ABSTRACT

Title of Dissertation: IMPROVEMENT IN ESTIMATING POLLUTION TRANSPORT BY DEVELOPING STREAMFLOW COMPONENTS ASSESSMENT IN THE GIS ENVIRONMENT

Amirpouyan Nejadhashemi, Ph.D., 2006

Dissertation Directed By: Professor Adel Shirmohammadi
Department of Biological Resources Engineering

Water by nature is a suitable domain for the transport of contaminants through watersheds. Evaluating the relative amounts of stored or moving water via the different components of the hydrological cycle is required for precise and strict management and planning of water resources. One of the most challenging parts of this process is the separation and quantification of baseflow from the total streamflow hydrograph. The aim of this study was to separate the storm runoff hydrograph into its components, thus being able to infer about sources and hydrological pathways of the storm runoff. The specific objectives of this study were to identify the most accurate and user-friendly streamflow partitioning method, to evaluate the accuracy of each of these methods using separately measured surface and subsurface flow data, and finally to improve available techniques or develop a more precise approach for separation of hydrograph components.

In the early stage of this study, forty different streamflow partitioning methods were reviewed and classified into three-component, analytical, empirical, graphical, geochemical and automated methods and five methods were identified as being the most relevant and least input intensive. The performance of these methods were tested against independently measured surface and subsurface flow data obtained on a field scale watershed Boughton's method produced the most consistent and accurate results. However, its accuracy depends upon the proper estimation of the end of surface runoff, and the fraction factor (α). It was demonstrated that incorporating physical and hydrologic characteristics of a watershed can significantly improve the accuracy of hydrograph separation techniques when used jointly with enhanced recession limb analysis, calibration approach, and time-discretization method. Finally, simulation of the model for different scenarios (e.g., soils, land use, etc.) was performed within the geographical information systems for a large scale watershed (Little River Watershed in Georgia). Results showed that the weighted discharge method is better than the weighted average curve number method and the modified Boughton's method because it divides a watershed into small filed scale pixels and treats each pixel separately, thus mimicking the field scale station Z conditions where the method was successfully applied.

IMPROVEMENT IN ESTIMATING POLLUTION TRANSPORT BY DEVELOPING STREAMFLOW COMPONENTS ASSESSMENT IN THE GIS ENVIRONMENT

By

Amirpouyan Nejadhashemi

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Advisory Committee:
Dr. Adel Shirmohammadi, Chair/Advisor
Dr. Glenn E. Moglen
Dr. Hubert J. Montas
Dr. Walter J. Rawls
Dr. Fred Wheaton

Dedication

To my parents

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Finally, I wish to acknowledge my father and my mother as being the source of inspiration in my studies and helping me every step along the way. I dedicate this dissertation to my parents.

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Chapter 1: INTRODUCTION

Water by nature is a suitable domain for the transport of contaminants through watersheds. Therefore, understanding water flow elements and its dynamics is vital for accurate analyses of environmental problems such as the effect of land use and urbanization on riparian ecosystems, point source and non-point source pollution transport, ecosystem response to decompositions including dam constructions or global warming, and long-term acidification or salinity of drinking water (Renshaw et al., 2003).

Evaluating the relative amounts of stored or moving water via the different components of the hydrological cycle is required for precise and strict management and planning of water resources (Shirmohammadi et al, 1984-a). Proper characterization of hydrological cycle components is even more critical since both water quality and quantity are considered as a sustainable resource and ecosystem within the content of the whole water management scheme. One of the most challenging parts of this process is the separation and quantification of baseflow from total streamflow hydrograph. Total flow to stream systems consists of surface runoff, interflow and baseflow (Figure 1). Each of these elements has its own variable timing and characteristics.

Streamflow partitioning methods are used for finding hydrograph elements in subjective or objective manners during storm events. Because of limited available data on streamflow, most of the studies related to baseflow separation are developed and tested on specific physiographic regions. Additionally, existing methods (statistical, graphical, analytical, etc.) have not been tested regarding accuracy and ease of use. Therefore, a study such as the one proposed here is required to both

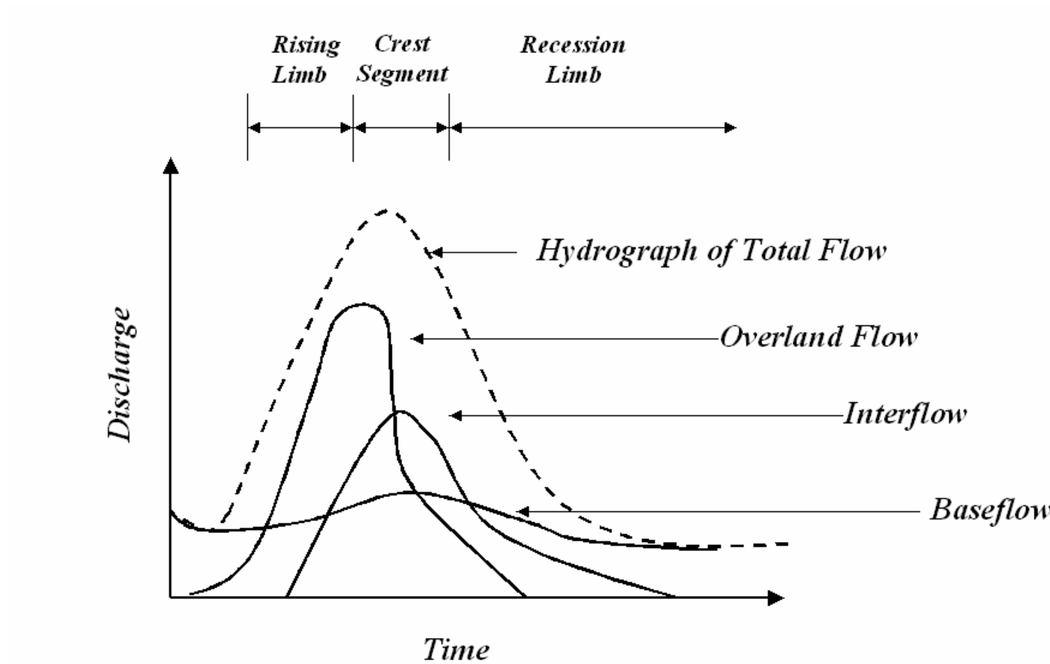


Figure 1. Schematic of total flow hydrograph and its components (Fleming, 1975)

determine a most accurate and easy to use streamflow partitioning method and a medium such as the Geographical Information Systems (GIS) for its global application. In the rest of this section, the importance of streamflow partitioning is discussed in different areas.

Historically, streamflow partitioning techniques have been important for the design of hydraulic structures, evaluation of rainfall-runoff models, assessment of flood control processes, and estimation and reduction of water contamination. Therefore, any accurate and easy to use method that helps water resources planners to estimate the hydrological cycle components is of vital importance.

Generally, rainfall-runoff models synthesize the hydrological behavior of the watersheds; however, accuracy of the output depends highly on the techniques and algorithms that are used for partitioning streamflow into its components. Improvement of available techniques or development of a more precise approach may help hydrologists to evaluate alternative management plans regarding water and ecosystem sustainability.

Water quality protection is becoming an important concept of watershed management. To be effective, water resources engineers should be knowledgeable regarding water and contaminant transport through different pathways in the watershed. An accurate streamflow partitioning method may be the key for the assessment and control of contaminant transport.

Floods are among the most common and widespread natural hazard phenomena causing billions of dollars in property damage each year (Societal Aspects of Weather, 2006)and timely assessment of such events is important in responding to the emergency conditions. To minimize the damage caused by a flood, comprehensive information about the water distribution is necessary. This goal is one of the most challenging concepts of hydrology, which can be achieved by an accurate streamflow partitioning approach.

The aim of this study is to separate the storm runoff hydrograph into its components, thus being able to infer about sources and hydrological pathways. Therefore, developing and assessing the new hydrological model using physical and hydrologic characteristics of a mixed land use watershed is the ultimate goal of this research.

Chapter 2: LITERATURE REVIEW

2.1 Streamflow Partitioning Methods

Like many problems in hydrology, a number of methods have been proposed for streamflow partitioning. Numerous hydrograph-partitioning techniques may be classified into three-component, analytical, empirical, graphical, geochemical, and automated methods. These methods are described in the following sections.

2.1.1 Three-Component Methods

A number of empirical and analytical models have been developed for hydrograph separation that considers streamflow to be composed of two components: overland flow and baseflow. However, Barnes (1939) presented a method, which considered subsurface flow, or interflow, in addition to overland and baseflow elements. In his study, interflow was defined as a part of the total runoff that moves laterally to surface runoff and finally enters the water body (lake, river, etc.).

Barnes' method of separation was evaluated by other researchers including Linsley and Ackermann (1942). They applied Barnes' method to several rivers in the Tennessee Valley. It was concluded that Barnes' method was not helpful in identifying the interflow component and the results were not consistent (Linsley and Ackermann, 1942). In addition, this method underestimated surface runoff when compared to other methods and was not capable of determining the peak and arrival time for groundwater and interflow. Finally, additional arbitrary assumptions needed to be made for hydrograph separation (Kulandaiswamy and Seetharaman, 1969).

The exponential equation (1) presented by Kulandaiswamy and Seetharaman (1969) for introducing subsurface flow or interflow was:

$$Q = Ke^{at} \quad (1)$$

where, K and a are constants and their values are different before and after the peak of interflow.

Mugo and Sharma (1999) applied the digital filter approach for separating the three components of the storm hydrograph (baseflow, interflow and surface flow) in humid tropical forested catchments in Kenya and East Africa. Two indices of baseflow and interflow were used to calibrate the conceptual technique. This method was developed based on studies by Nathan and McMahon (1990) and the schematic representation of this concept is shown in Figure 2. Figure 2 shows that the total storm hydrograph may be separated into baseflow, interflow and surface runoff by passing through two cascade filters of direct runoff and surface runoff. Mugo and Sharma (1999) showed that this technique was limited in large catchments with lag time exceeding 24 hours.

For all three-component methods, the storm hydrograph was separated into three distinct components (baseflow, interflow and overland flow). Therefore, contrary to other methods, more detailed results were found. However, the estimation of the hydrograph components in most of the cases was not consistent.

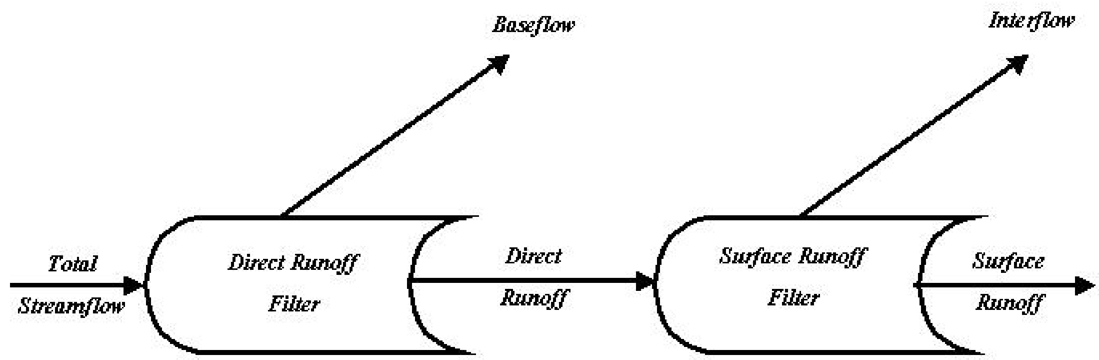


Figure 2. Schematic representation of Nathan and McMahon method (Mugo and Sharma, 1999)

2.1.2 Analytical Methods

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:

$$\frac{dQ}{dt} = -a(Q(t))^b \tag{2}$$

where, Q is a measured discharge, and a and b are constants. Singh (1988) solved the above equation for unknown time:

$$Q(t) = (Q_0^{\;1-b} - (1-b)at)^{\frac{1}{1-b}} \qquad , for \qquad b \neq 1 \tag{3}$$

$$Q(t) = Q_0 e^{-at} \qquad , for \qquad b = 1 \tag{4}$$

where, Q_o is the discharge at the initial time. One of the advantages of this method is that it is easily transformable into a computer algorithm and provides an estimation of baseflow maximum value in addition to the baseflow recession hydrograph. They concluded that the difference between the real and estimated results was due to prior hydrological conditions of the watershed (Szilagyi and Parlange, 1998).

Su (1995) introduced another method for streamflow partitioning. In this method, the unit hydrograph model was extended to study baseflow. The basic assumption in this method was that an output response of baseflow was caused by an impulse input from previously infiltrated water (Nash's cascade reservoir Instantaneous Unit Hydrograph (IUH) model).

Linsley (1982) and Chow (1988) proposed equation (5) for actual baseflow discharge as;

$$Q_b = R_g B_1 t^{\theta} \exp(-B_2 t) \tag{5}$$

where, Q_b is the actual baseflow discharge, R_g is the total depth of baseflow, t is time and B_1, B_2 and θ are parameters for the actual baseflow hydrograph. The unknown parameters in this equation were derived from the recession limb of the baseflow hydrograph. Then, these parameter values were used to determine the rising limb of the baseflow hydrograph through a proper mathematical approach (Su, 1995).

Contrary to the classical linear theories for reservoir yields from aquifers, research has indicated that this relation is not linear. Wittenberg and Sivapalan (1999) proposed a nonlinear reservoir algorithm for baseflow separation. In their method, the recession curve equation was derived from the continuity equation and a nonlinear storage-discharge relation:

$$Q_{t-\Delta t} = \left[Q_t^{b-1} + \frac{t(b-1)}{ab} \right]^{1/(b-1)} \tag{6}$$

where, Q is baseflow discharge (mm/day), t is time (day), a is a factor with dimension of $mm^{1-b}day^{b}$ and b is a dimensionless factor.

As shown in equation (6), the procedure is backward in time. During this process, the first intersection of the reverse baseflow recession curve with rising limb of storm hydrograph determines the peak of the baseflow hydrograph (by shifting the transition point one time step ahead). The other portion of the rising limb of the baseflow hydrograph can be determined by computing the recession discharge for a time step forward with respect to each total runoff value. This approach eliminated the problem of recharge consideration in the recession model. This model was developed under an analytical approach, but an empirical approach was used for determining the transition functions (Wittenberg and Sivapalan, 1999).

Chapman (1999) classified the numerical approach of baseflow separation techniques into three categories. The one-parameter algorithm was introduced for the first time by Lyne and Hollick (1979). In this algorithm, with a lack of direct runoff, baseflow would be constant. Chapman and Maxwell (1996) applied the average weighted method to calculate baseflow discharge in the following manner (Chapman, 1999);

$$Q_b(i) = \frac{k}{2-k} Q_b(i-1) + \frac{1+k}{2-k} Q(i) \qquad for \qquad Q_b(i) \le Q(i) \quad (7)$$

where, $Q_b(i)$ and $Q(i)$ are the baseflow and total streamflow, respectively, i is the time interval and k is the recession constant.

The second algorithm was developed by Boughton (1993). He defined an additional parameter, $C=1-k$, and included it to create Boughton's two-parameter algorithm model. This model is also known as the AWBM catchment water balance model.

Jakeman and Hornberger (1993) introduced the three-parameter algorithm. In this method, total runoff was divided into slow and quick components and the baseflow recession algorithm was expressed by the following equation;

$$Q_b(i) = \frac{k}{1+D} Q_b(i-1) + \frac{D}{1+D}\left[Q(i) + \alpha_q \cdot Q(i-1)\right] \qquad for \qquad Q_b(i) \le Q(i) \qquad (8)$$

where, $D = \beta_s/\beta_q$ and $k = -\alpha_s - \alpha_s\beta_s/\beta_q$ and q and s in the suffix meant quick and slow, respectively.

Some unreasonable results obtained by using one-parameter and three-parameter algorithms included a sharp peak in the slow flow hydrograph, which intersected with the total runoff hydrograph before the recession point. Among these three methods, the two-parameter algorithm gave the most satisfactory results, regardless of subjective approach of parameter selection (Chapman, 1999).

Fundamental theories of ground water and surface flow are the basic concepts of analytical methods such as the analytical solution of the Boussinesq equation, unit hydrograph model, and theories for reservoir yields from aquifers. In analytical methods, a whole hydrograph partitioning procedure may be separated into its components. Therefore, making it easy to examine their relation and transform it into a computer algorithm. Analytical approaches have been well known for their reliability. However, in the streamflow partitioning methods, pure mathematical procedures are far from reality because of the complexity and huge number of known and unknown factors. In addition, differences between real and estimated data from these methods are due to prior hydrological conditions and parameters, which are not considered.

2.1.3 Empirical Methods

Shirmohammadi et al. (1984-a) introduced an approximate method for partitioning daily streamflow data. The important advantage of this method over most of the traditional hydrograph separation techniques is that it does not require continuous data for detailed hydrograph analysis. This method defines an arbitrary threshold value for precipitation as an index that would result in some surface runoff. Therefore, surface runoff occurs on a day with precipitation exceeding the specified threshold value. Duration of the surface runoff would be considered the day of runoff initiation plus some number of arbitrary days, which depends on the watershed characteristics and size. In the next step, a straight line is drawn in order to connect the day before and the day after the storm event (curve of streamflow volume versus days). The upper part of the separation line is surface flow and the lower part is subsurface flow.

