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HYDROGRAPH SEPARATION BY INCORPORATING CLIMATOLOGICAL FACTORS: APPLICATION TO SMALL EXPERIMENTAL WATERSHEDS[1]

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ABSTRACT: Evaluating the relative amounts of water moving through the different components of the hydrological cycle is required for precise management and planning of water resources. An important aspect of this evaluation is the partitioning of streamflow into surface (quick flow) and base-flow components. A prior study evaluated 40 different approaches for hydrograph-partitioning on a field scale watershed in the Coastal Plain of the Southeastern United States and concluded that the Boughton's method produced the most consistent and accurate results. However, its accuracy depends upon the proper estimation of: (1) the end of surface runoff, and (2) the fraction factor (α) that is function of many physical and hydrologic characteristics of a watershed. Proper identification of the end of surface runoff was accomplished by using a second derivative approach. Applying this approach to 12 years of separately measured surface and subsurface flow data from a field scale watershed (study area) proved to be accurate for 87% of the time. Estimation of the α value was accomplished in this study using two steps: (1) alpha was fitted to individual hydrographs: and, (2) a regression equation that determines these alpha values based on climatological factors (e.g., rainfall, evapotranspiration) was developed. Using these strategies improved the streamflow partitioning method's performance significantly.

(KEY TERMS: streamflow partitioning; hydrograph separation; surface runoff/base flow; surface water/ground water interactions; watersheds.)

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INTRODUCTION

The shape of short-duration storm hydrographs occurring over watersheds follows a general pattern that consists of three major components: period of rise (or period of increasing discharge that reaches to the peak or crest), crest period, and period of falloff discharge which may or may not decrease to zero depending on the amount of ground-water flow and size of the watershed. Total flow to stream systems consists of surface runoff, interflow, and base flow (Figure 1). Each of these elements has their own variable timing and characteristics. Streamflow partitioning methods are used for finding the relative contributions of overland flow, base flow and (possibly) interflow to total storm hydrograph in subjective or objective manner during storm events. Such

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partitioning is important for the design of hydraulic structures and evaluation of rainfall-runoff models, especially for low-flow conditions. For example, evaluation of low surface flow and base-flow characteristics can provide valuable information about the ability of a stream to supply sufficient flow for waste disposal, irrigation, and ground-water recharge, while maintaining its natural conditions (DEQ, 2006). Improvement of available techniques or development of a more precise approach may help hydrologists to evaluate alternative management plans regarding water and ecosystem sustainability.

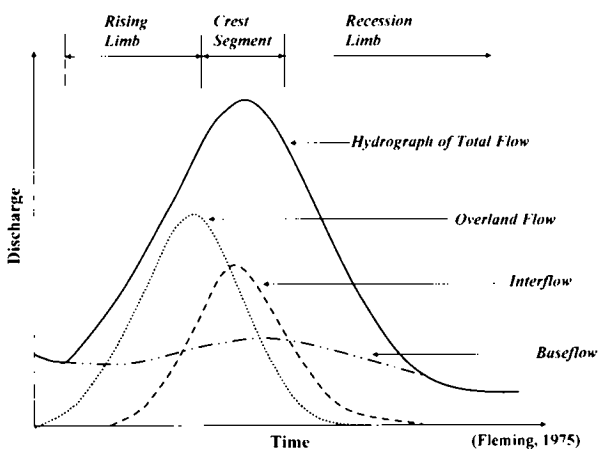

FIGURE 1. Schematic of Total Flow Hydrograph and Its Components.

Similarly, to be able to develop effective management plans, water resources engineers should have good knowledge of water and contaminant transport through different pathways in a watershed. The accurate streamflow partitioning method may be the key for assessment and control of contaminant transport.

Moreover, as floods are among the most common and widespread natural hazard phenomena causing billions of dollars in property damage each year, timely assessment of such events is key to respond to the emergency conditions. Minimizing the damage caused by a flood requires comprehensive information about the water distribution, which can be achieved by accurate streamflow partitioning approach.

Numerous hydrograph separation techniques have been proposed in recent decades. Forty different streamflow partitioning methods were recently reviewed by Nejadhashemi *et al.* (2003), and classified into three-component, analytical, empirical, graphical, geochemical, and automated methods. Their advantages and disadvantages were highlighted for appropriate use and avoid of misuses and five methods: (1) Wittenberg and Sivapalan (1999) and Wittenberg (1999); (2) Nathan and McMahon (1990), Mugo and Sharma (1999), and Eckhardt (2005); (3) Boughton's constant coefficient (1988); (4) Boughton's fraction coefficient (1988); and (5) Sloto and Crouse (1996) were identified as being the most relevant and least input intensive. The performance of these methods were tested against 12 years (1970-81) of independently measured surface and subsurface flow data obtained on a field scale watershed (0.345 ha in area) at the Southeast Watershed Research Laboratory of the USDA-Agricultural Research Service located in the coastal Plain physiographic region of the southeastern United States. Results of this analysis indicated that the Boughton with fraction coefficient (α) method, performs best. The fraction coefficient approach was proposed by Boughton (1988) as an automated method for hydrograph separation. Nejadhashemi *et al.* (2004) demonstrated that the accuracy of this method (the best among those tested) is highly dependent upon the proper estimation of the "fraction coefficient" that represents physical and hydrologic characteristics of the watershed. Proper application of the method further requires a consistent and robust strategy for determining storm hydrograph inflection points. Finally, it was observed that the Boughton's method could be viewed as a particular temporal discretization (backward difference) of the ordinary differential equation.

$$\frac{dQ_b}{dt} = -a_1 Q_b + a_3 Q_t \tag{1}$$

where Q_b is base flow, Q_t is total flow, t is time, and a_1 and a_3 are coefficients.

The goal of this study is to improve the base-flow estimation based on the Boughton's (fraction coefficient) method. The specific objectives are to: (1) develop a robust method for automatic identification of end of surface runoff on the recession limb of the storm flow hydrograph; (2) evaluate the accuracy of the Boughton's method as a function of: (a) the method used for the temporal discretization of Equation (1), and (b) the error criterion used to fit Boughton's method to observed flow; and (3) improve the α-value estimation by developing a regression equation based on watershed's climatological factors (e.g., rainfall, evaporation). The final outcome is expected to significantly improve the streamflow partitioning method's performance.

