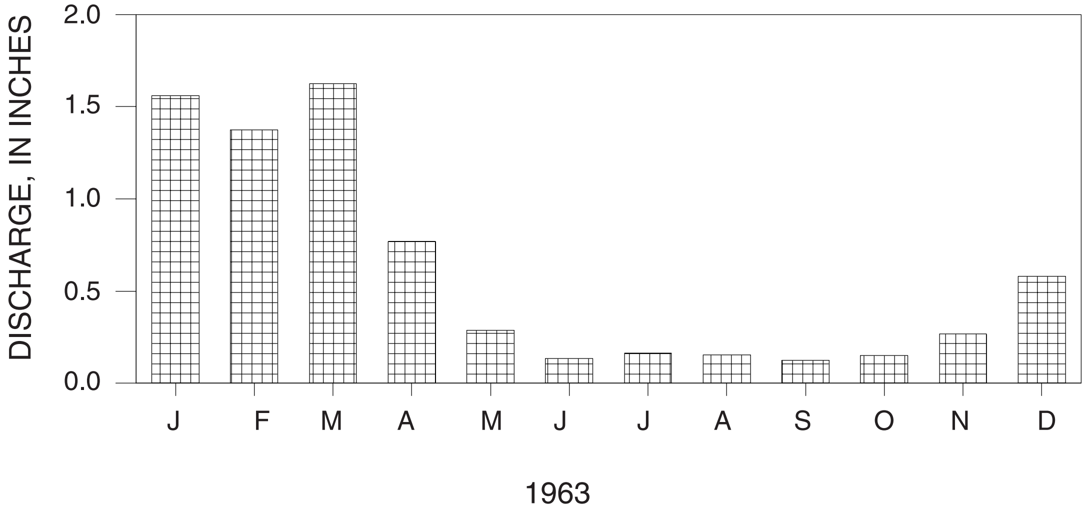


Figure 23. Model-estimated monthly ground-water discharge for Indian Creek near Troy, Alabama, for calendar year 1963. (Same station, time period, and model input as for figure 17. U.S. Geological Survey station number 02371200; Recession index = 102.0 days per log cycle; Drainage area = 8.88 square miles.)

COMPUTER IMPLEMENTATION OF THE MODEL

Computer files associated with this report can be obtained from the location identified in the preface of this report. The “read” file gives instructions for the use of the programs on a Data General AViiON Workstation that is equipped with a Green Hills Fortran compiler, and instructions for the use of the Statit graphics for display of hydrographs. These specific instructions are included because this equipment was used in the development of the programs. The programs can be used on various computer platforms, as long as a Fortran compiler, a line editor, and graphics software are available. The following information will assist in the application of the programs for various computers. Computer-program names and names of other computer files are given here in upper case letters, but the actual file names are in lower case letters.

In the simple application, the program PULSE can be used to generate ground-water discharge without the streamflow record. The user might experiment with this application to gain familiarity with the program. This application might also serve as a research or learning tool. Before program execution, the user must compile PULSE using a Fortran compiler, then create an input data file PULSE.IN. Numerous example input data files are included for this purpose. For example, the file FIG.4, if copied to PULSE.IN prior to execution of PULSE, will cause the program to create the ground-water discharge hydrograph shown in figure 4.

When PULSE is executed, it reads PULSE.IN, and writes output data to files PULSE.SUM and PULSE.OUT. The first of these files gives a summary of the execution of the model, including total recharge, total ground-water discharge, and other data. The file PULSE.OUT is the output data file giving daily mean estimates of ground-water discharge. Each line corresponds to a day. This data file is used to generate graphical displays of the ground-water-discharge.

Additional procedures are necessary prior to execution of PULSE to estimate a ground-water discharge hydrograph for a specific streamflow record. The user must have a daily-values streamflow record in “z-file” format (Rutledge, 1993, figure 2). Instructions for assembling this data file are in pages 7 and 9 of that report and the read file included here. The program TRANS is included for that purpose. When the z-file is available, the user executes program PREP. Program PREP will (1) read the daily-values streamflow file, (2) focus on a 1- or 2-year period of interest requested by the user, (3) write daily-values streamflow data to a flat-file FLAT.SF, (4) make initial estimates of recharge, and (5) create an input data file PULSE.IN that includes these initial estimates and other items needed by the program PULSE. After PREP has been executed, the user begins a repetitive three-step process of (1) modifying PULSE.IN, (2) executing PULSE, and (3) examining the graphical display of the calculated ground-water-discharge hydrograph along with the streamflow hydrograph.

The modifications can include changing recharge amounts for some events, deleting some events, and adding other events. Because initial estimates generated by PREP are based only on the Rorabaugh Model, the user may need to add GWET to file PULSE.IN. It may be necessary to change or delete lines in PULSE.IN that specify negligible recharge. The user should confirm that the “Number of pulse recharge events” on line 6 is correct. By default, program PREP designates the initial ground-water discharge to be equal to the streamflow on the first day of the year (January 1). This may be changed by the user.

After each execution, the user should produce a graphical display of output by executing software that can read PULSE.OUT and generate a graph of streamflow and the ground-water discharge. Editing of PULSE.IN, execution of PULSE, and graphical display are repeated until the user decides that the simulated ground-water discharge agrees reasonably well with the streamflow on those parts of the streamflow hydrograph that represent ground-water discharge. If the user has executed PULSE for analysis of a streamflow record, the program will write monthly results to file PULSE.MON. These monthly results are also written to file PULSE.SUM.

POSSIBLE FUTURE ANALYSIS AND APPLICATION OF THE MODEL

The model described in this report has potential applications other than those shown here. For example, the model might be used to evaluate and compare various “inverse” methods used in the estimation of ground-water recharge from a streamflow record. Two such methods -- the instantaneous-recharge method and the constant-recharge method (Mau and Winter, 1997) -- are based on the mathematical model described by Rorabaugh (1964).

Future application of the model could include various methods to enhance the calibration process. This might include the display of only certain parts of the streamflow hydrograph based on antecedent recession or other criteria that indicate that the streamflow represents ground-water discharge only. Another application of the model might use antecedent days of negligible precipitation (in addition to or instead of antecedent streamflow recession) to determine whether a daily streamflow amount represents solely ground-water discharge. Still another might include automated selection of the best tabulation of pulse recharge, based upon minimizing the sum of errors in the estimates of daily ground-water discharge.

The application of PULSE might be complemented by analysis of changes in ground-water levels in a basin. Recharge events used as model input should coincide in time with upward movements of the water table. This approach should include the use of several wells in the basin, because recharge can vary considerably throughout a basin, and a water-level record from one well represents only a very small part of the basin.

The PULSE model, which can simulate streamflow only during periods when streamflow can be assumed to consist only of ground-water discharge, might be linked to a rainfall-runoff model so that the entire streamflow hydrograph could be simulated. If this linkage is made for the purpose of making estimates at a small time scale (a day, for example), it may be necessary to treat each recharge event not as an instantaneous pulse, but as a gradual process (for example, the condition illustrated by figure 15.)

The PULSE model conceptualizes ground-water evapotranspiration as a loss term that is applied uniformly over the area of the aquifer. An improvement would be a model that would apply GWET only in the near-stream part of the section. Such a model also could be used to evaluate the seasonal variation of GWET.

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