Applying this technique in ten research watersheds produced high correlation between estimated and measured surface and subsurface flows (Shirmohammadi et al., 1984-a). Some disadvantages of this method are as follows:

a – Threshold value of precipitation varies during the year because of varying antecedent soil moisture conditions.

b – Those storm runoff events that occur within a day for short periods are considered daily as well.

The threshold problem became a subject of further studies by Shirmohammadi et al. (1984-b). A third degree polynomial function was developed to improve the performance and accuracy of the partitioning method. This polynomial was used to compute daily initial abstraction (IA) values based on twelve years of soil moisture data, thus the surface runoff was considered to initiate on any day that precipitation exceeded the initial abstraction. The equation is presented as;

$$IA = -(11.5 \times 10^{-7})J^3 + (4.9 \times 10^{-4})J^2 - (3.0 \times 10^{-2})J + 7.91 \qquad (9)$$

where, IA is a catchment initial abstraction or rainfall threshold value in mm and J is the Julian day. It was also recommended to use watershed weighted rainfall data instead of point rainfall data.

Boughton (1988) implemented two automated separation techniques in a number of flood events. In the first method, the amount of baseflow increases linearly with time. In the second method, baseflow is defined as a fraction of total runoff. Calibrating both methods with real data showed that the second method gave a better estimation of rainfall events (Nathan et al., 1990).

Nathan et al. (1990) categorized streamflow partitioning techniques into two basic groups. In the first class, it was assumed that baseflow and runoff is concurrent in each flood event; and in the next class, it was assumed that these two flow components (baseflow and runoff) do not coincide due to a bank storage effect. Thus, baseflow recession occurs after runoff events.

In 1980, the Institute of Hydrology developed the Smoothed Minima Technique. In this method, the streamflow hydrograph is separated by applying a simple smoothing rule. The first step in this separation technique is that the minimum amount of stream-gauging measurement for five-day non-overlapping periods needs to be determined. The series of obtained data are searched for values that are less than 1.1 times that of two values amongst the neighboring points. This point is called the turning point. By connecting the turning points to each other, the baseflow hydrograph can be drawn.

In this technique, two important notes should be considered. First, catchment nature does not affect the results. Second, sometimes in this method, unusual outcomes may be obtained due to closeness of turning points, which can lead to higher estimations of baseflow in relation to total streamflow (Nathan, 1990).

Another arbitrary and physically unrealistic technique in this category is the Recursive Digital Filter method. The concept originated from recursive digital filter in electronic circuitries (Lyne and Hollick, 1979). The filter is used to separate a low-frequency baseflow from high-frequency overland-quick flow and can be defined as:

$$f_k = \alpha \times f_{k-1} + \frac{(1+\alpha)}{2}(y_k - y_{k-1}) \qquad (10)$$

where, f_k is the filtrated quick response at kth sampling instant, y_k is the original streamflow, α is the filter parameter and y_k-f_k is filtrated baseflow.

The filter parameter can be obtained from visual inspection of several data series and the affect on the degree of attenuation. The degree of smoothing depends on the number of data passing through the filter. For each backward pass, a forward pass is needed to minimize the phase distortion. However, filter nullifies the anomaly results.

The calculated results from the recursive digital filter method are more likely to be close to the actual conditions under flashy peaks periods. Then, a more realistic and reasonable estimation of the index of baseflow in contrast with smoothed minima technique can be anticipated (Nathan, 1990).

Lack of high-frequency data has been a problem that hydrologists have been challenged with every day. Hughes et al. (2003) evaluated the continuous baseflow separation technique with monthly data based on Smakhtin's (2001) report. The digital filtering algorithm used in the experiment was:

$$q_i = \alpha \cdot q_{i-1} + \beta(1+\alpha) \cdot (Q_i - Q_{i-1}) \quad (11)$$

$$QB_i = Q_i - q_i \quad (12)$$

where, Q_i is total flow time series, q_i is high-flow time series element, QB_i is baseflow time series element ($0<QB_i<Q_i$), i is time step index and α and β are separation parameters ($0<\alpha<1$,$0<\beta<0.5$).

As was expected, the streamflow partitioning models that were calibrated and validated with daily data did not yield satisfactory results using low-frequency data. However, reasonable results were obtained by implying monthly data and regionalized parameters in some of South Africa's catchments (Hughes et al., 2003).

Empirical methods, the most common techniques used for hydrograph separation, often rely on experience or observation, without needed regard for system and governing theories. However, high correlation between estimated and measured data for surface and subsurface flow may be obtained from empirical methods. Despite simple procedures, they often suffer from arbitrary and unrealistic techniques and most are only valid for specific physiographic regions.

2.1.4 Graphical Methods

In most of the graphical methods, baseflow is separated in an arbitrary fashion from storm hydrographs. Although, they are distinguished as arbitrary, however, they are at least consistent (Nathan et al., 1990). The first graphical method used for hydrograph separation was recommended for those catchments in which groundwater contributions are relatively significant and reach the river promptly. In this method, a line is drawn backward after the depletion of flood point B (Figure 3) on the recession limb and continues till it reaches under the peak of the hydrograph (Gray, 1973), or under the point of inflection (Subramanya, 1994). In the next step, this point is connected to the beginning of the surface runoff event (point A, Figure 3).

One of the major difficulties of this method was the identification of the end of the direct runoff or point B. Linesly (1958) introduced an empirical equation to define this point;

$$N = A^{0.2} \tag{13}$$

where, N is the time interval from peak of hydrograph to point B in days and A is the drainage area in square miles.

The second graphical method of separation was achieved easily by connecting the beginning point of the surface runoff hydrograph to the end of the direct runoff event. The third graphical method of separation was obtained by extending a straight line from point A to a point beneath the crest of hydrograph, and then joining this point to point B.

Nash (1960) proposed a graphical separation method, which was based on 90 storm events in 48 catchments in Britain. In this method, a straight line is drawn from the starting point of rising limb of hydrograph to an arbitrary point on the recession limb. This point may be found by trial and error of the following equation:

$$t_r = 3\times(t_{csr} - t_{cer}) + t_{eer} \tag{14}$$

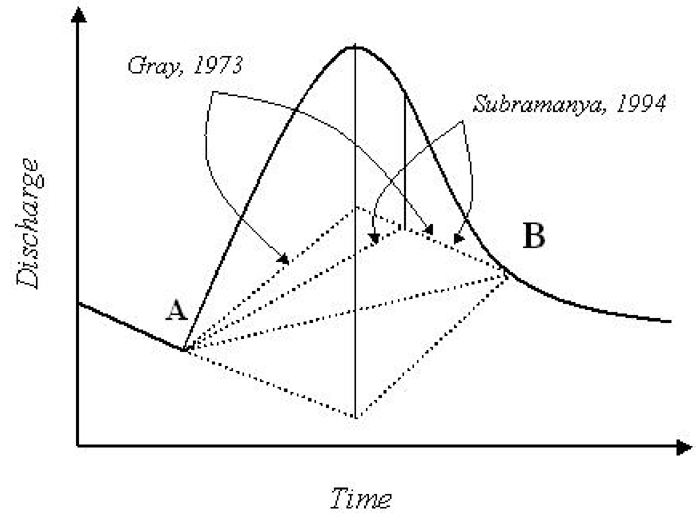


Figure 3. Baseflow separation method

In the above equation, all the terms have a unit of time and are defined as follows; t_r is the desired point on recession limb, t_{eer} is the end of the effective rain duration, t_{cer} is the center of the effective rain duration and t_{csr} is the center of storm runoff duration. This method regardless of the empirical nature was recommended by the USDA-Agricultural Research Service (ARS) for reasonable results (USDA-ARS, 1973).

USDA-ARS proposed another method in 1973. In this method, it is assumed that a groundwater reservoir acts as a single linear reservoir during recharge as well as during recession. It is also assumed that total precipitation is equal to the summation of infiltration and the excessive rainfall. Figure 4 shows that during the first phase (AB), baseflow continues to decline because groundwater recharge due to constant infiltration rate. The governing equation for this section is as follows:

$$Q = Q_A \exp\left[-\left(\frac{t - t_A}{K}\right)\right] \quad (15)$$

where, Q is the outflow at time t, Q_A is the outflow at time t_A, and K is the hydraulic conductivity.

Phase BC of Figure 4 and equation (16) show the linear behavior of groundwater reservoir with uniform recharge rate (R_o).

$$Q = (Q_B - R_0)\exp\left[-\left(\frac{t - t_A}{K}\right)\right] + R_0 \quad (16)$$

An exponential trend for recession is assumed after the cessation of precipitation (Figure 4 section CD) by:

$$Q = Q_C \exp\left[-\left(\frac{t - t_C}{K}\right)\right] \quad (17)$$

where, Q_B and Q_C represent outflow at time t_B and t_C, respectively. The approach is superior to purely empirical methods (USDA-ARS, 1973).

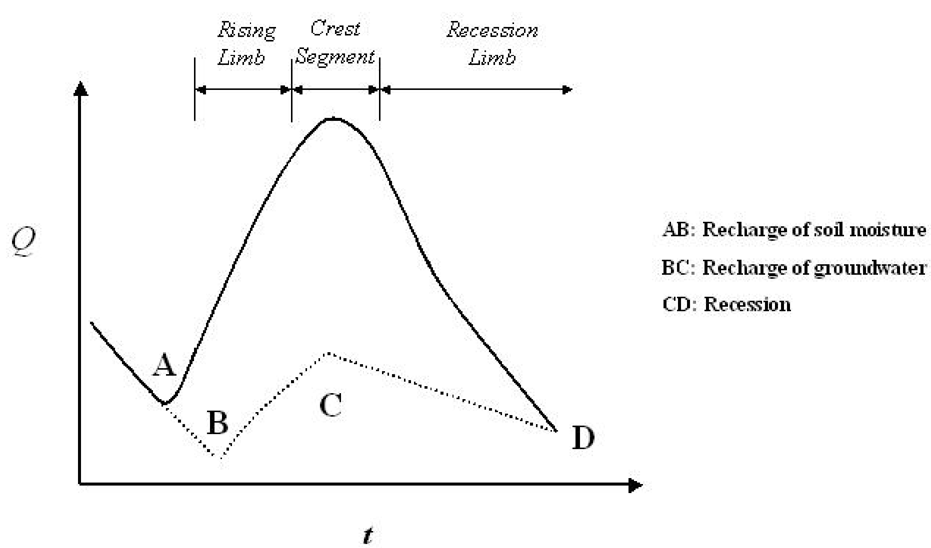


Figure 4. Separation of baseflow (USDA-ARS,1973)

Nazeer (1989) proposed a semi graphical and semi analytical approach. A two-parameter beta distribution is used to define the exact profile of the baseflow curve during the storm event. According to the probability density function of two-parameter beta distribution, equation (18) was introduced by Nazeer (1989):

$$\ln q^* = n \cdot \ln t^* + n \cdot \alpha \cdot \ln \beta^* \quad (18)$$

where, q^* is the dimensionless peak discharge factor, t^* and α are dimensionless peak time factors, $\beta^* = (1-t)/(1-t_p)$, t is time, t_p is time to peak and n is the shape factor.

First, any baseflow separation technique can be used to draw an approximate baseflow curve. Second, the shape factor is determined by drawing the trend line between lnq^* and $lnt^* + \alpha\ ln\beta^*$. The obtained shape factor is used to draw a new baseflow hydrograph. This procedure is repeated until the shape factor converges. This result along with other factors is used to provide the exact profile of the baseflow curve. Additionally, this method provides highly accurate streamflow separation estimation (Nazeer, 1989).

In most of the graphical methods, hydrograph separation techniques use arbitrary approaches. Nevertheless, these techniques are recommended for rough estimations. In addition, graphical methods are not economical, are time consuming and may contain a permanent source of error. However, they have the advantage of providing consistent results.

2.1.5 Geochemical Methods

During storm events, in addition to stream water level, the chemistry of water changes with fluctuating concentrations of solution and suspended elements.

Geochemical methods have dealt with identifying different chemical components before, during and after the flood events. Studies have showed that most water chemistry parameters associated with interflow and groundwater flow decrease during flood events. On the other hand, the discharge curve shows the response patterns of water components to hydrological phenomenon (Walling, 1975).

Scientists have proposed a number of techniques with different chemical characteristics such as conservative natural isotopes and chemical tracers (Sklash, 1979). One such technique showed that hydrograph separation method needs long term sampling from surface and subsurface flow in different seasons during wet and dry years (Criss, 1999). In addition, pH, turbidity and concentrations of major ions (Ca, Mg, Na, K, and Cl) are required before final conclusions could be made (Winston, 2002).

Many studies have shown that water chemistry components change due to the geomorphology of the area, intensity of precipitation, water temperature, specific conductivity, soil depth, pathways by which water contributes to the stream, fraction of new and old water in stream, composition and soil structures, underlying bedrock topography and dozens of other factors (Winston, 2002; Renshaw, 2003).

Geochemical methods are included as some of the most powerful techniques in streamflow partitioning. They are helpful in developing the physical measurement techniques and provide valuable information concerning the hydrological cycle. However, they are expensive, complex and highly dependent on external factors that affect water chemistry components.

2.1.6 Automated Methods

Kim and Hawkins (1993) proposed the SAM technique (a computer program for plotting and formatting surveying data for estimating peak discharges by the Slope-Area Method) for hydrograph separation. This technique is able to read daily streamflow data from the U.S. Geological Survey database. The advantages with this method in addition to the general usage of computers are that this program optimizes the recession limb of the hydrograph and prepares weighted baseflow and surface flow for the duration of the study (Mankin et al., 1999).

Shirmohammadi et al. (1987) examined and automated a previously developed streamflow partitioning method (Shirmohammadi et al., 1984). For automating this procedure, two factors were considered. First, the threshold rainfall value was defined by a third degree polynomial function based on twelve years of soil moisture data, which replaced the arbitrarily selected constant threshold value. Second, storm-time base was evaluated as the sum of the time of the concentration (T_c) and the time from hydrograph peak to an arbitrary point on the recession limb determined based on the watershed area using Linsley's method (1982). The storm-time base determined in this manner highly depends on geomorphic characteristics such as channel length, slope and channel conditions. Satisfactory results were obtained by applying this method to different physiographic regions (Shirmohammadi et al., 1987).

Another automated approach for streamflow partitioning was proposed by Bethlahmy (1971). In this method, the amount of baseflow/interflow at any time can be computed from the value of baseflow/interflow from the previous time step plus an incremental value (Boughton, 1988).

Boughton (1988) developed and evaluated two automated models for streamflow partitioning. In the first model, the amount of increment in each time step is invariable. In this model, some assumptions were considered for an automation algorithm in each time step. For instance, if the current total flow is less than or equal to the summation of prior baseflow and maximum increment, then baseflow for the present time is considered as the total flow for the previous time step. In the other case, former baseflow plus maximum increment is substituted. Nevertheless, the difference between total flow and baseflow is defined as the surface flow. In the second model, the amount of baseflow is a portion of the total runoff, thus it increases as the total runoff rises. This value is a fraction of the total runoff and the rate of baseflow in the most recent time step. In this model, surface runoff has the same definition as the first model.

Reasonable results were obtained from applying both models in some Australian catchments. However, the second model provides a better estimation of the hydrograph components. These methods are also able to provide valuable information about recharge of baseflow, which is useful in flood routing, rainfall-runoff modeling and water balance modeling (Boughton, 1988).

Because of the laborious nature of traditional baseflow separation methods, automated techniques have been considered by hydrologists. Automation of streamflow partitioning gives researchers the ability to imply and compare different approaches in small periods of time. It also helps to synthesize the hydrological behavior, which is applicable in rainfall-runoff models. However, according to the origin of automated techniques, they suffer from the same disadvantages.

2.1.7 Summary

Among numerous hydrograph-partitioning techniques about forty different approaches were investigated and classified into three-component, analytical, empirical, graphical, geochemical, and automated methods (Table 1). Then, their advantages and disadvantages were highlighted for appropriate use as follows (Nejadhashemi, et al., 2003):

Table 1. Reviewed Streamflow Partitioning Methods

Methods	References
Three-Component	Barnes (1939), Linsley and Ackermann (1942), Kulandaiswamy and Seetharaman (1969), Nathan and McMahon (1990), Mugo & Sharma (1999)
Graphical	Linesly (1958), Nash (1960), Gray (1973), USDA – ARS (1973), Nazeer (1989), Nathan et al. (1990), Subramanya (1994)
Empirical	Lyne and Hollick (1979), Institute of Hydrology (1980), Shirmohammadi (1984), Boughton (1988), Nathan (1990), Smakhtin (2001), Hughes (2003)
Analytical	Lyne and Hollick (1979), Linsley (1982), Chow (1988), Singh (1988), Jakeman & Hornberger (1993), Boughton (1993),Su (1995), Chapman & Maxwell (1996),Szilagyi Parlange (1998),Chapman (1999), Wittenberg and Sivapalan (1999)
Automated	Bethlahmy (1971), Shirmohammadi et al. (1987), Boughton (1988), Kim and Hawkins (1993), Mankin et al. (1999)
Geochemical	Walling (1975), Sklash (1979), Criss (1999), Winston (2002), Renshaw (2003)

a. Three-component methods: A numbers of models have been developed for hydrograph separation that consider streamflow to be composed of two components; overland flow and baseflow. However, in three component methods, interflow in addition to overland and baseflow is considered. These methods are confronted with the problem of being too detailed.without having advantages to other methods.

b. Mathematical and numerical approaches for analytical hydrograph separation: The complex nature of these methods makes them less attractive for users other than the researchers. However, they are more accurate given proper input values.

c. Empirical methods: These methods may produce satisfactory results but have regional application and are very site specific.

d. Traditional graphical methods: These methods have been used widely. They are easy to use, especially for watersheds with fewer hydrographs. However, results obtained by these methods may suffer due to estimation errors.

e. Geochemical methods: Geochemical methods deal with identification of different chemical components, before, during and after the flood events. Dozens of conditions need to be considered in such methods and most of them are expensive and sophisticated to use.

f. Automated techniques: These methods were originally developed based on traditional baseflow separation methods. Despite their robustness they suffer from the same disadvantages as the other methods described before. However, automated techniques are recommended because they are economical to use and technically sound.