The method was tested on the 700 ha Back Creek catchment producing results that are similar to the manual separation techniques (Boughton, 1988). The Boughton's method is based on the following assumptions:

(1) Increase in base-flow discharge varies as a function of the total flow increment.
(2) The amount of subsurface flow for the current time step is computed as a fraction of the differ-

ence between the total flow and the base flow on the previous time step. The value of "fraction" is determined by an iteration method based on an operator identified point on the hydrograph, which marks the end of surface runoff. By assuming an initial value for fraction, repetitive computations of base flow are made. The value of fraction for which the base-flow value computed by the program equals to the selected end of surface runoff is identified and used for the entire hydrograph.

(3) Surface flow is equal to the difference between the total flow and the base flow at each time step.

(4) Surface runoff ceases whenever the amount of the total flow at a given time step is less than the base-flow value at the previous time step.

MATERIALS AND METHODS

All steps identified in this study were programmed using Visual BASIC language. The computer programs eliminate the laborious efforts usually undertaken in manual hydrograph separation and provide capabilities for efficient handling of large datasets.

Twelve years of independently measured surface and subsurface flow data, along with 8 years of climatological and management practice data were used to calibrate and verify the developed method. These data are from a small, field-sized watershed in the Coastal Plain physiographic region of Southeast United States. The time interval for all computations is one day because both precipitation and runoff data are based on the daily time step. However, the method can readily be used for smaller time intervals. For all scenarios, the output of the method was constrained so that the sum of the separated flow components was not negative or greater than the total flow. The following sections describe the methods used to analyze the recession limbs, evaluate discretization methods, predict α by regression, and finally describe the study area used in this work.

Identification of the End of Surface Runoff

Recession analysis has long been a topic of interest in the science of hydrology. Base-flow recession curve itself contains valuable information about the ground-water flow and it is widely used in hydrological models such as HEC-1 and other water resources applications. During the last few decades, an important number of case studies have been made with the aim of identifying the recession analysis and physical factors. However, because of the limitation of available data, most of them were developed and tested on a specific physiographic region. The large number of existing techniques and high level of subjectivity in recession analysis indicate that the problem is not fully understood.

Recession analysis is one of the common procedures that is frequently used in hydrological analysis. In this examination, the rate at which a groundwater aquifer stores in the absence of recharge is investigated. Since the early 1900s, the application of recession analysis have been innumerable and include such areas as low-flow forecasting, separation of base flow from surface runoff, and the assessment of evaporation loss.

Recession Limb Analysis. Theoretical investigation and empirical studies have shown that the recession curve can be expressed by

$$Q_t = Q_0 \exp(-\beta \times t) \tag{2}$$

where Q_t is the discharge at time t, Q_0 is the initial discharge, and β is a constant value; the term exp(-β) is normally replaced by k, which is called the recession constant (Smakhtin, 2001).

The end of surface runoff represents the condition of maximum storage. However, marking the end of direct runoff is rather difficult. Linsley *et al.* (1982) suggested that this point could be identified arbitrarily by inspecting several hydrographs from the basin. He also introduced an equation to calculate the number of days after the peak of a hydrograph based on the size of the drainage area, thus identifying the end of surface runoff (Sloto and Crouse, 1996);

$$N = A_d^{0.2} \tag{3}$$

where N is the number of days after the peak of hydrograph, at which base flow and total flow hydrographs meet, and A_d is the drainage area in square miles. The problem with this method is that N does not consider many physical/hydrologic factors that affect duration of the recession limb.

In the Boughton's method, the user is responsible for identifying this point on the total flow hydrograph. One of the challenges with this technique is that it is very difficult to manually define the end of surface runoff for each single flood event when the period of study is long. Manual identification is also highly dependent on the user's previous experience, which can be highly variable.

In contrary with the general assumption about direct relation between storage (S) and outflow (Q), it

was shown that there is a nonlinear correlation between Q and S in the Wittenberg and Sivapalan (1999) method. Mathematical assessment also supports the nonlinear storage-base-flow behavior. This fact was further extended through sequence of statements to automate the hydrograph separation with daily discharge values (Nejadhashemi *et al.*, 2004).

Based on the Wittenberg study, the starting point for base-flow recession is assumed to be two days after inflection point of the hydrograph. However, the size of the watershed and the duration of the storm event are two major factors that affect this issue. Nejadhashemi *et al.* (2004) modified the method for more accurate results. The effect of the two aforementioned factors (i.e., watershed area and the storm duration) was considered in their study. The starting point for base-flow recession and the inflection point both were assumed to be the same point on the hydrograph.

Szilagyi and Parlange (1998) proposed a method based on the analytical solution of the Boussinesq equation. Regardless of the duration of the experiment, the slope of the recession limb for unconfined saturated aquifer was expressed as:

$$\frac{dQ}{dt} = -a(Q(t))^b \tag{4}$$

where Q is the measured discharge, and a and b are positive constants.

Singh (1988) solved the above equation for unknown time [Equations (5) and (6)];

$$Q(t) = (Q_0^{1-b} - (1-b)at)^{\frac{1}{1-b}}, \quad \text{for} \quad b \neq 1 \tag{5}$$

$$Q(t) = Q_0 e^{-at}, \quad \text{for} \quad b = 1 \tag{6}$$

where Q_0 is the discharge at the beginning of the storm event.

General assumption for this method is that the recession limb of the hydrograph should last longer than 45 h without any break. This was necessary to provide enough data points for the above method, which makes its applicability to many storm events and small watersheds very limited.

Poor predictions and lack of applicability to general conditions lead us to consider other approaches for identifying the end of surface runoff for each hydrograph. This approach should be sensitive to physical and hydrologic conditions of watersheds and applicable for different storms regardless of their durations. In this study, inflection points on the recession limb of several storm hydrographs were tested. Mathematically, inflection points of the total flow hydrographs are those points where the discharge function [Equation (7)] changes from positive to negative concavity or vice-versa (they are points of zero concavity). On the other hand, inflection points show noticeable change in discharge behavior. Therefore, these points were assumed as end of surface runoff for each single event. This theory was first introduced in the rational method as the time of concentration. The time of concentration is the time required for a unit volume of water from the farthest point of catchment to reach to the outlet. It represents the maximum time of translation of the surface runoff of the catchment, which in gauged areas, are equal to the time interval between the end of the rainfall excess and the point of inflection of the resulting surface runoff (Subramanya, 1994).