Despite the large number of methods and techniques for hydrograph separation, it is clear that major research is needed if an accurate, easy to use, and more economical approach is desired in this area. In addition, consideration of the spatial variability is lacking from most of the existing methods. With advances in geo-referencing through a geographical information systems (GIS) package, development of a new technique capable of considering spatial variability in soils, land use, and climate patterns seems desirable.

2.2 USGS Computerized Method of Streamflow Partitioning

2.2.1 PART: A Computerized Method of Base-Flow-Record Estimation

The computer program, PART, uses streamflow records and the aerial diffuse concept of ground-water-movement under the USGS format to appraise a daily record of baseflow. The method used to partition streamflow in the PART program employs a daily record of streamflow values. Using daily data, the program estimates baseflow (based on antecedent streamflow recession) by considering the groundwater flow allocation to be equal to the streamflow on the initial day plus the following days in which a daily decline is not less than 0.1 log cycle (Barnes, 1939). In the next step, the linear interpolation technique is used to estimate the baseflow for the remaining days. Sometimes, unrealistic results (i.e. groundwater estimated value is greater than total streamflow) are obtained using the linear interpolation method and corrected in the final procedure (Rutledge, 1998).

Regardless of the fact that the computation is based on daily streamflow records, it was recommended that the results should be more reliable if long-term data (monthly or even yearly) are used as input in the program (Rutledge, 2003). In addition, more accurate result should be obtained in the basin, where most ground water discharges to the stream and a streamflow gaging station is located at the downstream end of the basin.

2.2.2 HYSEP: Hydrograph Separation Program

The three methods of fixed-interval, sliding-interval, and local minimum, which were introduced by Pettyjohn and Henning (1979), are included in the HYSEP program. Therefore, the program is capable of separating the streamflow hydrograph into its components (overland flow and groundwater flow) in three fashions. Although the HYSEP program accelerates the required time for hydrograph separation, the hydrograph separation techniques still remain subjective processes (Sloto and Crouse, 1996).

In all three methods, the duration of surface runoff from the point of peak to the recession point is calculated from the empirical relation (Linsley et al., 1982):

$$N = A^{0.2} \tag{19}$$

where, N is the number of days after the peak of hydrograph and A is the drainage area in square miles. Also, $2N$ is defined as one interval. In the fixed-interval method, the lowest discharge in each interval is considered as baseflow for the interval (Figure 5).

The next method is called the sliding-interval method. This method assumes that an imaginary bar with a width of $2N$ is sliding upward until it intersects the hydrograph. Then, the discharge value at the intersection is assigned to the median day. The process is continued until the imaginary bar reaches the end of the desired time period. Finally, the assigned points are connected to define two-distinct sections of the hydrograph (Figure 6).

The last method is called the local-minimal method. In this technique, each day is compared within an interval of [0.5(2N-1)] days. If the desired day has the lowest discharge among the remaining days, it is considered as a local minimal day. By connecting the local minimal points with straight lines, the hydrograph is separated into its components (Figure 7).

Although the daily mean streamflow values are the required input data for the program, average annual estimation is more reliable than monthly or daily baseflow estimation. The program is also more suitable for long-term record rather than extreme climatological conditions.

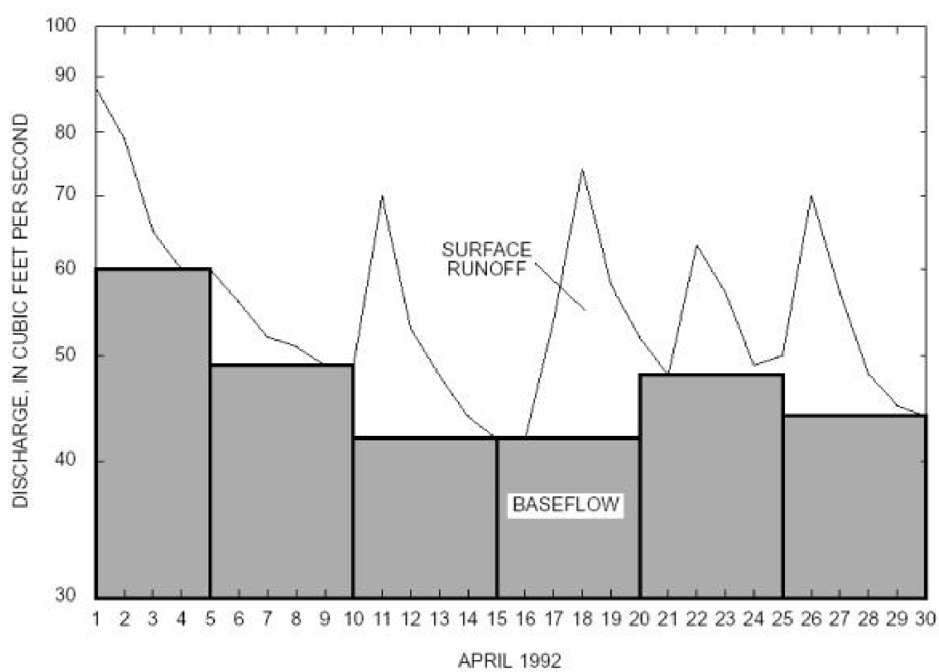


Figure 5. Hydrograph separation using the fixed-interval method for French Creek near Phoenixville, Pa. (USGS report 96-4040)

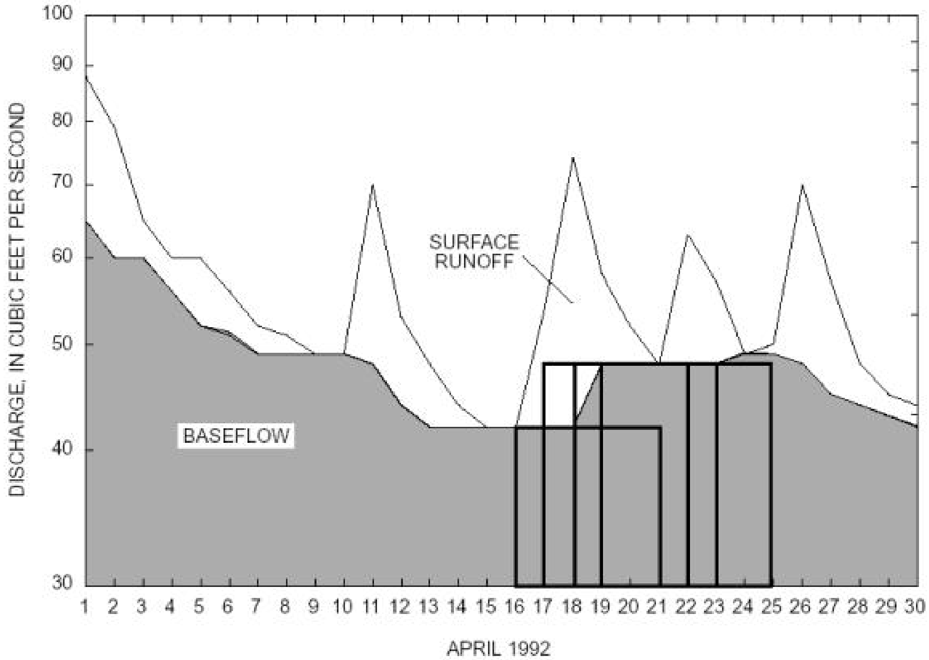


Figure 6. Hydrograph separation using the sliding-interval method for French Creek near Phoenixville, Pa. (USGS report 96-4040)

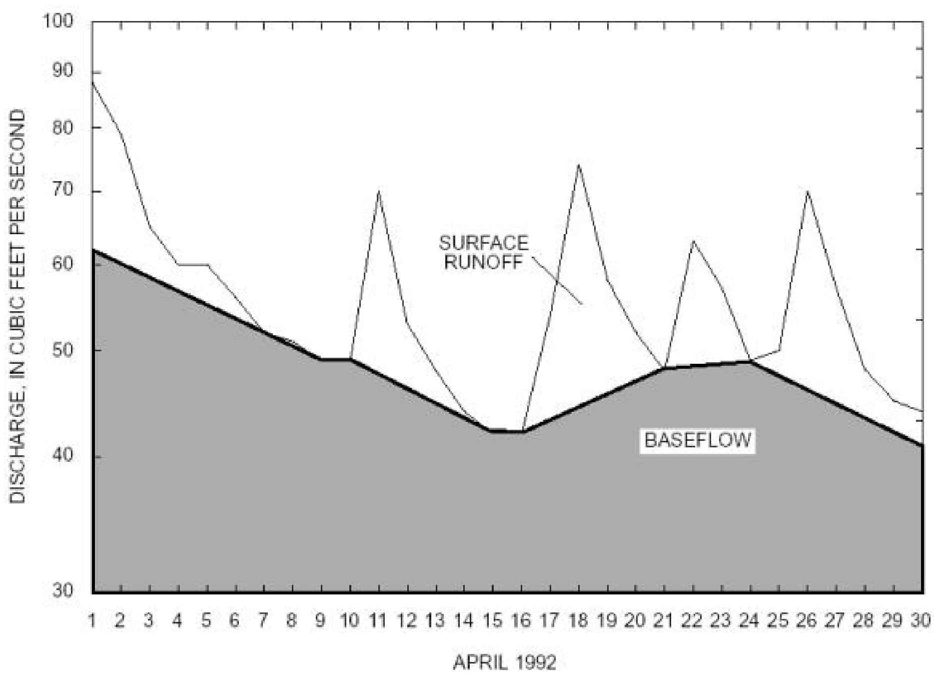


Figure 7. Hydrograph separation using the local-minimal method for French Creek near Phoenixville, Pa. (USGS report 96-4040)

2.2.3 BFI: A Computer Program for Determining an Index for Baseflow

The British Institute of Hydrology proposed a deterministic procedure for baseflow separation in 1980, which is a combination of a recession slope test and local minimums method. In this method, the water-year is divided into five day intervals and the lowest discharge value is determined for each interval. Then, the desired value is compared with adjacent lowest values. If 90% of the given values is less than both adjacent values, then the point is considered the turning point on the baseflow hydrograph. In the next step, the turning points are connected by a straight line to separate the baseflow (area beneath the line) from the streamflow hydrograph. This technique is implied in the BFI (Base Flow Index) program.

One of the advantages of a computerized system is that it can handle large amounts of data. BFI is not an exception to this rule. BFI was recently run on all USGS stream-gages using their historical database (about 19,000 stream-gages). Although, the annual baseflow index (the ratio of baseflow to total flow volume) has been found to be reliable, any user should be cautious about using this program for regulated streams and short-term periods (Wahl et al., 2003). In addition, the estimated baseflow by this method is not consistent with results of more sophisticated approaches such as Szilagyi and Parlange (1998) and Wittenberg and Sivapalan (1999).

2.2.4 TOPMODEL: A Rainfall-Runoff Model

TOPMODEL is a rainfall-runoff model that is based on the concept of hydrologically similar zones. This model is capable of reproducing the hydrological behavior of the catchment in a distributed or semi-distributed way (Wolock, 2003).

The major input requirements for TOPMODEL are: 1) topographic input (derived from digital elevation model (DEM)) in the form of topographic index values, 2) soil characteristics (derived from a digital database called the State Soil Geographic Data Base (STATSGO), 3) geographical coordinate of the watershed, and 4) daily precipitation and temperature data. TOPMODEL uses a stochastic approach to generate the time series of precipitation and temperature along with the evaporation potential (Human, 1961) and day length (Kreith and Kreider, 1978). The outputs of the model include depth to water table, total streamflow, and overland and subsurface estimation (Brookes et al., 2003).

The latest research on TOPMODEL usage for streamflow partitioning was conducted by Brookes et al. (2003). A network saturation value was used to determine the initiated point of time and location of overland flow. Afterward, the overland flow is easily routed by considering travel time for each single cell. Therefore, only three attributes were assigned for each cell (travel time, location and network saturation values), which are the bases for the hydrologically similar zone definition. It should be noted that the model suffers from different sources of errors such as inaccurate climate, soils and terrain data, all of which magnify the uncertainty of the saturation overland-flow percentages (Brookes et al., 2003).

2.2.5 PULSE: Model-Estimated Groundwater Recharge and Hydrograph of Groundwater Discharge to Stream

PULSE is a computer program that estimates the groundwater flow discharge to the stream based on assigned transmissivity, storage coefficient, head difference caused by recharge, streamflow records and distance from the stream. Required assumptions of the model are: 1) recharge to the groundwater flow system is in the form of diffuse areal distribution, 2) groundwater discharge hydrograph can be constructed by user-specified recharge values, 3) recharge may be implied in the form of instantaneous quantities or gradual rates, and 4) groundwater evapotranspiration (GWET) can be treated as negative gradual recharge (Rutledge, 2002).

In each run, the model only calculates the groundwater discharge to the stream in one of the two following cases:

a. Instantaneous recharge:

$$Q = \frac{1.866 A R_i}{K} \sum_{m=1,3,5}^{\infty} e^{(-0.933 m^2 \pi^2 t)/(4K)} \tag{20}$$

where, Q is total basin baseflow discharge, A is basin drainage area, R_i is the instantaneous recharge depth, K is recession index and t is the time elapsed after the instantaneous recharge.

b. Instantaneous recharge amount followed by gradual recharge rate:

$$Q = R_g A + 2 R_g A \times \sum_{m=1,3,5}^{\infty} \left[\frac{0.933 R_i}{R_g K} - \frac{4}{\pi^2 m^2} \right] \times e^{(-0.933 m^2 \pi^2 t)/(4K)} \tag{21}$$

where, R_g is the gradual recharge rate.

For both of the above equations, the recession index is required to be estimated by the program. Rorabaugh and Simons (1966) derived an equation used in PULSE program to calculate the recession index:

$$K = \frac{0.933 a^2 S}{T} \tag{22}$$

where, T is transmissivity, S is storage coefficient, and a is the distance from the stream to the hydrologic divide.

More accurate results may be obtained if all or most of the groundwater discharges to the stream and the stream-gauging measures most of the outflow. However, aerial variation of transmissivity along with parallel groundwater flow to the stream and flow to a deeper aquifer system make the estimation less reliable (Rutledge, 2002).

2.3 Geographical Information Systems: Nature, Scope and Challenges

Generally, variability in physical conditions in each watershed makes the hydrologic assessment more complex and unique. Therefore, one should consider that quantitative results of one model or procedure for a specific hydrologic condition might not easily be transformable to another condition. Geographical information systems provide many advantages for hydrological practitioners. The large amount of spatially detailed information have been derived and embedded within the geographical information system. In addition, the GIS provides an efficient storage and update system. Further, it promotes data sharing and facilitates decision-making. Here, some practical uses of current GIS systems are addressed briefly (Schumann et al., 2000):

- Estimation of conceptual models' parameters (e.g., in the SCS model, curve number can be easily determined from digital land use data and soil maps) (Pilgrim et al., 1992).

- Parameterization of a lumped model: Schumann et al. (2000) presented the conceptual event-based rainfall-runoff model. In this model, the parameters can be derived in the form of averaged catchment characteristics from a GIS analysis.
- Discretization of the catchment into equally spread square grid elements, which allows incorporation of spatial variability of the catchment in its operation (e.g. ANSWERS (Areal Non-point Source Watershed Environment Response Simulation was developed by Beasley and Huggins (1978)). The model was designed primarily to simulate the behavior of watersheds during and immediately following a rainfall event.
- Application of separate models within each subdivision of a watershed based on Hydrologic Response Units (HRUs) concept (e.g. the Precipitation-Runoff Model System (PRMS) that was developed by Leavesley et al. (1983)).

As it was mentioned above, GIS could be used to improve the estimation of model parameters. However, it "is a very limited use of the available information and the power of the GIS. There is no reason to limit ourselves to model parameterizations that were developed decades ago in an era without the information and computing facilities available today" (Schumann et al., 2000).

2.3.1 Data Structures

The spatially distributed data in GIS can be stored in two basic formats: vector and raster. In the vector format, the geographic features are stored in the form of points, lines and polygons, e.g. rivers are best represented by a line, and stream gauging or climate stations in the basin are best represented by points. Vector data is generally considered best for map production because it can represent the position of objects with great precision, which is important in geographical analysis. In the raster format, all spatial features are divided into two-dimensional uniform-sized square cells, which contain an index that identifies the attribute being mapped. For example, land surface terrain elevation can be derived from raster representation (Digital Elevation Models). This format is best suited for attributes that continuously vary in space. Regardless of structure in which the data are available, moving back and forth between these two representations is an important topic of spatial hydrology (Garbrecht et al., 2001; Moglen, 2002; Montas, 2002).

2.3.2 Projections

Each point on the earth's surface can be defined by latitude, longitude, and elevation above sea level. To this effect, in GIS, the positions of the features are expressed as coordinates in a geo-referenced system. Since maps are flat, rather than ellipsoidal, a mathematical transformation has been developed to represent an oblate spheroid surface (such as Earth) onto these maps. This technique is known as projection. Several projection methods have been developed such as: a) a cylindrical projection that defines the Universal Transverse Mercator (UTM) system of coordinates, which is widely used in the United States for projection of lands with north-south extent, b) conical projection, which defines the Lambert coordinates system that is widely used in the United States for projection of land with east-west orientation, c) Albert Equal Area projection, which is commonly used for maintaining the true earth surface area, d) Hydrologic Rainfall Analysis Project (HRAP), which is used by the United States National Weather Service to represent radar estimation of rainfall (Garbrecht et al., 2001; Montas, 2002).

Regardless of the advantages and disadvantages of each projection technique, they all suffer from distortion that is caused by the transformation process of positioning the objects from a three-dimensional surface to a two-dimensional surface. For this reason, one needs to be cautious about minimizing the angles, areas and distances distortion and seek a method that is best fitted by project goal, because none of the known projection methods preserve all three attributes (Garbrecht et al., 2001; Montas, 2002).

2.3.3 Digital Terrain Models (DTMs)

A digital terrain model determines a systematic arrangement of spatial distribution from terrain attributes data. In the case that a DTM includes only elevation data of terrain characteristics, it is called a digital elevation model (DEM). In a hydrologic model, the consistency of grid sizes with project scale needs to be considered. It means that the accuracy of the elevation along with mesh size and vertical increment (quality and resolution of DEMs) are the most important aspects in the selection of a digital model. With respect to surface representation, DEMs can be stored, acquisitioned and analyzed in three ways: a) square grid matrix, b) Triangular Irregular Network (TIN) or c) contour based network.

A square grid DEM is one of the most widely used elevation attributes due to its easy implementation to computer algorithms. However, in this form of representation, mesh size adjustment for computational efficiency is a difficult task. In addition, this system suffers from inaccurate computation of upslope flow path (Vieux, 2001).

The TIN structures are more efficient than the DEM grid for its accommodation in inter-visibility analysis on topographic surfaces and reliable extraction of distributed watershed model requirements such as slope and channel network. In addition, the sizes of the triangles vary with slope steepness. In spite of this, the TIN structure format is not widely available for all regions because of complicated computational procedures (Garbrecht et al., 2001).

Representation of the surface using a contour provides better outlines of landscape features such as gradients. In this format, many equations, which describe water flow, can be transformed into a one-dimensional layout that is much simpler in implementation in hydrologic models. However, they need considerably more information than DEM structures for two-dimensional landscape representation (Garbrecht et al., 2001).

Many sources provide digital elevation data. For example, the USGS provides DEM data in several forms: a) 7.5-degree DEM at 10×10m resolution with vertical accuracy of 1 dm, b) 7.5-minute DEM, 30×30m data spacing casts on UTM projection, c) 1 degree DEM consisting 3×3-arc-second data spacing, d) 1×2 degree DEM, e) 30-minute, 2×2-arc-second data spacing, f) 15-minute Alaska DEM, 2×3-arc-second data spacing, g) 7.5-minute Alaska DEM, 1×2-arc-second data spacing.

Additional examples include the National Imagery and Mapping Agency, the National Oceanic and Atmospheric Administration and commercial providers (Garbrecht et al., 2001; Vieux, 2001).

2.3.4 Drainage Networks

Surface drainage networks are generally derived from digital elevation models or digitized stream data.

2.3.4.1 DEMs Based Drainage Network

Several methods have been developed and embedded in the GIS environment for automatic extraction of the drainage network. These methods are accurate and save time. However, results are highly dependent upon the resolution of the digital elevation data. Two major consequences of coarse resolution are underestimating the overall drainage length and therefore making inaccurate judgments about runoff arrival time at the outlet. A flattened slope is the other shortcoming of the low resolution DEM, which may result in disappearance of features (the hill slope and valley).

The D8 method is one of the widely used techniques for flow derivation (O'Callaghan and Mark, 1984). In this method, the drainage pathway is defined by connecting each cell to one of its eight neighbors in the direction of steepest descent. The Rh08 method uses a probabilistic approach for targeting one of its eight neighboring cells as the next drainage path. Besides single flow-direction methods, multiple flow-direction algorithms are also provided. However, interpolation error, data noise, systematic production error, depression, flat areas, and surface obstruction may cause difficulty in drainage network extraction (Garbrecht et al., 2001; Vieux, 2001).

2.3.4.2 Digitized Stream Data

As was discussed above, divergence between actual maps or aerial photos and automatically produced drainage networks originate from landscape and/or computational problems in the drainage network derivation. In order to solve this problem, digitized stream data are “burned” in the digital elevation map, thus forcing the drainage network to occupy the same relative position as the vector map. On the other hand, by lowering the elevation of a DEM at the location of actual streams, software can automatically correct the stream network.

For example, some of the popular sources of digital stream data are the United States Geographical Survey (1:20,000-scale, 1:24,000-scale, 1:250,000-scale, and 1:100,000-scale), the United States Environmental Protection Agency (River Reach files in the form of RF1, RF2, and RF3-Alpha), National Hydrography Dataset (1:100,000-scale) and commercial vendors (Garbrecht et al., 2001; Vieux, 2001).

2.3.5 Soil Data

The Natural Resources Conservation Service (NRCS) developed a digital soil map, STATSGO, which consists of soil and non-soil areas with probable classification for the entire United States at 1:250,000 scale. According to the STATSGO user guidelines, this digital soil map was primarily designed for “regional, multicounty, river basin, State, and multistate resource planning, management, and monitoring." However, it does not contain detailed information for county level conceptualization. Attribute data consists of more than 25 physical and chemical soil characteristics (available water capacity, soil reaction, salinity, flooding, water table, woodland management, pastureland, wildlife, crop yield, forest understory, soil layer, map unit, plant composition, plant name, range site production, crop yield, and soil interpretation ratings) (Garbrecht et al., 2001).

Another digital soil map that was developed by the Natural Resources Conservation Service is SSURGO. These digitized maps were prepared at county level scale (1:12,000 to 1:63,360) and contain information regarding the kinds of geographic occurrence of soils on a landscape. The spatial data are stored in vector format, which represents the boundaries of soil mapping units. This soil database is also recommended by the USDA for erosion related studies, land-use assessment, aquifer area investigation (especially sandy and gravely), and wetland distinction. The attribute database of SSURGO is called Map Unit Interpretations Record (MUIR), which contains similar attributes as the STATSGO database (USDA, 1999).

Generally, distributed hydrological models rely on detailed hydrological soil groups and properties, which are not easily available. In order to solve this problem, the Natural Resources Conservation Service (NRCS) has conducted a detailed digitized form of data at the county level, such as MIADS soil database compiled by NRCS for Oklahoma (Garbrecht et al., 2001; Vieux, 2001).

2.3.6 Land Cover/Use

During the past few decades, remote sensing technology has been applied increasingly in the field of water resources engineering. Among all of these applications, land use/cover has seen the largest impact. Not many types of maps have been developed for land use/cover classification that are directly applicable in hydrology. However, remote sensing maps can be used to derive hydrological parameters such as Manning's coefficient of roughness and albedo. This is not a simple procedure and extensive training should be considered for the calibration task (Vieux, 2001).

Land use influences hydrological parameter values, thus affecting runoff volume. Some of these changes are very significant and by using multi-temporal imagery, such changes can be easily observed. Usually, development of these maps requires a limited number of ground observations. However, in large-scale watersheds, this approach is not economical. In such cases, a software package performs automatic classification of the remotely sensed image according to the land cover category for areas with similar reflectance (Schultz, 1996).

Studies show that the land use/cover accuracy may highly depend on the spatial resolution of sensors, which range from about 10 m to 1 km. SPOT Image Corporation and EROS Data Center are two examples of customer-specified land-cover classification providers (Garbrecht et al., 2001).

2.3.7 Precipitation

Precipitation data may be based on rain gauge measurements or on radar observations. The following sections describe each database including rain gauge and radar data.

2.3.7.1 Rain Gauge Data

Traditionally, knowledge of point estimates of rainfall is used to analyze the spatial distribution of rainfall. Most popular methods that have been used include Thiessen polygon, inverse distance weighting, and kriging (Garbrecht et al., 2001).

In the United States, three forms of rainfall data are archived. The first form includes daily rainfall, which can be accessed through the internet. This data is gathered through a collaboration of the National Climatic Data Center (NCDC) and the National Weather Service (NWS). Hourly rainfall data is the second form of data that can be used in hydrologic models. The last common format of data is in the form of 15-minute rainfall rates at selected stations around the United States. The data can be reached through the internet and commercial vendors (Garbrecht et al., 2001).

2.3.7.2 Radar Data

Rainfall data that is often obtained from sparse networks of rain gauges has been widely used in hydrology models. However, this data is in the form of distinct points inside a terrain, which may not accurately reflect the spatial distribution of precipitation, especially during convective storms. Lack of knowledge regarding the spatial and temporal distribution of rainfall can incorporate an undesirable amount of errors in a model. This deficiency can be reduced on large scales by using radar-rainfall estimation.

NEXRAD is a Doppler radar with a ten centimeter wavelength transmitter, which records reflectivity, velocity and spectrum width of the reflected signal. The reflectivity measured by radar can be estimated by distribution and relative size of raindrops over a basin. More than 120 WSR_88D or NEXRAD radars have been deployed by the NWS throughout the United States. This ground-based radar offers unique advantages such as generation of continuous digital 3D scanning of rainfall events, long-term coverage, and high space resolution and measurements. WSR-88D rainfall data has increased the expectation of spatial and temporal distributions of precipitation over large-scale watersheds.

A wide range of data is provided by the National Information Dissemination Service (NIDS) through vendors who are responsible for disseminating real-time data to the public. However, none of the existing native formats of WSR_88D radar data is usable in the GIS environment. For this reason, the NIDS provides an hourly Digital Precipitation Array (DPA) product that is in a non-graphical and digital form. This product is currently available in a georeferenced coordinate system, which is suitable for watershed modeling. The rest of the NEXRAD generated data are distributed in polar form that need to be transformed by resampling the polar-coordinate data into a georeferenced gridded format through a standard set of transformation equations.

Common grid resolution of WSR-88D radar is 4×4 km. However, it may vary from 3.5 to 4.5 km within the contiguous United States. Recent studies show that radar-rainfall data are useful for hydrologic models, and under optimal conditions, it is quite comparable to ground observation of precipitation. Although free access to radar-rainfall product is limited, NEXRAD data can be obtained from the NCDC, NIDS, and commercial vendors (Garbrecht et al., 2001; Vieux, 2001).

Chapter 3: OBJECTIVES

The large number of existing techniques and high level of subjectivity in separating baseflow from streamflow indicates that the problem is not fully understood. Therefore, a better understanding and improvement of existing methods for streamflow partitioning is the initial motivation for this study. While many hydrological model software packages are currently available, no model has been developed for examining watershed characteristics on hydrograph separation estimation. Therefore, developing and assessing the new hydrological model using physical and hydrologic characteristics of a mixed land use watershed is the ultimate goal of this research.

The aim of this study is to separate the storm runoff hydrograph into its components, thus being able to infer about sources and hydrological pathways of the storm runoff. The specific objectives of this study are to:

1) Identify the most accurate and user-friendly streamflow partitioning method using literature synthesis.
2) Evaluate the accuracy of each of these methods using separately measured surface and subsurface flow data from the Coastal Plain of the Southeastern United States.
3) Improve available techniques or develop a more precise approach that can help resource managers such as United States Department of Agriculture - Natural Resources Conservation Service (USDA-NRCS) and the United States Geological Service (USGS) to evaluate alternative management plans regarding water and ecosystem sustainability. In this stage of study,

the selected method under phase (2) will be modified by incorporating different physical and hydrologic characteristics of watersheds. This model will use different georeferenced data such as digital elevation model, soil type, land use, soil moisture, and radar or ground network precipitation records as its input data. This kind of approach should be more robust and capable of providing timely predictions.

Chapter 4: MODELING PHASE

Accurate and up-to-date information on land use, soil moisture distribution, soil types, watershed geometry, topography, evaporation, transpiration and ground water flow are the critical components of watershed modeling (Al-Sabhan et al., 2003; Starks et al., 2002). The use of a geographical information system in hydrologic modeling has gained increasing attention in recent years. That is mainly due to the fact that a good hydrology model is highly dependent upon the availability of spatially distributed parameters, and GIS is a powerful tool that can store and manipulate large quantities of georeferenced data very efficiently. To conduct the study, the following five phases were pursued:

I. Model determination and evaluation. Through literature synthesis, a best streamflow partitioning method was identified among each category of models such as empirical, graphical, and analytical. Then each of these models was tested against separately measured streamflow data from a field-scale watershed (Field-scale watershed normally refers as a watershed that it size is too small, which its physical and hydrologic characteristics can be considered as homogeneous) located in the Coastal Plain physiographic region in Tifton, Georgia. Through this exercise, the best possible streamflow partitioning method considering both accuracy and ease of use was selected. Finally, required calibration and modifications to the model was implemented.

II. In order to examine the effect of climatological factors on hydrograph components estimation, the selected model under phase (I) was modified by incorporating these elements into the model.

III. In this stage of study, both physical and hydrologic characteristics of the watershed were incorporated to test the accuracy of the streamflow partitioning technique.

IV. The Little River Watershed in Tifton, Georgia was selected for the model implementation. Then, GIS-based data (land use, soil type, soil moisture, digital elevation model, long-term streamflow, temperature and precipitation) was acquired and compiled. Data for the Coastal Plain physiographic region (1968-2000) was available through the USDA-ARS Watershed Research Laboratory in Tifton, Georgia.

V. Simulation of the model for different scenarios (e.g., soils, land use, etc.) was performed. In this regard, the acquired data such as rainfall, soils, land use, topography, and other attributes from phase (IV) was incorporated into the developed model to make the model more versatile and interactive with the georeferenced data. This will allow the examination of "what if" scenarios with the model.

4.1 Model Determination and Evaluation

The first goal of this study was to identify the most reasonable and accurate streamflow partitioning technique. To achieve this goal, two specific objectives were specified as: 1) to perform a thorough literature synthesis and identify at least five most widely used methods, and 2) evaluate the accuracy of each of these methods using separately measured surface and subsurface flow data from the Coastal Plain of the Southeastern United States. The final outcome is expected to suggest the most accurate and practical streamflow partitioning method.

The first objective of this research was performed in an earlier study by Nejadhashemi et al. (2003) and the five selected methods are described in the following sections. This is followed by the evaluation of each method's accuracy using measured Coastal Plain hydrologic data.

4.1.1 Method I (Wittenberg and Sivapalan)

This method was proposed in two papers by Wittenberg (1999) and Wittenberg and Sivapalan (1999). In contrast to the general assumption about a direct relationship between storage (S) and outflow (Q), it was revealed that there is a nonlinear correlation between Q and S in the Wittenberg and Sivapalan (1999) method. This fact was proven by analyzing the flow recession curves and the relationship is described as;

$$S = aQ^b \qquad (23)$$

where, b varies between 0 and 1 with a high correlation obtained around 0.5 for an unconfined aquifer conditions. The coefficient a depends on catchment properties, primarily area, shape of the basin, pore volume and transmissivity; however, to date no equation has been derived to describe such a relationship. If volumes are expressed as heights over a unit area and the time step in days then, S is in mm, Q is in mm d^{-1}, a is in unit of $mm^{1-b}\,d^{b}$ and b is dimensionless.

Mathematical assessment also supports the nonlinear storage-baseflow behavior. This fact was further extended through a sequence of statements to automate the hydrograph separation with daily discharge values.

In order to derive the recession curve equation for nonlinear conditions at any initial discharge value, Q_o, equation 23 was combined with the continuity equation to form the following equation (inflow was not considered, *dS/dt*= - *Q*):

$$Q_t = Q_o \left[1 + \frac{(1-b)Q_o^{1-b}}{ab} t \right]^{1/(b-1)} \qquad (24)$$

In the above equation, the parameter values *a* and *b* are unknown. An iterative least-squares method is applied to calibrate both parameters for each series of flow recession data. This goal can be achieved by systematically varying one parameter in each iterative step and computing the other parameter by considering the equality of a computed outflow with the measured flow for the given recession curve. Following this approach, the parameter *a* is described as:

$$a = \frac{\sum (Q_{i-1} + Q_i)\Delta t}{2\sum (Q_{i-1}^b - Q_i^b)} \qquad (25)$$

Where Q_i is the discharge at time *i* of an observed flow recession. Therefore, a set of values of *a* and *b* that produce a least-squares deviation of discharge from an observed flow is the optimum representation of an aquifer characteristics.