In this study, second derivative of all points on the recession limb of each hydrograph was calculated (Figure 2). The inflection point was defined as the point on the recession limb of the hydrograph where the second derivative is zero. This point is generally located between two points, one before the inflection point where the second derivative is negative and the other after the inflection point where the second derivative is positive (e.g., Figure 2; corresponding arrows indicate the inflection points). The following equation can be used to obtain an approximation to the second derivative:

$$\frac{\partial^2 Q_t}{\partial t^2} = \frac{Q_t^{i+1} - 2Q_t^i + Q_t^{i-1}}{(\Delta t)^2} \tag{7}$$

where Q_t^i is total flow discharge at time step i and Δt is time interval.

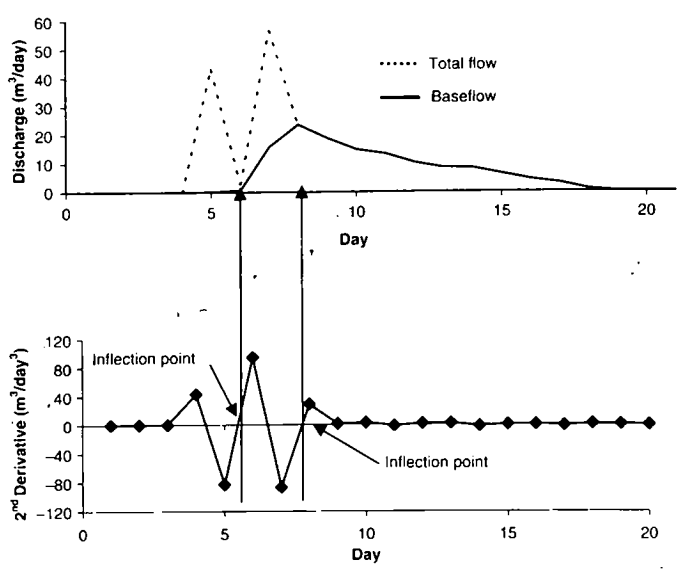

FIGURE 2. Schematic of the Automated Detection of the Ends of Surface Runoff Based on Identifying the Inflection Points.

In order to evaluate the accuracy of the above method, all storm events during 12 years of study were investigated using separately measured surface and subsurface flow hydrographs. In other words, on the recession limb of each single hydrograph, the end of surface runoff was identified using data for separately measured surface and subsurface flows. Results obtained by this method were compared with computer-generated end of surface runoff data.

Evaluation of the Accuracy of the Boughton's Method as a Function of Time Discretization Method and Error Criterion

Nejadhashemi *et al.* (2004) showed that most of the base-flow separation equations might be derived as specialized forms of the first-order, non-homogenous, nonlinear, Ordinary Differential Equation (ODE):

$$\frac{dQ_b}{dt} = -a_1[Q_b(t)]^{a_2} + a_3 Q(t) + a_4 \frac{dQ}{dt} \tag{8}$$

where Q_b is base flow, Q represents a driving force such as total streamflow or rainfall, and a_1 to a_4 are constant parameters reflecting watershed physical and hydrologic characteristics.

Based on this fact, Boughton's method can be rewritten as a finite difference approximation of Equation (8) with $Q = Q_t$ (the total streamflow), $a_2 = 1$ and setting a_1, a_3, and a_4 all to be non-zero. This analysis further reveals that the Boughton's method is the most complete linear technique in the sense that it has the most nonzero coefficients in Equation (8), thus avoiding any truncation error (Nejadhashemi *et al.*, 2004). This gives

$$\frac{dQ_b}{dt} = -a_1 Q_b + a_3 Q_t. \tag{1}$$

It is notable that this deterministic expression is very close to the first-order autoregressive (Markovina) model common in stochastic analyses of time series (e.g., Vanmarcke, 1983, Equation 3.7.3). The major difference is that Q_t is not a zero-mean uncorrelated random function (it is random due to climate variability, but has significant autocorrelation and a positive mean).

Time Discretization. In this stage of study, three scenarios were tested using separately measured surface and subsurface flow data from field scale watershed Z located in the southeast United States for the period of 1970 through 1981. The goal of this stage was to improve in base-flow estimation by considering different difference approximations.

Case I (*Backward Difference*): The amount of subsurface flow for the current time step is computed as a fraction of the difference between the total flow and the base flow on the previous time step. This is the standard Boughton's method, and corresponds to a first-order approximation of the time derivative in (8)

$$Q_b^i = Q_b^{i-1} + \alpha[Q_t^{i-1} - Q_b^{i-1}] \tag{9}$$

where Q_b^i is base-flow discharge at time step i, Q_t^{i-1} is total flow discharge at time step i-1, and α is the fraction value.

Case II (*Central Difference*): The amount of subsurface flow for the current time step is computed as a central difference approximation of total flow and the base flow on the previous time step. This is a modified Boughton's method where the time derivative in (8) is approximated to second-order.

$$Q_b^i = Q_b^{i-1} + \alpha\left[\frac{Q_t^i + Q_t^{i-1}}{2} - Q_b^{i-1}\right] \tag{10}$$

Case III (*Forward Difference*): The amount of subsurface flow for the current time step is computed as a fraction of the difference between the total flow for the current time step and the base flow on the previous time step. This is a modified Boughton's method with a first-order approximation of the time derivative in (8).

$$Q_b^i = Q_b^{i-1} + \alpha[Q_t^i - Q_b^{i-1}] \tag{11}$$

In this study, the developed program is able to identify the end of surface runoff for all storm events though period of consideration. These points were used to automatically calculate fraction values for calibration purposes. Thereafter, the program computes the fraction value for the designated period of surface runoff with an iterative technique up to three digits accuracy. In this method, the fraction value needs to satisfy the assumption that the base flow increases to equal the total flow at the specified point at the end of separation process.

Error Criterion. In this stage of study, the least squares method was also applied to all three scenarios to evaluate the maximum amount of possible improvement in base-flow estimation. To perform this task, for each single hydrograph through the period

of study, all three scenarios were applied. The program conducted an iteration approach for calculating the fraction value. The difference between this value and the previous approach is that by applying the new fraction value, the amount of difference in baseflow estimation from observed data is minimized in each single event (Figure 3). After calculating all fraction values for storm events, the program uses the fraction values for the entire period of study to calculate base flow. This task gives us an idea that how well each scenario can perform if we can calculate the appropriate fraction values based on climatological factors.