In cases where groundwater originates from another aquifer, the following equation is used. The term Q_1 may be interpreted as outflow from a second, confined aquifer.

$$Q_t = Q_1 + Q_0 \left[1 + \frac{(1-b)Q_o^{1-b}}{ab} t \right]^{1/(b-1)} \qquad (26)$$

The last value of the time-series is a beginning point for baseflow separation. Baseflow at time *t-Δt* is computed from following baseflow value at time *t* by using equation 27. Equation 27 may be derived by rearranging equation 24 as:

$$Q_{t-\Delta t} = \left[Q_t^{b-1} + \frac{t(b-1)}{ab} \right]^{1/(b-1)} \tag{27}$$

This procedure can easily model the recession component of the hydrograph. Using equation 27 and marching back in time from two days after the inflection point (i.e., the point at which surface runoff ceases), the shape of the baseflow separation line may be defined. This process continues until the separation line intersects the rising limb of the hydrograph. The Wittenberg (1999) adopted a technique to identify the peak of the baseflow separation line (hydrograph) and the rising limb of the baseflow hydrograph as; "When the reverse computed baseflow recession curve intersects the rising limb of the total streamflow hydrograph (Figure 8), a transition point (going one time-step forward) is adopted as the peak of the baseflow. Values of the rising limb of the baseflow hydrograph are then found as the computed recession for one time-step forward for each given total flow value" selected on the rising limb of the total streamflow hydrograph.

The above procedure has not been physically adapted to the recharge process, thus further research was suggested by Wittenberg and Sivapalan (1999). They tested the application of this method on 14 stations in the upper Weser and Ilmenau basins in Germany. Using the nonlinear reservoir algorithm from time-series of daily discharge showed a close relationship between precipitation in different seasons, geologic characteristics, and annual and seasonal recharge. In addition, another set of experiments was conducted for the small catchment (72 ha) of the Lange Bramke in the Harz Mountains in North Germany for the hydrologic year of 1999 (Wittenberg and Sivapalan, 1999). Results of their study showed high correlation between the groundwater level hydrograph and computed storage, using the nonlinear reservoir algorithm.

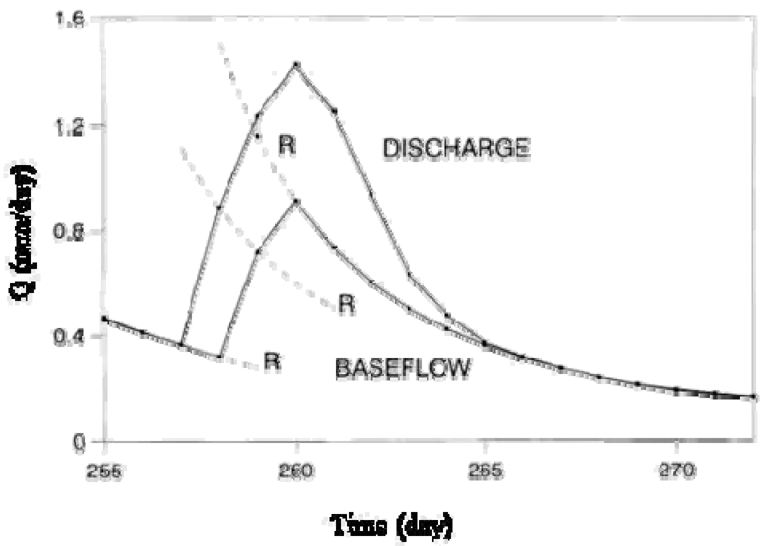


Figure 8. Construction of transition curve between two recession curves, R: recession curves computed by equation 5, (Wittenberg and Sivapalan, 1999).

4.1.2 Method II (Nathan & Mugo)

A recursive digital filter is a concept in electrical engineering, which is commonly used for analyzing and processing signals. Nathan & McMahon (1990) and Mugo & Sharma (1999) applied this idea to evaluate and automate a baseflow separation technique. The filter has a simple form as;

$$f_k = \alpha \times f_{k-1} + \frac{(1+\alpha)}{2}(y_k - y_{k-1}) \tag{28}$$

where, f_k is the filtered quick response at the kth sampling instant, y_k is the original streamflow, and α is the filter parameter, which affects the degree of attenuation. The filtered baseflow is thus defined as y_k-f_k.

The principle behind the method was originated from the fact that filtering out baseflow from the higher frequencies of quick surface flow is similar to the filtering of high frequency signals in an electronic circuit. This method like other graphical methods is not subjected to a solid physically based theory. However, the method has several advantages such as the estimation of an index of baseflow (the ratio of baseflow volume to the total streamflow volume), it is a repeatable procedure, and also the concept can easily be described by computer codes.

Nathan and McMahon (1990) suggested that the filter should be passed three times (forward, backward, and again forward) over data to increase the degree of smoothing. The forward pass of the filter can distort data, thus the reverse pass was conducted to nullify any phase distortion of the data. The output of the model is checked and limited between zero and total flow. This procedure eliminates any negative or unrealistic results. In order to evaluate the performance of this method, the results were compared with the smoothed minima method (Nathan and McMahon, 1990). Studies have revealed that the recursive digital filter method simulates better for flashy peak flow conditions than for normal flow conditions. Additionally, this method bypasses the deficiencies associated with manual or graphical methods, where accuracy depends highly on visual approximation and skills of the operator. Regardless of all the disadvantages associated with the graphical methods, their results are necessary for the recursive digital filter parameter calibration (Nathan et al., 1990).

4.1.2.1 Methods of Data Analysis

a) Graphical Method for Hydrograph Separation and Computation of Flow Indices

Mugo and Sharma (1999) used Meyboom (1961) streamflow partitioning technique for estimating daily hydrograph components. Like other graphical methods, reliance on eye approximation and/or operator's skill at plotting is the main shortcoming of this method. However, using graphical streamflow partitioning methods for a long study period is practically impossible, thus they are only applied to selected hydrographs representing the hydrology of a given site under consideration.

The exponential decay recession curve can be expressed as;

$$q_{bt} = q_{bo} K_b^t = q_{bo} e^{-\alpha t} \tag{29}$$

where, q_{bt} is the baseflow discharge at time, t, from the initiation of baseflow recession; q_{bo} is the initial baseflow discharge at the initiation of recession, K_b is the baseflow recession constant and α_b is a baseflow exponential decay parameter.

As it was mentioned before, the recursive digital filter method takes advantage of the graphical techniques for calibration and validation of its own parameters. The baseflow indices, B_g, for each year is a key term for this method.

b) Conceptual Method of Hydrograph Separation and its Implementation

Figure 9 shows the schematic drawing of the conceptual recursive digital filter method. The quick response filter partitions the total streamflow into surface flow and baseflow based on a filter parameter value, α.

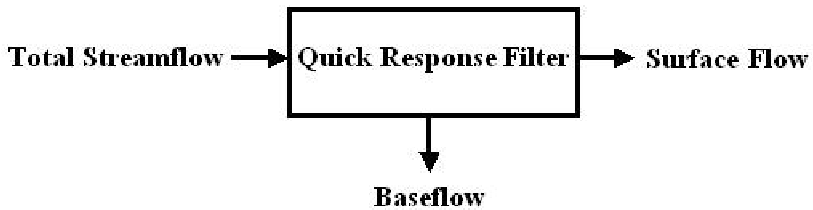


Figure 9. Schematic representation of the recursive digital filter method

Values of α (filter parameter) are determined in a series of computations. An assumed initial value for this term is substituted in the model, thus helping to determine the baseflow indices (B_f) for each year. The filter parameter varies until such time when baseflow indices for both graphical and computational methods become equal for a particular year ($B_f = B_g$). Amongst all of the filter parameters determined in the previous step, one value should be chosen. To do so, program tests the filter parameters within the allowable range of filter values obtained from the analysis of individual years as described above. Next, the sum of the error squares for each quick response filter parameter is determined as follow;

$$E = \Sigma(B_g - B_f)^2 \qquad (30)$$

where, E is the sum of the error squares and B_g is the graphically determined baseflow index. The optimum value of the quick response filter parameter is computed based on the least-squares error criterion.The value of α that results in minimum E is selected as the optimal value.

The quick response filter model was run using the data from three forest catchments in Kimakia, Kenya, and East Africa (Mugo & Sharma, 1999). There was evidence that the model gave satisfactory results. However, some limitations should be pointed out before running the model for other watersheds. For example, this method should not be used for a large-scale catchment, with a lag time of less than 24 hours, which is only equipped with a single daily staff gauge height. In whatever way, for a small-scale catchment with shorter lag time, autographic stage heights should be used. Therefore, the lag time is a vital term for selecting the time interval for the model. Generally, the lag time should be always less than the selected time interval in small catchments.

4.1.3 Methods III and IV (Boughton)

In Australia, various recession characteristics have been defined based on manual separation of baseflow from surface runoff on a semi-log graph (discharge on log scale; time on natural scale). Generally, manual hydrograph separation methods are tedious, time consuming and need a skillful operator to the conduct partitioning procedure. That is why computer based methods have become popular among hydrologists in recent decades.

Two automated methods for hydrograph separation were proposed by Boughton (1988). The following describes each model:

Method III was developed under the following assumption:

I. Baseflow at time *t* is equal to the baseflow at time *t-Δt* plus the preset value (constant value). A constant value is either assumed or computed by user identification of the end of a period of surface runoff on the hydrograph (inflection point). Generally, the point of initiation of surface runoff is connected to the inflection point by a line and an average constant value for baseflow is determined for that duration. Therefore, whenever the total runoff at any time *t* exceeds the amount of baseflow, surface runoff is generated and its amount is calculated by obtaining the difference between the total flow and the baseflow. Surface runoff ceases whenever the total flow at time *t* is less than or equal to the amount of baseflow at time *t-Δt* plus the preset value.

Method IV was developed under the following assumptions:

I. Baseflow discharge varies as a function of the total flow increment,

II. The amount of subsurface flow for the current time step is computed as a fraction of the difference between the total flow and the baseflow on the previous time step. The value of "fraction" is determined by an iteration method based on an operator identified point on the hydrograph (inflection point), which marks the end of surface runoff. By assuming an initial value for fraction, repetitive computations of baseflow are made. The value of fraction for which the baseflow value computed at the inflection point equals to the measured value is identified and used for the entire hydrograph.

III. Surface flow is equal to the difference between the total flow and the baseflow at each time step.

IV. Surface runoff ceases whenever the amount of the total flow at a given time step is less than the baseflow value at the previous time step.

As it was described above, both methods consist of simple techniques for partitioning streamflow into subsurface flow and surface runoff components. The methods were tested over 3 years of streamflow data. These methods like the previous two methods are daily time step methods. This means that daily river discharge data is used for all computations. In both methods, the user needs to manually identify a single point on the streamflow hydrograph that shows the end of the surface runoff (i.e. inflection point). Afterwards, each method automatically computes the surface and subsurface flow components. In general, the difference between the automated hydrograph partitioning techniques is small, however, both methods use non-physically based approaches for their performance.

Methods III and IV were computerized for their easy and widespread use. These two methods use the iteration technique to determine a constant and a fraction, both of which are needed for further computations. In addition, both methods are capable of distinguishing the starting point of surface runoff and automatically calibrating the model to match the computed inflection point with user-defined runoff cessation point on the hydrograph.

The major difference between these two methods originates from the fact that in Method III, baseflow is related to the duration of the surface runoff. However, in Method IV, baseflow is proportional to the volume of the surface runoff.

Both methods are capable of being automatically calibrated. The computer operator only needs to identify a single point as the inflection point (the point at which runoff ceases) on the recession limb of the hydrograph. In order to determine the constant value (the slope of the linear streamflow delineation line) or fraction for the second model, the computer program defined in this study initiates an arbitrary value, as first guess, and iterates it until the baseflow increment intersects the pre-selected inflection point. Amongst the generated constants or fractions for different hydrographs for the watershed, the program computes a weighted average and uses it for subsequent computations of the streamflow components.

Regional analysis of streamflow partitioning from the time-series of daily discharge was carried out from the 700 ha Back Creek catchment. Overall, the difference between the results of Method III and Method IV is not significant and both give similar results in simulating large runoff events. However, there is more similarity between Method IV and the manual separation techniques. In addition, Method III overestimates surface runoff more than Method IV (Boughton, 1988).

4.1.4 Method V (Smoothed Minima Technique)

In 1980, the Institute of Hydrology in Wallingford, U.K. developed the Smoothed Minima Technique to partition the streamflow (Nathan, 1990). In this method, a streamflow hydrograph is separated by applying a simple smoothing rule. The first step in this separation technique is that the minimum value of stream-gauging measurements for several nonoverlapping 5-day periods needs to be determined. Then, amongst the series of obtained minimal data points, those minimal points with values less than 1.1 times each of the values of the two neighbor-points are selected. These points are called the turning points. By connecting the turning points to each other, the baseflow hydrograph can be drawn.

In this technique, two important notes should be considered. First, the catchment nature does not affect the results. Second, sometimes in this method, unusual outcomes may be obtained due to the closeness of turning points, which can lead to higher estimations of baseflow in relation to total streamflow (Nathan, 1990).

4.1.5 Evaluation of Selected Methods

Separately measured surface and subsurface flow data from a small, field-sized watershed in the Coastal Plain physiographic region of Southeast United States was used to evaluate each of the five methods described in previous sections. A separate computer program using the Visual BASIC language was developed to execute tasks involved in each method (Appendix A). The following sections provide background on the study site, instrumentation, data analysis, and model calibration.

4.1.6 Study Site

The Coastal Plain Province of the U.S.A. extends in the north-south direction, from New England along the Atlantic Coast and then west 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., 1984b).

4.1.6.1 Location and General Description

The field scale watershed (station Z) is located in the Little River Watershed near Tifton, Georgia (Figure 10). 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), and make separate measurement of subsurface and overland flow, and precipitation. The watershed boundaries are slightly different for surface and subsurface flow; the areas are 0.3436 and 0.3464 ha for surface and subsurface topographic maps, respectively (Figures 11 and 12). 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 13 shows the location of the watershed relative to the stream and the surface ground profile before and after surface development. The watershed is bounded by a soil berm on the top and contours for subsurface clayish layer (Rawls, 1976).

4.1.6.2 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 (Figure 13). 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).

4.1.6.3 Surface Flow Instrumentation

According to the general slope of the watershed, a 0.3048-m (1 foot), H-flume was installed in June 1969 on the southwest corner of the surface watershed to measure overland flow. On account of the difference between the 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).

4.1.6.4 Availability of Data

Separately measured surface and subsurface flow data for field scale watershed Z are available for the period of 1970 through 1981. This data set forms the basis for the evaluation of the performance of each of the five methods identified in this study.

4.1.7 Methods of Analysis

All streamflow partitioning methods identified in this study were programmed using the Visual BASIC language for operation on an IBM PC compatible personal computer (Appendix A). The computer program eliminates all of the laborious and time-consuming efforts that are usually undertaken using manual hydrograph separation techniques. In addition, it provides capabilities for more efficient handling of data than the manual methods. One of the biggest challenges for the hydrograph separation methods is that separately measured data of storm hydrograph elements are not widely available. Therefore, analysis of storm event components is inherently arbitrary in nature. Lack of proper data has created a difficult situation in that the existing methods have not been tested regarding their accuracy and ease of use prior to the present study. In this study, twelve years of separately measured surface and subsurface flow dat-a were used for methods' calibration and verification. For all methods, the output of the methods was constrained so that the sum of the separated flow components was not negative or greater than the total flow.

The time interval for all computations is one day because both precipitation and runoff data are based on a daily time step. However, some methods already have been tested for smaller time intervals than the daily time step, which is not a concern in this thesis.

Calibration or optimization can be described as a numerical procedure of deriving relationships between one or more random variable and the measured values. In this process, the minimum or maximum value of some function can be found based on the values of a vector of unknowns (Ayyub and McCuen, 2003). Calibration of each method was performed as follow:

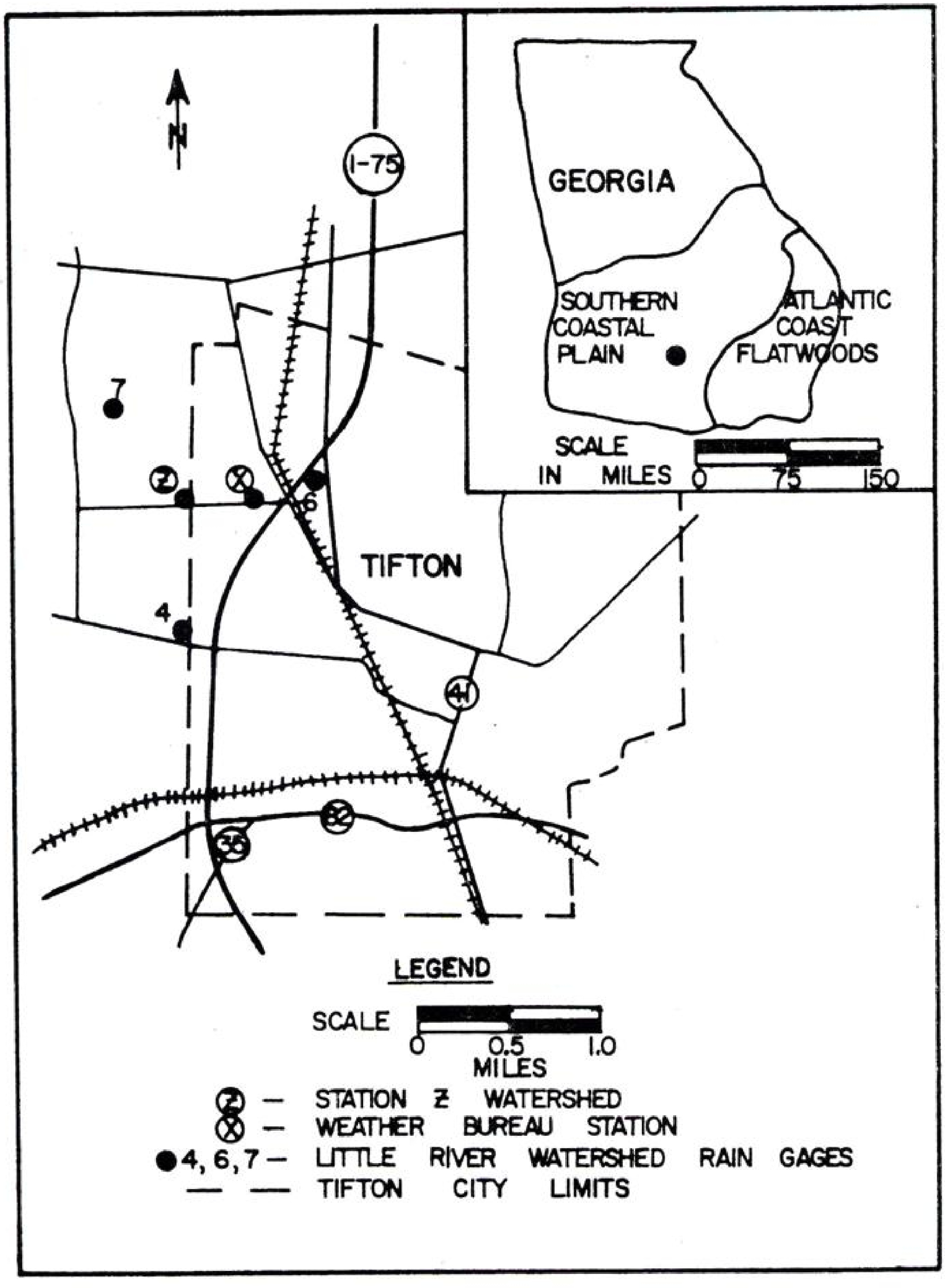


Figure 10. General location map (Rawls, 1976).

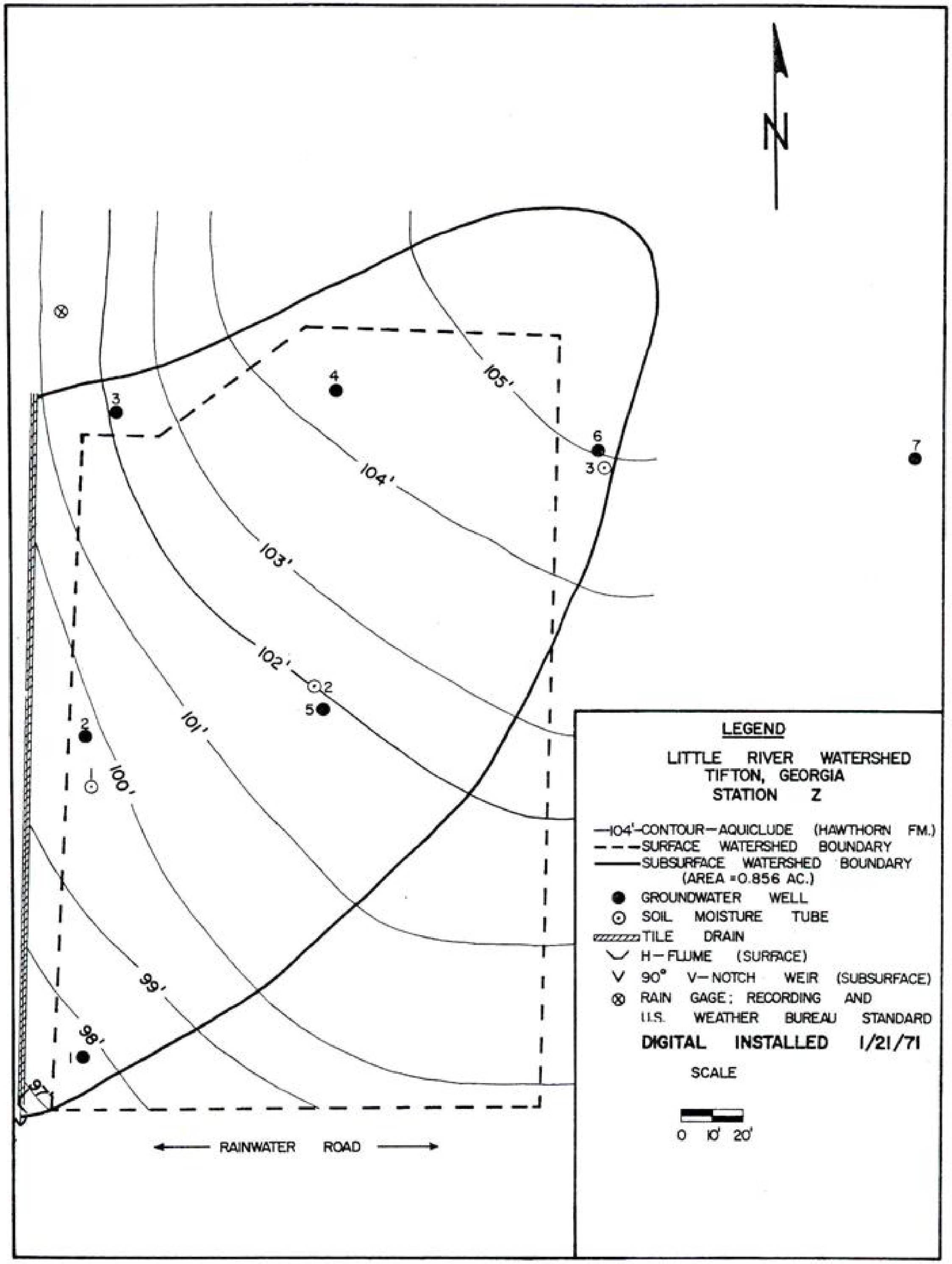


Figure 11. Topographic map of the surface watershed (Rawls, 1976).

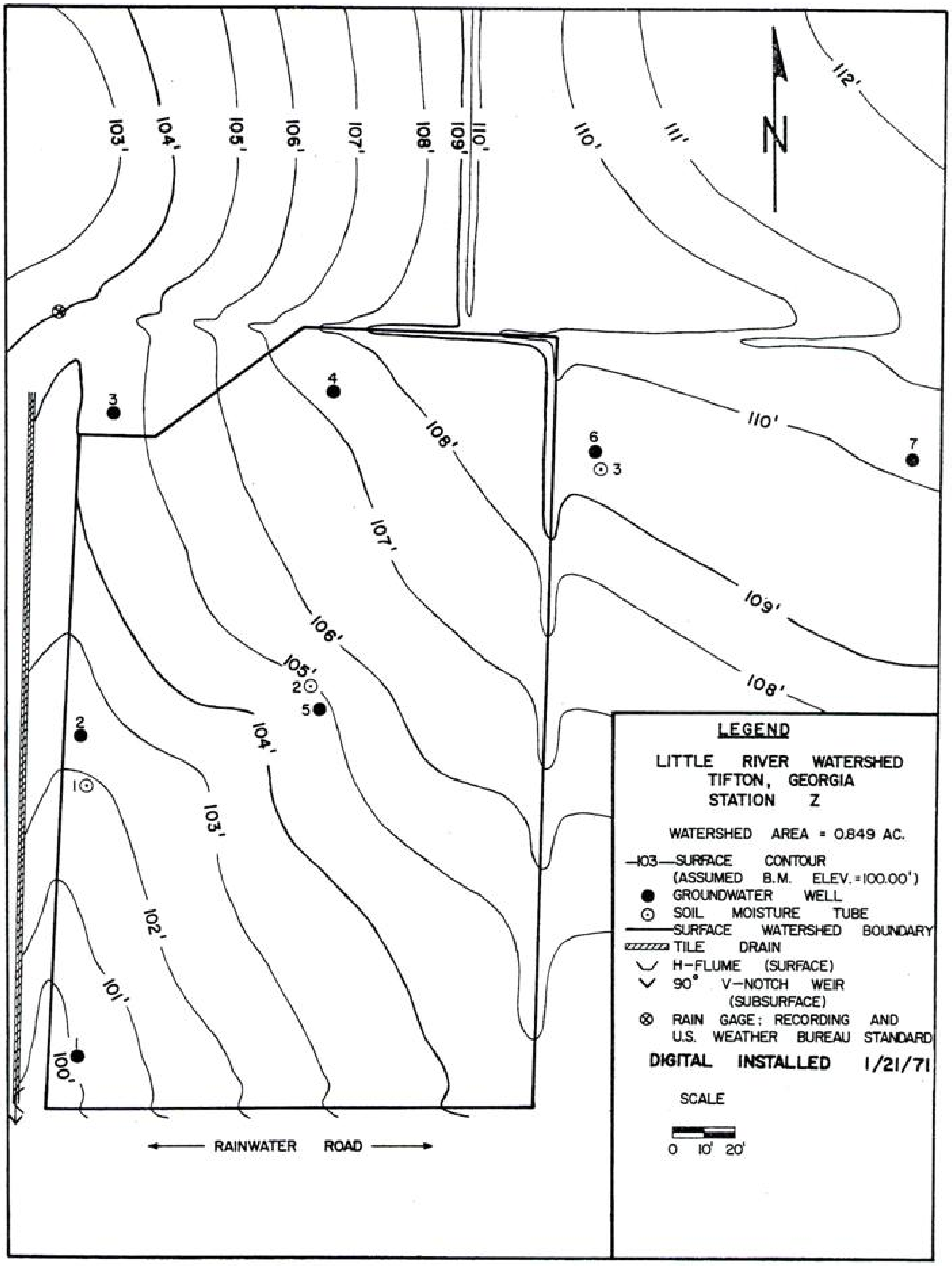


Figure 12. Topographic map of the subsurface watershed (Rawls, 1976).

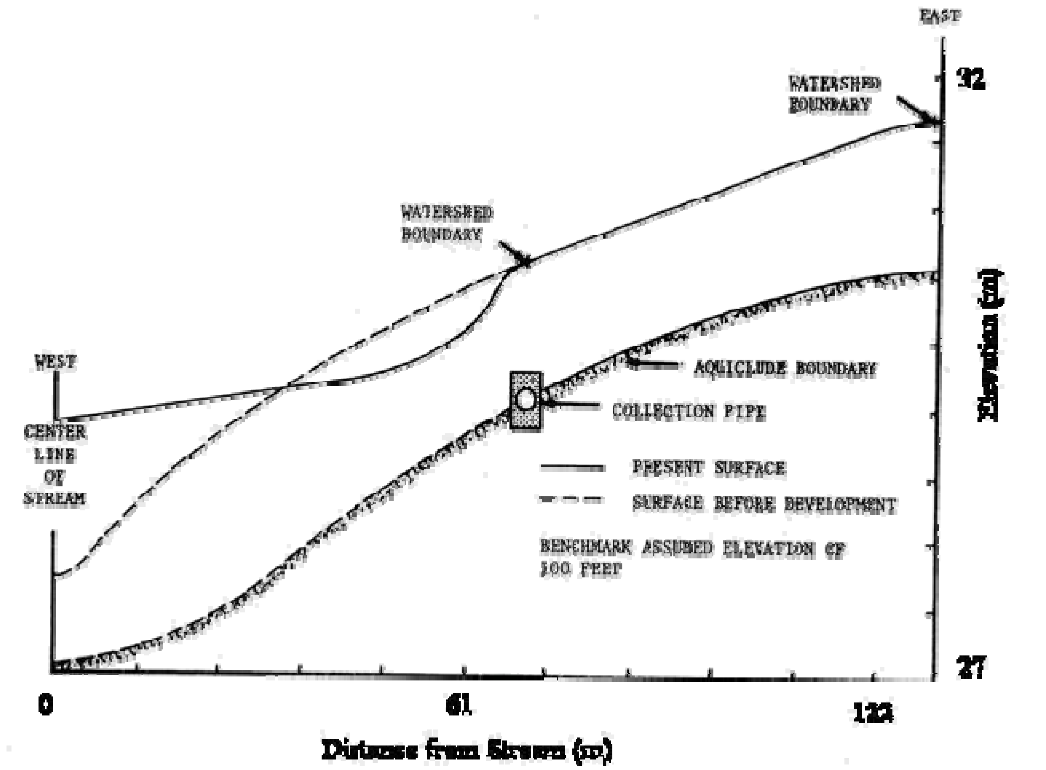


Figure 13. Generalized profile map of the watershed (Rawls, 1976).

4.1.7.1 Calibration of Method I (Wittenberg and Sivapalan)

Six recession limbs of representative hydrographs were selected. Then, the computer program (Appendix A.1) performed an iterative least squares method to calibrate both parameters *a* and *b* for a series of flow recession data. An average or weighted average of these parameters was then taken for use in calibration of the parameters (Appendix A.2). Table 2 shows the range of the parameters that were obtained from the first six years of data from station Z in the Little River Watershed in Tifton, Georgia.

Based on the Wittenberg study (Wittenberg and Sivapalan, 1999), the starting point for baseflow recession is assumed to be two days after the inflection point of the hydrograph. However, the size of the watershed and duration of the storm event are two major factors that affect selection of these two points. To modify the method for more accurate results, the effects of the two above factors (i.e., watershed area and the storm duration) were considered in this study. Therefore, the starting point for the baseflow recession and the inflection point were both assumed to be the same point on the hydrograph.

Table 2. Calibration of Method I (Wittenberg and Sivapalan, 1999)

Year	Representative Recession limb	*a*	*b*
1970	30 March –16 April	6.410	0.999
1971	3 -15 March	3.452	0.999
1972	27 June –11 July	4.159	0.999
1973	10 February –6 May	40.944	0.817
1974	8- 23 September	31.774	0.802
1975	29 April –11 May	4.0917	0.999
Average		15.138	0.936
Standard Deviation		16.721	0.098

4.1.7.2 Calibration of Method II (Nathan & Mugo)

The Meyboom (1961) graphical separation of the baseflow component was suggested for calibration of Method II by Nathan & McMahon (1990) and Mugo & Sharma (1999). To automate the procedure and incorporate more data in the calibration procedure, the generated baseflow data from Method IV were used. This kind of approach is more robust and is capable of providing more accurate prediction. Instead of calibrating the method based on limited number of representative hydrographs, the entire six years of baseflow data (1970-1975) were employed to determine a proper value for α parameter. It should be noted that operator's drawing skills are not required here, which reduces the level of subjectivity. The computed filter parameter (α) values are shown in Table 3 using six years of data (Appendix A.3).

Table 3. Calibration of method II (Nathan, 1990 & Mugo, 1999)

Year	α
1970	-0.0906
1971	-0.1450
1972	-0.2544
1973	-0.4645
1974	-0.2077
1975	-0.4362
Mean	-0.2660
Standard Deviation	0.4755

4.1.7.3 Calibration of Methods III and IV (Boughton)

For calibration of Methods III and IV, seven hydrographs were selected as representative hydrographs from the first six years of observed data (Table 4). The program developed in this study automatically calibrates and calculates a constant value (Method III – Appendix A.4) and a fraction (Method IV – Appendix A.5) based on an operator identified point on the hydrograph, which marks the end of surface runoff. The program calculates a constant value based on the difference between the total flow at the starting point and the ending point of the surface runoff period. The program also computes the fraction value for the designated period of surface runoff, up to three digits accuracy with the iterative technique. In both methods, the constant and fraction value each need to satisfy the assumption that the baseflow increases to equal the total flow at the specified point at the end of the separation process.

Table 4. Calibration of methods III and IV (Boughton, 1988)

Year	Specified End of Surface Runoff	Constant Value	Fraction Value
1970	31 May	7364	0.451
1971	5 December	2750	0.406
1972	26 June	7109	0.885
1972	29 June	289	0.053
1973	13 February	1721	0.122
1974	9 February	9376	0.233
1975	26 March	928	0.095
Weighted Average		4061	0.293
Standard Deviation		3640	0.292

4.1.7.4 Calibration of Method V (Smoothed Minima Technique)

Method V (Smoothed Minima Technique) does not need any special procedure for calibration. Therefore, all twelve years of data were used to evaluate the model's performance (Appendix A.6).