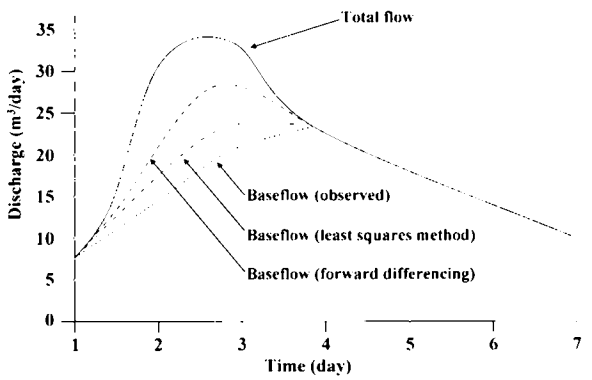

FIGURE 3. Schematic of Total Flow Hydrograph and Different Base-Flow Separation Techniques.

Improvement in the Fraction (α) Value Estimation by Incorporating Climatological Factors

The comparative study of streamflow partitioning methods showed that despite the simplicity of Boughton's method, it produced reasonably accurate data. Results also indicated that accuracy of this method is highly dependent upon the proper estimation of the "fraction coefficient" that is based on many physical and hydrologic characteristics of the watershed (Nejadhashemi *et al.*, 2004).

In this study, among numerous climatological factors that may affect the fraction coefficient, seven factors were selected and put into test. These seven factors are, total rainfall during a storm event in cm, total evapotranspiration during a storm event in cm, duration of a runoff storm event in days, average soil moisture (cm/cm) in top 137 cm of soil, average soil moisture (cm/cm) in top 15 cm of soil, total rainfall during storm event divided by duration of surface runoff in cm/day, and daily rainfall intensity in cm/day. The time interval for all computations is 1 day.

It is not unusual that the nature of the relationship between one or more independent variables and a dependent variable changes over the range of the independent variables. Many statistical models rely on the assumption that the effects of continuous predictors are linear. However, the linearity assumption may be too simple to represent the effects of some factors correctly. The incorrect linearity assumption leads to underestimation of results over some range and overestimation over some other range, or both. Among different regression models, piecewise linear regression was used to allow greater flexibility in modeling of the fraction value. Piecewise linear regression is usually used for conditions that there is a discontinuity in the regression line. Therefore, modeler needs to estimate two separate linear regression equations: one for the criterion values, which are less than the breakpoint value, and one for the criterion values that are greater than the breakpoint value. Estimation of the breakpoint is not a difficult task, however, piecewise regression model can only be used for conditions that user have presumptions about the possible range of criterion values before calculating them. Therefore, the user needs to build up rules on which a judgment or decision can be based.

Correlation analysis provides a means of drawing inferences about the strength of the relationship between two or more variables. Correlations between each pair of variables in a data set are best presented in matrix form. Therefore, a correction matrix was developed for this study reflecting the relationship α value and each of the seven independent variables (e.g., total rainfall, total evapotranspiration). After examining the degree of common variation, two variables, which have large correlation with dependent variable (α), were selected. In the next step, these two predictor variables were used to develop a quadratic equation relating α to both of those parameters. This quadratic equation can assist modelers to build up standards about the possible range of criterion values (the fraction values). Finally, the STATISTICA software version 4.3 and SAS software version 9.1 were used to develop piecewise linear regression model for predicting the fraction value based on climatological factors (Marques de Sá, 2003).

Study Site

The Coastal Plain Province of the United States extends in north-south direction, from New England down the Atlantic Coast and then into Texas. The U.S. Department of Agriculture-Agricultural Research Service (USDA-ARS), maintains a research watershed within the Tifton upland physiographic area of the Southeastern Coastal Plain. The watershed is in the outcrop area of the Miocene series. Geological parent material originated from the Hawthorn Formation and is overlaid by Quaternary sands. This formation is continuous and serves as an

aquiclude in the Tifton Upland. The infiltration rates of soils in that region can be characterized as being high (Shirmohammadi *et al.*, 1984).

Location and General Description. The field scale watershed (station Z) is located in the Little River Watershed near Tifton, Georgia (Figure 4). The Southeast Watershed Research Laboratory (SEWRL) routinely monitors this watershed for soil moisture at different depths (15, 30, 46, 61, 91, 122, and 137 cm), separate measurement of subsurface and overland flow, and precipitation. The watershed boundaries are different for surface and subsurface flow; the areas are 0.3436 and 0.3464 ha for surface and subsurface topographic maps, respectively. Average slopes are also dissimilar for the ground surface and the Hawthorn Formation, with values of 2.5 and 2%, respectively. The watershed is generally extended in the east-west direction with an average elevation of 110 m above the mean sea level. Figure 5 shows surface and subsurface watershed boundaries along with topographic maps of the surface and subsurface contributing areas of watershed Z. (Rawls, 1976).

Subsurface Flow Instrumentation. On the top of the clay Hawthorn Formation and lower end of the watershed, gravel packed, 10 cm terra cotta tile with an approximate length of 73 m was installed to gather the subsurface flow. Subsurface flow was recorded every 5 minutes by binary stage recorder, which was operated on a 15 cm, 90-degree, v-notch weir. These series of equipments were set in position in June 1968 (Rawls, 1976).

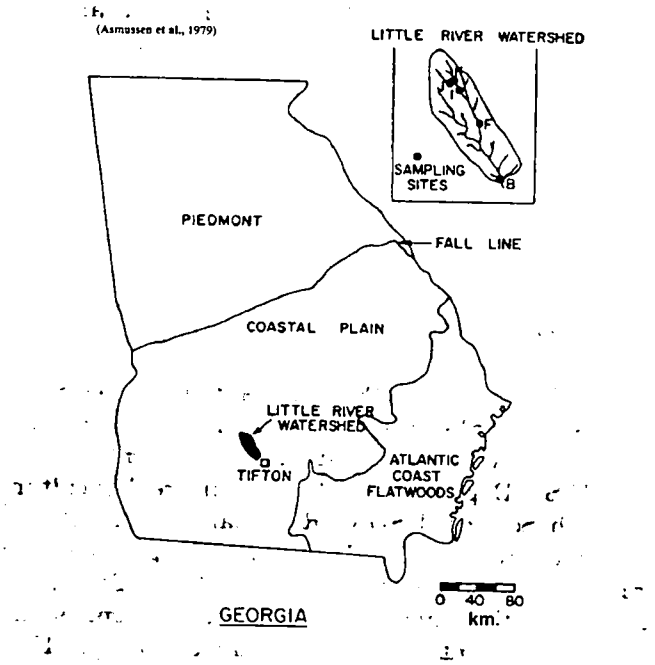

FIGURE 4. Location of the Little River Watershed in the State of Georgia.