4.1.8 Results and Discussion

The five separation techniques were applied to station Z to partition the total streamflow for the period of 1970 through 1981. As mentioned earlier, this effort helps us to define the best available streamflow partitioning method with respect to its accuracy and practicality of use. Previous studies using each of these methods evaluated their performance based on manually delineated streamflow components. Thus, their results could not be compared with our results because of lack of a common measured database.

Tables 2 through 4 show the range of the parameter values obtained for methods I, II, III, and IV during the calibration phase. In Method I, two physically based parameters, *a* and *b,* were obtained by calibrating the method with observed streamflow data for six consecutive years (Table 2). However, average values for both parameters were incorporated into the computer program for partitioning streamflow for the entire twelve years (1970-1981). As shown on Table 2, the calibrated values for parameter b are all more than 0.5. Wittenberg (1999) proposed that b varies between 0 and 1 with a high correlation obtained around 0.5 for unconfined aquifer. However, several explanations were suggested for deviation of b from 0.5 such as, high retention capacity in the river channel, significant presence of turbulent subsurface flow, and contribution of water discharge to a stream from confined aquifer. In this study, based on regional geology, significant presence of turbulent subsurface flow, which may be caused by macrospores, seems to be a more reasonable culprit than the two other phenomena. For the parameter a, much greater spread can be observed. Additional tests showed that in addition to catchment properties, the selection of the inflection point, the starting point for baseflow recession, and shape of the hydrograph have a considerable effect on the value of parameter a.

The α values for Method II are shown in Table 3. The level of scattering in the α values about the central tendency (average value) is about 58%. The reason for the relatively small level of scattering is due to the incorporation of all six years of data during calibration. Employment of more data points (more storm events) in this approach than the manual graphical methods of hydrograph separation, makes calibrated α values more reliable. However, the filter parameter of α that yielded the most acceptable baseflow separation was far from the suggested range of 0.9-0.95 by Nathan (1990). It can be concluded that physiographical and hydrological conditions may be the two major factors that dictate the variation on filter parameter (α) values.

Table 4 shows the constant and fraction values for a number of representative hydrographs. The calibrated values of the fraction for Method IV show a much greater spread than the calibrated values of the constant for Method III. It may be concluded that the results obtained by Method IV are more sensitive to changes in the value of the fraction than the results obtained by Method III due to changes in the value of the constant. However, this conclusion is not valid for all cases and may produce a completely different sensitivity level to the constant or fraction by selecting another set of hydrograph data.

The most frequently used fitting model to test the performance of any given method, which is also used in this study, is a linear regression. The principle behind the linear regression model is the least squares method. Figures 14 and 15 show a set of lines of best fit that are obtained using the method of least squares. These graphs are examples indicating variation of annual and daily baseflow and overland flow obtained by Method IV versus measured values. In addition, in each graph, the coefficient of determination (R^2) along with the regression equation for the line of the best fit is shown.

Because the statistical analysis is often a primary element of the decision-making process, the two sets of statistical analysis were considered here to examine the performance of each of the five-hydrograph separation techniques. Two sets of tests were conducted for the full period of study to evaluate the performance of each streamflow partitioning method for annual analysis of hydrograph elements. These tests are:

a. Two indices of baseflow (baseflow/total flow) and surface flow (surface flow/ total flow) were employed to test each model's performance against measured data. Results are shown in Tables 5 and 8.

b. Statistical analysis comparing specific characteristics (e.g., standard error of estimations, etc.) of measured and computed data. A total of 1266 data points for 12 years of flow observation were used for this analysis. These data points included all runoff events for the duration of the study. Results are shown in Tables 7, 8, 9 and 10.

Descriptive statistical measures are desirable in science to characterize some data. This kind of representation facilitates evaluation of the main characteristics in an easy and quantitative manner. In this study, a couple of statistical parameters were employed for the evaluation of each methods' performance (Tables 7 through 10).

The first descriptor of the data, which is discussed here is the mean. The mean measures the central tendency of the data. Amongst all methods, Method IV resulted in the closet average baseflow and surface flow estimation when compared to the observed data. Contrary to Method IV, Method V resulted in poorest results when compared to the measured data. Also for 50% of the annual predictions, Method IV estimations were the best representation of the measured data (Tables 5 and 6). For the remaining years of study, Methods II and III represented the measured flow components well. Results obtained using Method IV are comparable to the results obtained by Shirmohammadi et al. (1984a) for the same watershed data using an approximate streamflow partitioning method. In fact, Shirmohammadi, et al. (1984a) results favor the measured data better when a variable initial abstraction (*IA*), as an index of surface runoff initiation, is used. Method IV's performance may also be improved by determining a more accurate "fraction" coefficient by relating the "fraction" to the watershed physical and hydrologic conditions.

The mean can be considered as the best estimation of the criterion variable in the absence of additional information. However, standard deviation (*Sy*) and standard error of estimates (*Se*) may be used for more detailed evaluation of the accuracy of predictions. Generally, a smaller ratio of these parameters (*Se/Sy*) is an indication of higher accuracy in model estimation. Between the five methods, Method IV has the lowest ratio in daily baseflow predictions (Table 9). However, Method I resulted in higher relative prediction accuracy in daily surface flow because of lower (*Se/Sy*) values than the other methods (Table 10).

Another parameter for the methods' performance evaluation is the coefficient of determination (R^2), which represents the fraction of the total variation in data that is explained by the model. If the explained variation equals the total variation, *R* will equal to 1 or for the case of inverse relationship, it will equal to –1. If the explained variation equals zero, R^2 equals zero. In the case of annual analysis of hydrograph elements, Method I has the highest R^2 values for both baseflow and surface runoff (Tables 7 and 8). However, evaluation of daily hydrograph components showed that Method IV has provided higher R^2 value for baseflow component than the other methods. On the other hand, Method I resulted in the highest R^2 value for daily surface runoff analysis. Examples of the regression equations and coefficient of determinations are also given in Figures 14 and 15.

The residual is the last parameter, which was considered for statistical analysis in this study. The residuals are an important criterion in assessing the validity of linear regression model. In addition, the absolute ratio of residual to the mean represents the average error relative to central tendency of data. Therefore, smaller values in both absolute residual and the absolute ratio show higher accuracy in the estimation of the linear regression. As shown in Tables 7 through 10, Method IV resulted in the smallest values for both parameters in all cases (daily and annual base). This result is another evidence of the superiority of Method IV to the other methods.

Finally, in order to narrow down the most accurate streamflow partitioning method, 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 annual average values of measured data and computed values. Results indicated that there is a significant difference between at least one pair of means. The second set of tests (Tukey test,) was performed for pairwise comparison of the annual average values (Ott et al., 2001). Results from this section showed that at the $p = 5\%$ level of significance, only predicted values from Method IV are not significantly different from measured data, in both surface flow and baseflow cases.

Table 5. Comparison of the measured and computed baseflow indices for a representative watershed in the Coastal Plain physiographical region.

Year	Measured Base Flow / Total Flow	Computed Base Flow / Total Flow	Computed Base Flow / Total Flow	Computed Base Flow / Total Flow	Computed Base Flow / Total Flow	Computed Base Flow / Total Flow
		Method I	Method II	Method III	Method IV	Method V
1970	0.803	0.718	0.908	0.683	0.745*	0.395
1971	0.667	0.583	0.853	0.600	0.648*	0.038
1972	0.788	0.665	0.887	0.703	0.721*	0.066
1973	0.848	0.684	0.893*	0.673	0.754	0.094
1974	0.788	0.649	0.884	0.590	0.704*	2.54E-05
1975	0.847	0.703	0.897*	0.689	0.746	0.068
1976	0.782	0.662	0.889	0.684	0.709*	0.568
1977	0.452	0.466	0.821	0.452*	0.571	0.082
1978	0.683	0.547	0.842	0.621*	0.618	0.066
1979	0.933	0.782	0.931*	0.820	0.806	0.417
1980	0.718	0.615	0.873	0.663	0.720*	0.031
1981	0.742	0.670	0.877	0.679*	0.655	0.111
Average	0.755	0.645	0.880	0.655	0.700*	0.161

* Represent estimates closest to measured data.

Table 6. Comparison of the measured and computed surface flow indices for a representative watershed in the Coastal Plain physiographical region.

Year	Measured Surface Flow / Total Flow	Computed Surface Flow / Total Flow	Computed Surface Flow / Total Flow	Computed Surface Flow / Total Flow	Computed Surface Flow / Total Flow	Computed Surface Flow / Total Flow
		Method I	Method II	Method III	Method IV	Method V
1970	0.197	0.282	0.092	0.317	0.255*	0.605
1971	0.333	0.417	0.147	0.399	0.352*	0.962
1972	0.212	0.335	0.113	0.297	0.279*	0.934
1973	0.152	0.316	0.107*	0.327	0.246	0.906
1974	0.212	0.351	0.116	0.410	0.296*	1.000
1975	0.153	0.297	0.103*	0.311	0.254	0.932
1976	0.218	0.338	0.111	0.316	0.291*	0.432
1977	0.548	0.534	0.179	0.548*	0.429	0.918
1978	0.317	0.453	0.158	0.379*	0.382	0.934
1979	0.067	0.218	0.069*	0.180	0.194	0.583
1980	0.282	0.385	0.127	0.337	0.280*	0.969
1981	0.258	0.330	0.123	0.321*	0.345	0.889
Average	0.246	0.355	0.120	0.345	0.300*	0.839

* Represent estimates closest to measured data.

Table 7. Summary of statistical test for annual baseflow indices

Baseflow	$\overline{Q}$ Mean	*Sy* Standard Deviation	R^2 Coefficient of Determination	*Se* Standard Error of Estimate	*Se/Sy*	$\overline{e}$ Residual	$\overline{e}/\overline{Q}$
Measured	0.7543	0.1206					
Method I	0.6454	0.0835	0.9075	0.0266	0.3185	-0.1088	-0.1686
Method II	0.8796	0.0297	0.8838	0.0106	0.3570	0.1254	0.1426
Method III	0.6547	0.0867	0.8113	0.0395	0.4555	-0.0995	-0.1520
Method IV	0.6998	0.0655	0.8596	0.0257	0.3972	-0.0545	-0.0779
Method V	0.1613	0.1867	0.1373	0.1819	0.9741	-0.5930	-3.6768

Table 8. Summary of statistical test for annual surface flow indices

Surface Flow	$\overline{Q}$ Mean	*Sy* Standard Deviation	R^2 Coefficient of Determination	*Se* Standard Error of Estimate	*Se/Sy*	$\overline{e}$ Residual	$\overline{e}/\overline{Q}$
Measured	0.2458	0.1206					
Method I	0.3546	0.0835	0.9075	0.0266	0.3185	0.1088	0.3068
Method II	0.1204	0.0297	0.8838	0.0106	0.3570	-0.1254	-1.0417
Method III	0.3453	0.0867	0.8113	0.0395	0.4554	0.0995	0.2882
Method IV	0.3002	0.0655	0.8596	0.0257	0.3922	0.0545	0.1815
Method V	0.8387	0.1867	0.1373	0.1819	0.9741	0.5930	0.7073

Table 9. Summary of statistical test for daily baseflow analysis

Baseflow	$\overline{Q}$ Mean (l/day)	*Sy* Standard Deviation (l/day)	R^2 Coefficient of Determination	*Se* Standard Error of Estimate (l/day)	*Se/Sy*	$\overline{e}$ Residual (l/day)	$\overline{e}/\overline{Q}$
Measured	8958.93	9512.54					
Method I	7639.64	8346.62	0.7055	4531.39	0.5429	-1319.29	-0.1727
Method II	10298.17	12054.05	0.6833	6786.25	0.5630	1339.23	0.1300
Method III	7739.56	6606.04	0.6803	3736.57	0.5656	-1219.38	-0.1576
Method IV	8304.46	8411.75	0.7778	3966.84	0.4716	-654.48	-0.0788
Method V	2113.17	3755.41	0.1228	3518.64	0.9370	-6845.76	-3.2396

Table 10. Summary of statistical test for daily surface flow analysis

Surface Flow	$\overline{Q}$ Mean (l/day)	*Sy* Standard Deviation (l/day)	R^2 Coefficient of Determination	*Se* Standard Error of Estimate (l/day)	*Se/Sy*	$\overline{e}$ Residual (l/day)	$\overline{e}/\overline{Q}$
Measured	2690.65	10681.77					
Method I	4009.94	12828.33	0.8448	5056.43	0.3942	1319.29	0.3290
Method II	1351.42	4534.62	0.8335	1851.20	0.4082	-1339.23	-0.9910
Method III	3910.03	12963.04	0.8259	5411.19	0.4174	1219.38	0.3119
Method IV	3345.13	9535.12	0.8240	4001.86	0.4197	654.48	0.1957
Method V	9536.42	15028.49	0.6578	8794.47	0.5852	6845.77	0.7179

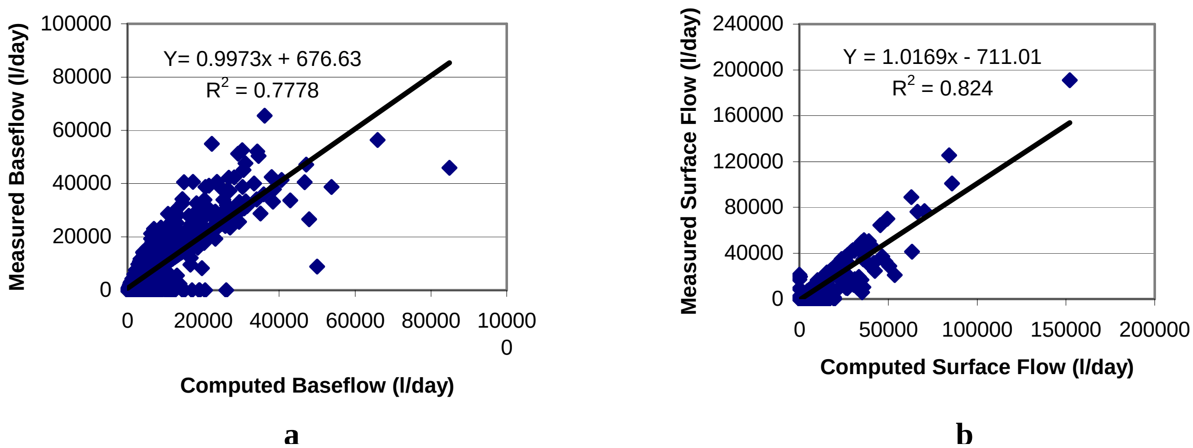


Figure 14. Variation of daily computed values from Method IV versus measured values (a) baseflow (b) surface flow

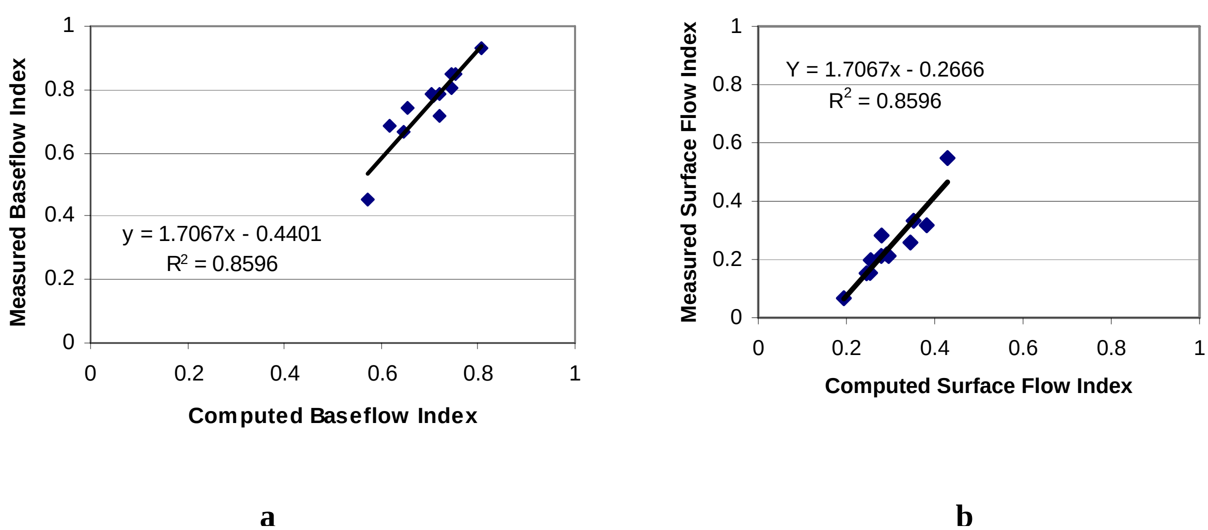


Figure 15. Variation of annually computed flow indices from Method IV versus measured flow indices (a) baseflow (b) surface flow

4.1.9 Conclusion

The comparative study of five methods showed that despite the simplicity of Method IV, it produced reasonably good estimates of the observed data. The foregoing discussion shows that Method IV (Boughton) is one of the best methods for streamflow partitioning based on its accuracy and ease of use compared to the other methods examined in this study. However, its accuracy will depend upon the proper estimation of the "fraction" coefficient that is based on many physical and hydrologic characteristics of a watershed.