Surface Flow Instrumentation. According to the general slope of the watershed, a 0.3048-m (1 foot), H-flume was installed on June 1969 on the southwest corner of the surface watershed to measure overland flow. On the account of difference between length of surface and subsurface flow records, the only pre-installation surface runoff event (April 16,1969) was visually estimated to make records comparable (Rawls, 1976).

Management Practices. Table 1 shows cropping and cultural practices during 1970 through 1978. This data along with the weather and climatological data were used for calculating evapotranspiration. The term of "management practice" is commonly used to imply soil or water conservation practices. However, in this paper, the term "management practice" is used to refer to an activity or field operation in the course of the study period.

Weather and Climatological Data. Weather and climatological data were obtained from the U.S. Weather Bureau rain gauge located at the Georgia Costal Plain Experiment Station in Tifton, Georgia. This station is located about 1 km east-northeast of the study area. Soil temperature, daily maximum and minimum temperatures, pan evaporation, water temperature, daily radiation, relative humidity, and wind speed and direction are among the supplementary data recorded in this station (Knisel *et al.*, 1991).

Evapotranspiration. Evaporation of water from soil surface and vaporization of liquid water contained in plant tissues occur simultaneously; however, it is difficult to distinguish between the two processes. Studies showed that weather parameters, crop characteristics, management, and environmental aspects are the major factors affecting evapotranspiration. Since the rate of evaporation from an evaporation pan is primarily dependent upon climate factors, an evaporation pan cannot directly predict differences in transpiration due to differences in crop species or management practices. This requires that data from a pan must be adjusted for specific conditions of the crops. Therefore, in the early stage of this study, potential evapotranspiration was calculated by multiplying the rate of evaporation from the pan to correction factor (pan coefficient) on daily bases. FAO Irrigation and Drainage Paper No. 56 were used as guideline for calculating crop evapotranspiration from meteorological data and crop coefficients during the study period. Crop coefficients were calculated based on crop type, variety, and development stage of growth (Table 1), and cultural conditions (Allen *et al.*, 1998).

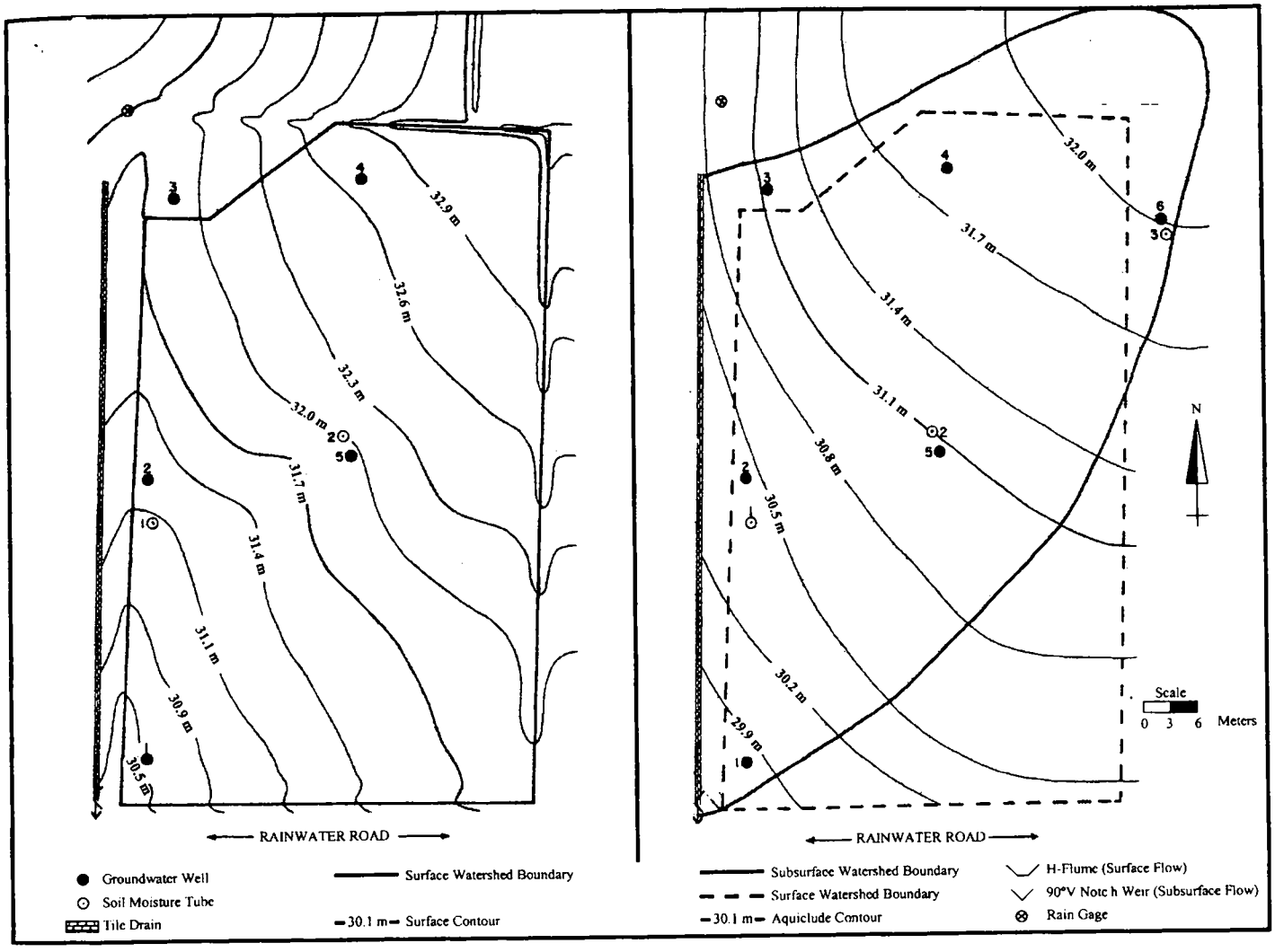

FIGURE 5. Topographic Maps of the Surface and Subsurface Contributing Areas of Watershed Z, Costal Plain Experiment Station, Tifton, Georgia.

Availability of Data. Separately measured surface and subsurface flow data for field scale watershed Z are available for the period of 1970 through 1981. However, weather and climatological data are only available for the period of 1970 through 1978. These data set forms the basis for the evaluation of the performance of the method identified in this study.

RESULTS AND DISCUSSION

Identification of the End of Surface Runoff

In the original Boughton's method, a human operator had to manually identify a point on the hydrograph, thus marking the end of the surface runoff. Then, this point is used for calibration purposes. The accuracy of the method is therefore highly dependent on the skill and familiarity of the operator with a particular watershed's behavior. In addition, the manual approach is very difficult to be applied to long periods of study because of large numbers of events. In a previous study, a couple of representative hydrographs were used to identify the end of the surface runoff, thus calibrating the model using several observations. However, it was found that this method is time consuming and has a permanent source of error (Nejadhashemi *et al.*, 2004).

The method introduced here (considering inflection point as the end of the surface runoff) does not need any special procedure for calibration. Therefore, all 12 years of data were used to evaluate the model performance. About 300 storm hydrographs were investigated to perform this evaluation. Applying this

TABLE 1. Management Practices on Watershed Z (Knisel *et al.*, 1991).

Date	Practice
1970	
4/10	Plant corn
9/17	Shred; no harvest
1971	
4/21	Plant corn
9/27	Harvest corn
1972	
4/12	Plant corn
9/20	Harvest corn
10/17	Plant oats
1973	
3/19	Cut oats (hay)
5/31	Moldboard , Plant peanuts
10/20	Moldboard; no harvest
11/29	Plant oats
1974	
4/24	Cut oats (hay)
7/11	Fertilize; plant soybeans
11/13	Harvest soybeans
11/22	Plant oats
1975	
5/16	Cut oats (hay)
5/13	Plant soybeans
11/13	Harvest soybeans
11/21	Plant oats
1976	
3/1	Cut oats (hay)
6/9	Plant soybeans
11/10	Harvest soybeans
1977	
4/8	Bed; plant corn
8/11	Harvest corn
10/27	Plant rye
1978	
3/13	Mow rye
4/17	Bed; plant corn
9/29	Harvest corn

approach to 12 years of streamflow data proved that the method is accurate in about 87% of the time. However, in 6% of storm events, the inflection point was found to be one day off from the actual end of the surface runoff and in 7% of the time, no base flow was recorded or the difference between the computed and observed inflection point was more than one day. Applying Wittenberg (1999) approach equipped with automated determination of the end of the surface runoff for the same period of streamflow data proved that the method is accurate in about 4% of the time, however, Linsley *et al.* (1982), and Szilagyi and Parlange (1998) methods are not applicable for this case study because of the watershed size and magnitude and duration of storms.. These results show considerable improvement in the prediction of the end of the surface runoff by mathematical definition of inflection point in comparison with previously developed methods such as Wittenberg (1999), Linsley *et al.* (1982), and Szilagyi and Parlange (1998) where the end of surface runoff is arbitrarily determined. In addition, it has the advantage to be consistent and applicable for any shape of hydrograph regardless of its magnitude and/or duration.

Evaluation of the Accuracy of the Boughton's Method as a Function of Time Discretization Method and Error Criterion

Three scenarios (backward, central, and forward difference) for streamflow separation were tested using separately measured surface and subsurface flow data from field scale watershed Z for the period of 1970 through 1981. All three scenarios were programmed using Visual BASIC language and the programs are capable of identifying the end of surface runoff for each single storm event during the course of study. The developed programs also automatically calibrate and calculate the fraction (α) values based on an estimated inflection point on the hydrograph, which marks the end of surface runoff (Figures 6 through 8). Results showed that the coefficients of determination (R^2) values for backward, central, and forward difference approximation approaches are 0.64, 0.79, and 0.87, respectively. The comparative study of three approximation methods showed that despite the simplicity of the forward difference approximation, it produced reasonably accurate results.

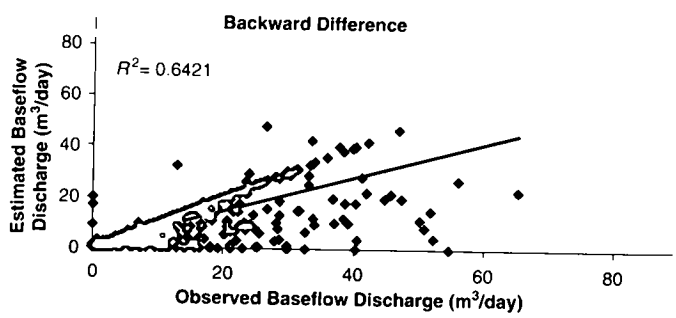

FIGURE 6. Observed Base-Flow Discharge *vs.* Estimated Base Flow Using Backward Difference Approximation.

In addition to above test, two more sets of tests were conducted. In the first set, the analysis of variance (ANOVA) was used to find out if there is a significant difference between total annual values of observed data and computed values. Results indicated that there is a significant difference between observed data and estimated base-flow values using

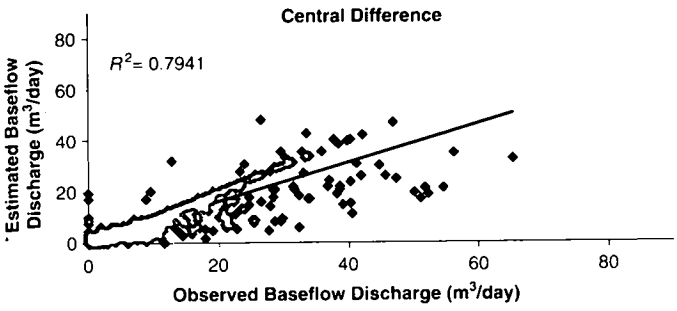

FIGURE 7. Observed Base-Flow Discharge *vs.* Estimated Base Flow Using Central Difference Approximation.

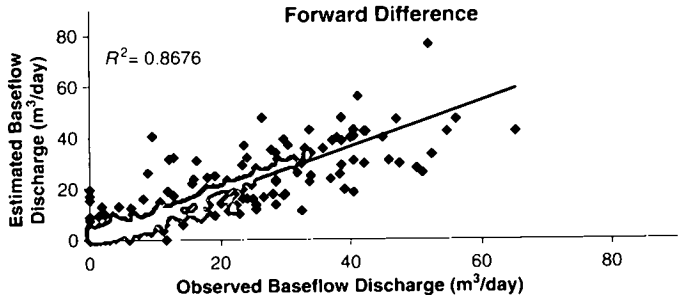

FIGURE 8. Observed Base-Flow Discharge *vs.* Estimated Base Flow Using Forward Difference Approximation.

central and backward difference approaches. The second set of tests was also performed by using analysis of variance (ANOVA). The goal in this series is to find out if there is a significant difference between daily average values of observed data and computed values. Results from this section showed that at p = 5% level of significance, only the forward difference method is not significantly different from measured data on daily bases. Results further indicate that using new approaches (inflection point) in the identification of the end of the surface runoff has significantly improved the Boughton method's prediction of base flow, even before incorporating climatological factors into the method (Ott and Longnecker, 2001; Nejadhashemi *et al.*, 2004).

The most frequently used fitting model, which is also used in this study, is linear regression model. The principle behind the linear regression model is the least squares method. Figures 9 through 11 show a set of lines of best fit that are obtained using the method of least squares to estimate the best possible fraction values in all three scenarios. These graphs are examples indicating variation of daily base flow obtained through the backward, forward, and central difference approaches. In addition, in each graph, coefficient of determination is shown.

Results showed that the forward difference approximation method could provide the most accurate result if the fraction values can be reasonably estimated using physical and hydrological characteristics of watersheds. On the other hand, results from ANOVA test showed that at the p = 5% level of significance, backward difference approach is not reliable even when proper physical and hydrologic characteristics of the watershed were taken into consideration.

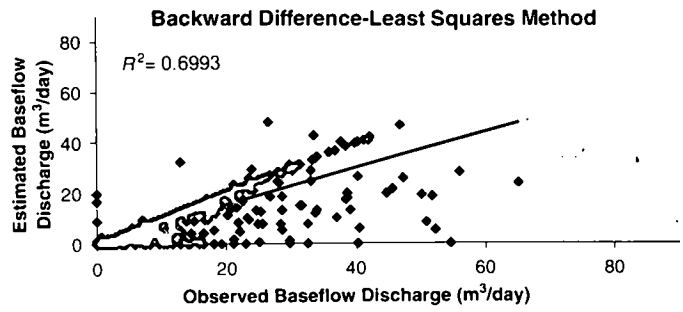

FIGURE 9. Observed Base-Flow Discharge *vs.* Estimated Base Flow Using Backward Difference Approximation and Least Squares Method.

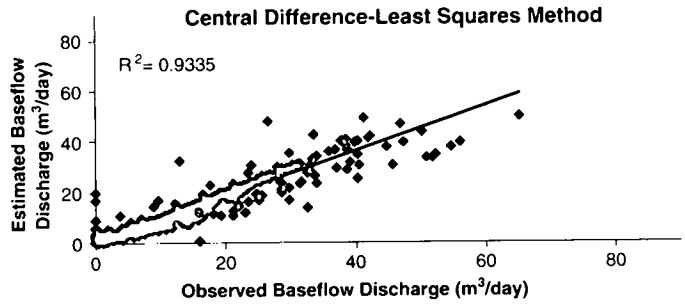

FIGURE 10. Observed Base-Flow Discharge *vs.* Estimated Base Flow Using Central Difference Approximation and Least Squares Method.

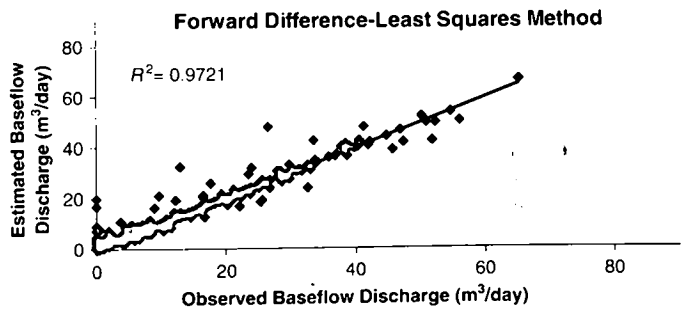

FIGURE 11. Observed Base-Flow Discharge *vs.* Estimated Base Flow Using Forward Difference Approximation and Least Squares Method.

Improvement in the Fraction (α) Value Estimation by Incorporating Climatological Factors

The correlation matrix is used to present the correlations between pairs of variables used in the study. The correlation matrix, based on 9 years of daily measurements, is presented in Table 2. The correlations between variables are mostly below 0.3 with a largest correlation of 0.47 between alpha and the duration of surface runoff. The squares of predictor-criterion correlations indicate that the fraction of variance explained by individual variables ranges from 0 to 0.22. These results indicate that accurately predicting alpha by regression will require the use of more than one predictor variable, or of a non-linear model. Preliminary analysis of the dataset indicated that a linear regression model predicts alpha poorly, even when all seven predictor variables are included. This study therefore focused on applying a piecewise linear regression model for predicting alpha.

TABLE 2. Correlation Matrix for the Fraction Variable.

	Var_1	Var_2	Var_3	Var_4	Var_5	Var_6	Var_7	α
Var_1[1]	1.00	0.23	0.32	−0.16	−0.05	0.94	0.72	−0.14
Var_2[2]		1.00	−0.02	−0.13	−0.04	0.27	0.27	−0.19
Var_3[3]			1.00	0.03	0.02	0.03	−0.07	0.47
Var_4[4]				1.00	0.13	−0.20	−0.25	0.34
Var_5[5]					1.00	−0.07	−0.08	0.00
Var_6[6]						1.00	0.79	−0.32
Var_7[7]							1.00	−0.37
α[8]								1.00

[1]Total rainfall during a storm event in cm.
[2]Total evapotranspiration during a storm event in cm.
[3]Duration of runoff storm event in day.
[4]Average soil moisture (cm/cm) in top 137 cm of soil.
[5]Average soil moisture (cm/cm) in top 15 cm of soil.
[6]Total rainfall during storm event divided by the duration of surface runoff in cm/day.
[7]Daily Rainfall intensity in cm/day.
[8]The fraction coefficient.

The piecewise linear regression equations for predicting the fraction (α) value based on climatological factors was developed using the forward difference form of Boughton's equation and streamflow data for the period of 1970 through 1978. The first 6 years of data, from 1970 to 1975, were used to adjust model parameters (calibration) and the remaining 3 years, from 1976 to 1978, were used for model validation. This partitioning was selected such that the number of storm events in the calibration period (6 years) was nearly equal to that in the validation period (3 years). After developing the piece-wise linear regression equation, a principle components analysis along with systematic elimination of variables were performed for eliminating redundancy and improving the coefficient of determination for Equation (12a, b). However, our major goal here was to reach the maximum possible coefficient of determination in developing the regression equation and not performing optimization of objective function with specific parameters. After examining the correlation between the fraction coefficient (α) and the seven climatological variables, Var_5 (average soil moisture in top 15 cm of soil) was eliminated because of no correlation with the fraction coefficient as is evident in Table 2 (i.e., $R^2 = 0.0$). A SAS program was developed to automatically perform the piecewise linear regression and identify the threshold α value between two lines. The breakpoint was identified as alpha = 0.5 and the resulting set of regression equations were obtained as:

$$\begin{cases} \text{For } \alpha \le 0.5 \\ \quad \alpha = -0.188 + 0.069\,Var_1 - 0.087\,Var_2 + 0.186\,Var_3 \\ \quad\quad + 0.13\,Var_4 + 0.212\,Var_6 + 0.009\,Var_7 \qquad (12a) \\ \text{For } \alpha > 0.5 \\ \quad \alpha = 1.072 + 0.044\,Var_1 + 0.066\,Var_2 - 0.045\,Var_3 \\ \quad\quad + 0.043\,Var_4 - 0.302\,Var_6 + 0.0004\,Var_7 \qquad (12b) \end{cases}$$

The correlation coefficient between the measured fraction coefficient and that predicted by these equations was found to be very high: 0.97, thus indicating the strength of Equation (12a, b) in predicting α values.

In order to select which of the two above equations to apply, it is necessary to have preliminary order of magnitude estimate (predictor) for alpha. If this estimate is less than 0.5 then the first equation above should be applied, and, if the estimate is greater than 0.5 then the second equation should be applied. This issue is well known in marketing research where piecewise regression models appear to be used more frequently than in hydrology (Kuhfeld and Garratt, 1992). In this study, the predictor variable, α*, is determined by quadratic regression of alpha values on selected climatological variables. After examining the degree of common variation (Table 2), two predictor variables that have large correlations with the fraction (α) coefficient and low intercorrelation with each other, were selected as: (1) total rainfall during storm event divided by the duration of surface runoff (Var_6), cm/day; and (2) duration of runoff storm event in days (Var_3). The first variable was selected because of having the largest correlation with the fraction (α) coefficient and the next variable was selected as the one that had both the lowest intercorrelation with first variable and it is easy to obtain data for. A program was developed within SAS to perform the

quadratic regression using the same calibration and validation datasets as were used in the piecewise regression. The resulting predictor regression equation is

$$\alpha^* = -2.826 - 0.733 \times \mathrm{Var}_6 + 1.789 \times \mathrm{Var}_3 + 0.13 \times \mathrm{Var}_6^2 - 0.192 \times \mathrm{Var}_3^2 + 0.041 \times \mathrm{Var}_6 \times \mathrm{Var}_3 \quad (13)$$

This equation, used by itself [without Equation (12a, b)], was found to be accurate in predicting the range of the fraction values in 83% of the storm events during validation period. Therefore, this study suggests using Equation (13) to identify initial α value, thus helping the user in deciding what piece of Equation (12a, b) to use in predicting a precice α value.

The accuracy with which the predictor-corrector Equations (12) and (13) can predict alpha values was evaluated using 3 years (1976-78) of dataset. First, Equation (13) was used to estimate the fraction value (α^*) for each flow event. Then, the computed α^* value was used as an indicator to choose whether Equation (12a, or b) should be used for each event. The corresponding Equation (12a, or b) was then used to predict the fraction coefficient for each event, and finally, the estimated α values were used to partition the total streamflow for each event during the validation period.

Figure 12 compares estimated base-flow discharge values obtained by the above predictor-corrector method with observed base-flow discharge values. The coefficient of determination between estimated and observed base-flow discharge values is found to be 0.97. This result indicates that the predictor-corrector method developed in this study can predict alpha values based on climatological parameters with significant accuracy for station Z.

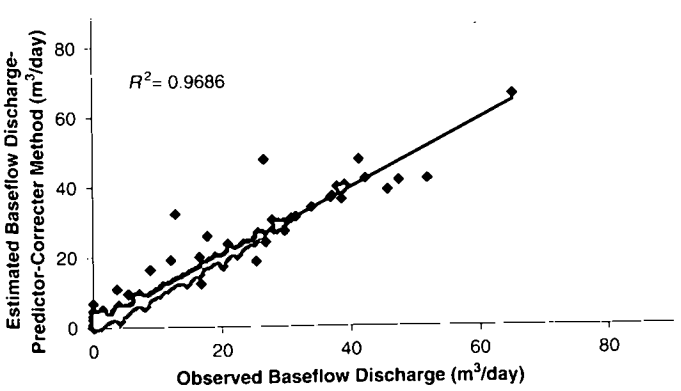

FIGURE 12. Observed Base-Flow Discharge *vs.* Estimated Base Flow Using the Predictor-Corrector Method.

CONCLUSIONS

The main objective of this study was to use climatological factors to improve estimation of streamflow partitioning techniques. Four different strategies were developed and evaluated to improve the Boughton's method of daily base-flow estimation. It was demonstrated that inflection-point analysis can accurately identify the end of surface flow in 87% of measured storms. Results further demonstrated that the least squares calibration and proper temporal discretization (forward difference approach) can improve model performance by up to 23% (R^2 = 0.64 for the backward difference technique and R^2 = 0.87 for forward difference technique). It was also shown that proper estimation of the fraction coefficient, using a novel predictor-corrector approach, can provide very accurate estimates of daily base flow with coefficient of determination of up to R^2 = 0.97. Overall, this study demonstrated that incorporating the climatological factors can significantly improve the accuracy of hydrograph separation techniques when used jointly with enhanced recession limb analysis, calibration approach, and time-discretization method. Even though extrapolating small-scale analysis to large scale implementation can distort the model results (Shirmohammadi *et al.*, 2005), application of our model to large-scale watershed with proper input data may provide reasonable estimate of surface and subsurface flow components. This was tested in an earlier study by Shirmohammadi *et al.* (1987) where they calibrated their model with station Z data (the same dataset used in this study) and applied their model to large watersheds ranging in size from 22 km^2 to 1030 km^2. These findings are expected to provide significant help to engineers and hydrologists faced with the task of estimating base flow in regions where only total stormflow is measured. Future studies will focus on identifying how the regression parameters used in the predictor-corrector formulas for alpha can be defined in terms of such factors as soil type and management practices in arbitrary watersheds, and in implementing the developed strategy within a GIS environment.

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