Method V (Smoothed Minima Technique) is one of the easiest approaches for hydrograph separation, but simulation results showed that this method is not reliable. However, the method's prediction accuracy may be improved by varying the number of days in nonoverlapping periods based on the watershed size.

Despite poorer values in statistical parameters for Methods I, II, and III than Method IV, relatively high coefficient of determinations show that these methods may result in reliable estimation of streamflow components. However, further efforts are needed to characterize the inherent parameters in each of these methods for improved accuracy.

4.2 Hydrograph Separation by Incorporating Climatological Factors

As discussed earlier in this study, 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 to avoid misuses, and five methods (a. Wittenberg and Sivapalan, 1999, Wittenberg; 1999: b. Nathan and T.A. McMahon; 1990. Mugo and Sharma; 1999, and Eckhardt; 2005, c. Boughton's constant coefficient; 1988, d. Boughton's fraction coefficient; 1988, and e. Sloto and Crouse, 1996) were identified as being the most relevant and least input intensive. The performance of these methods were tested against twelve years (1970-1981) 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 method with fraction coefficient (α) 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.

$$\frac{dQ_b}{dt} = -a_1 Q_b + a_3 Q_t \tag{31}$$

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

The goal of this stage of study is to improve baseflow estimation based on the Boughton's (fraction coefficient) method. The specific objectives are to: 1) develop a robust method for automatic identification of the end of surface runoff on the recession limb of the storm flow hydrograph, 2) evaluate the accuracy of Boughton's method as a function of: (a) the method used for the temporal discretization of equation (31), 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 the watershed's climatological factors (e.g. rainfall, evaporation). The final outcome is expected to significantly improve the streamflow partitioning method's performance.

4.2.1 Materials and Methods

All steps identified in this study were programmed using the Visual BASIC language (Appendix A). 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 eight years of climatological and management practice data were used for calibration and verification of the developed method. These data are from a small, field-sized watershed (station Z) 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.

4.2.1.1 Identification of the End of Surface Runoff

Recession analysis has long been the topic of interest in the science of hydrology. The baseflow recession curve itself contains valuable information about the ground water flow and it is widely used in hydrological models such as HEC-1 (U.S. Army Corps of Engineers) and other water resources applications. During the last few decades, an important number of case studies have been done with the aim of identifying the recession analysis and physical factors that affect it. 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 drains in the absence of recharge is investigated. Since the early 1900s, the applications 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.

4.2.1.1.1 Recession Limb Analysis

Theoretical investigation and empirical studies have shown that the recession curve can be expressed by

$$Q_t = Q_0 \exp(-\beta \times t) \quad (32)$$

Where Q_t is the discharge at time t, Q_0 is the initial discharge, and β is a constant value; the term $exp(-\beta)$ 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 et al., 1996);

$$N = A_d^{0.2} \quad (33)$$

where N is the number of days after the peak of the hydrograph, at which baseflow 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 Boughton's method, the user is responsible for identifying the end of surface runoff 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 user's previous experience, which can be highly variable.

In contrast with the general assumption about direct the relationship 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-baseflow behavior. This fact was further extended through a sequence of statements to automate the hydrograph separation with daily discharge values (Nejadhashemi et al, 2004).

Based on the Wittenberg (1999) study, the starting point for baseflow recession is assumed to be two days after the 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 baseflow 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 Boussinesq equation. Regardless of the experiment duration, the slope of the recession limb for unconfined saturated aquifer was expressed as:

$$\frac{dQ}{dt} = -a(Q(t))^b \qquad (34)$$

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

Singh (1988) solved the above equation for unknown time (equations 35 and 36);

$$Q(t) = (Q_0^{\,1-b} - (1-b)at)^{\frac{1}{1-b}} \qquad ,for \qquad b \neq 1 \tag{35}$$

$$Q(t) = Q_0 e^{-at} \qquad ,for \qquad b = 1 \tag{36}$$

where, Q_o is the discharge at the beginning of the storm event.

The general assumption for this method is that the hydrograph recession limb should last longer than 45 hours 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 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 37) 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 the 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, the second derivative of all points on the recession limb of each hydrograph was calculated (Figure 16). 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 16- where arrows indicate the inflection points). The following equation can be used to obtain an approximation to the second derivative:

$$\frac{\partial^2 Q_t}{\partial t^2} = \frac{Q_t^{i+1} - 2Q_t^i + Q_t^{i-1}}{(\Delta t)^2} \tag{37}$$

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

In order to evaluate the accuracy of the above method, all storm events during twelve years of study were investigated using separately measured surface and subsurface flow hydrographs. 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 (Appendix A.7).

4.2.1.2 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 baseflow separation equations might be derived as specialized forms of the first-order, non-homogenous, nonlinear, Ordinary Differential Equation (ODE):

$$\frac{dQ_b}{dt} = -a_1[Q_b(t)]^{a_2} + a_3 Q(t) + a_4 \frac{dQ}{dt} \tag{38}$$

where, Q_b is baseflow, 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.

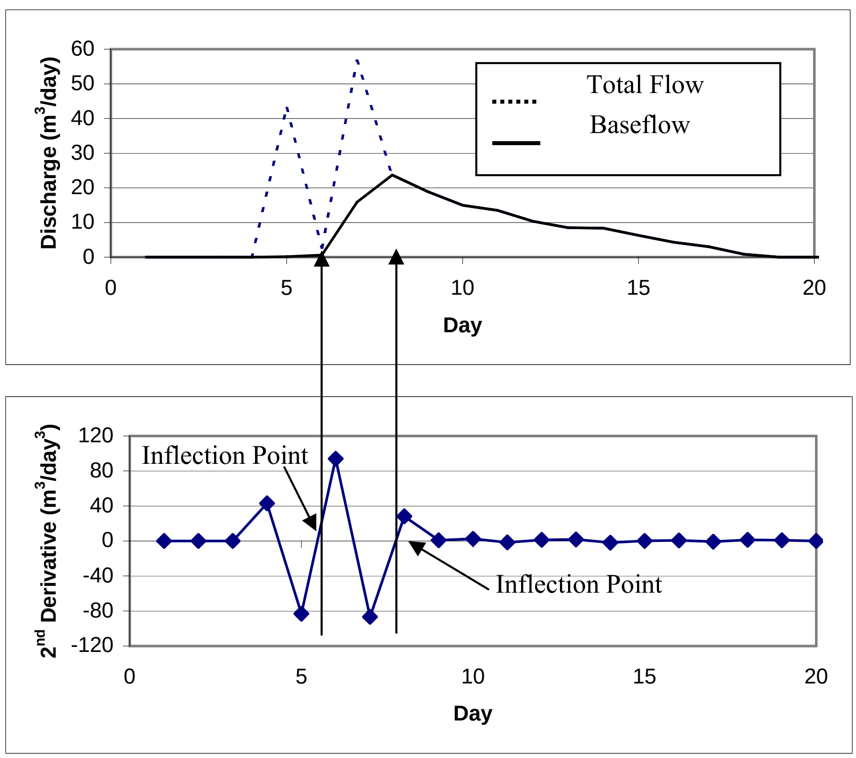


Figure16. Schematic of the Automated Detection of the Ends of Surface Runoff Based on Identifying the Inflection Points.

Based on this fact, Boughton's method can be rewritten as a finite difference approximation of equation 38 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 Boughton's method is most complete linear technique in the sense that it has the most nonzero coefficients in equation 38, thus avoiding any truncation error (Nejadhashemi et al., 2004). This gives;

$$\frac{dQ_b}{dt} = -a_1 Q_b + a_3 Q_t \qquad (31)$$

It is notable that this deterministic expression is very close to the first-order autoregressive (Markovian) 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).

4.2.1.2.1 Time Discretization

In this stage of study, three scenarios were tested using separately measured surface and subsurface flow data from a 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 baseflow 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 baseflow on the previous time step. This is the standard Boughton's method, and corresponds to a first-order approximation of the time derivative in (38)

$$Q_b^i = Q_b^{i-1} + \alpha\left[Q_t^{i-1} - Q_b^{i-1}\right] \tag{39}$$

where Q_b^i is baseflow 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 baseflow on the previous time step. This is a modified Boughton's method where the time derivative in (38) is approximated to second-order.

$$Q_b^i = Q_b^{i-1} + \alpha\left[\frac{Q_t^i + Q_t^{i-1}}{2} - Q_b^{i-1}\right] \tag{40}$$

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 baseflow on the previous time step. This is a modified Boughton's method with a first-order approximation of the time derivative in (38).

$$Q_b^i = Q_b^{i-1} + \alpha\left[Q_t^i - Q_b^{i-1}\right] \tag{41}$$

In this study, the developed program is able to identify the end of surface runoff for all storm events though the 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 with up to three digits accuracy (Appendices A.8, A.9, and

A.10). In this method, the fraction value needs to satisfy the assumption that the baseflow increases to equal the total flow at the specified point at the end of separation process.

4.2.1.2.2 Error Criterion

In this stage of study, the least square method was also applied to all three scenarios to evaluate the maximum amount of possible improvement in baseflow 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 17). After calculating all fraction values for storm events, the program uses the fraction values for the entire period of study to calculate baseflow (Appendices A.11, A.12, and A.13). This task illustrates how well each scenario can perform if we can calculate the appropriate fraction values based on climatological factors.

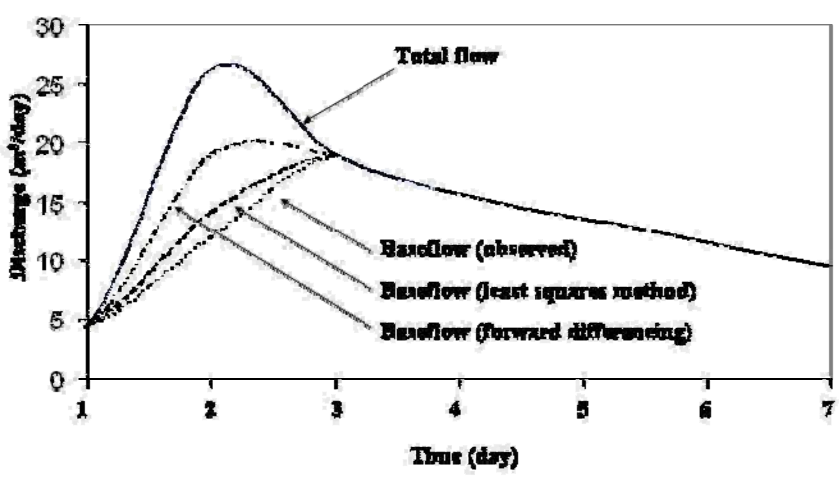


Figure 17. Schematic of Total Flow Hydrograph and Different Baseflow Separation Techniques.

4.2.1.3 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 tested. 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 a 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 one 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 where there is a discontinuity in the regression line. Therefore, the 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 where the user has 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 between the 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 (StatSoft, Inc.) and SAS software version 9.1 (SAS Institute Inc.) were used to develop a piecewise linear regression model for predicting the fraction value based on climatological factors (Marques de Sá, 2003).

4.2.1.4 Study Site

4.2.1.4.1 Location and General Description

The field scale watershed (station Z) is located in the Little River Watershed near Tifton, Georgia (Rawls, 1976).

4.2.1.4.2 Management Practices

Table 11 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.

4.2.1.4.3 Weather and Climatological Data

Weather and climatological data were obtained from the U.S. Weather Bureau rain gauge located at the Georgia Coastal 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).

4.2.1.4.4 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 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 by a correction factor (pan coefficient) on a 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 11), and cultural conditions (Allen et al., 1998).

4.2.1.4.5 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. This data set forms the basis for the evaluation of the performance of the method identified in this study.

Table 11. Management practices on watershed Z (Knisel et al., 1991)

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

4.2.2 Results and Discussion

4.2.2.1 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 apply to long periods of study because of the 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 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 approach to 12 years of streamflow data proved that the method is accurate 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 7% of the time, no baseflow was recorded or the difference between the computed and observed inflection points was more than one day. Applying the Wittenberg (1999) approach equipped with automated determination of the end of the surface runoff for the same period of streamflow data proved that the Wittenberg's 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 the 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 of being consistent and applicable for any shape of hydrograph regardless of its magnitude and/or duration.

4.2.2.2 Evaluation of the Accuracy of 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 the 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 (Appendix A). 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. 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 (Figures 18 through 20). The comparative study of three approximation methods showed that despite the simplicity of the forward difference approximation, it produced reasonably accurate results.

In addition to the 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 baseflow values using 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 a daily bases. Results further indicate that using the new approache (inflection point) to identify the end of the surface runoff improved Boughton method's prediction of baseflow significantly, even before incorporating climatological factors into the method (Nejadhashemi et al., 2004; Ott et al., 2001).

The most frequently used fitting model, which is also used in this study, is the linear regression model. The principle behind the linear regression model is the least squares method. Figures 21 through 23 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 baseflow obtained through the backward, forward, and central difference approaches. In addition, in each graph, the 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, the backward difference approach is not reliable even when proper physical and hydrologic characteristics of the watershed were taken into consideration.

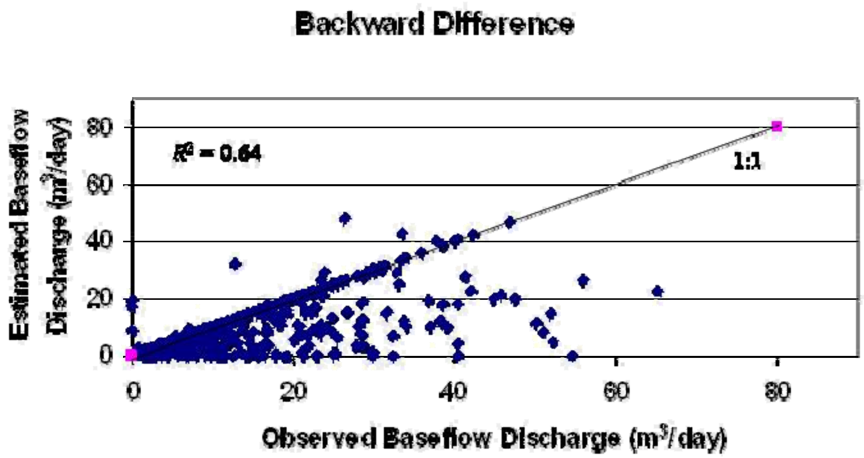


Figure 18. Observed Baseflow Discharge vs. Estimated Baseflow Using Backward Difference Approximation.

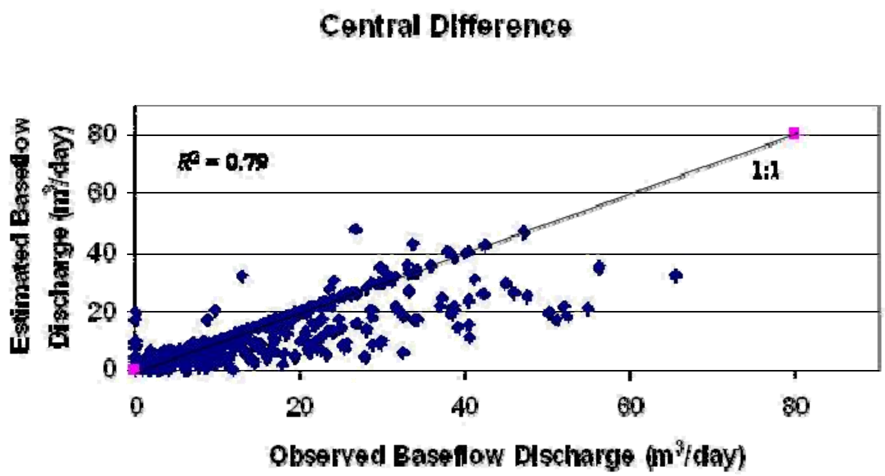


Figure 19. Observed Baseflow Discharge vs. Estimated Baseflow Using Central Difference Approximation.

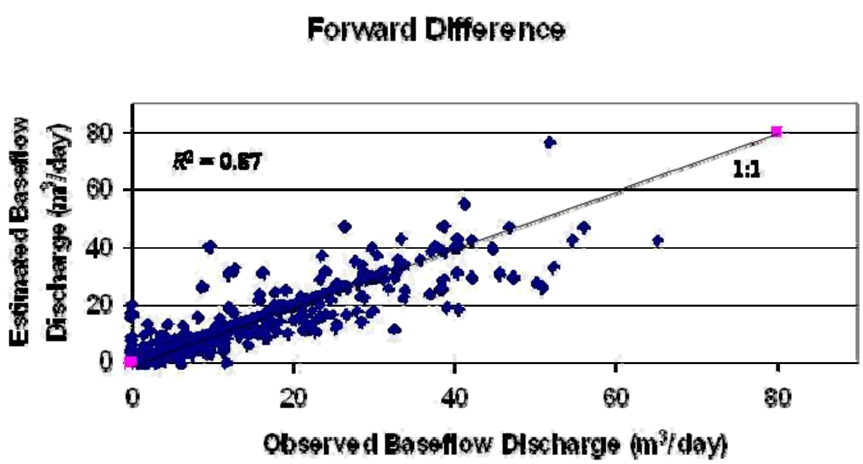


Figure 20. Observed Baseflow Discharge vs. Estimated Baseflow Using Forward Difference Approximation.

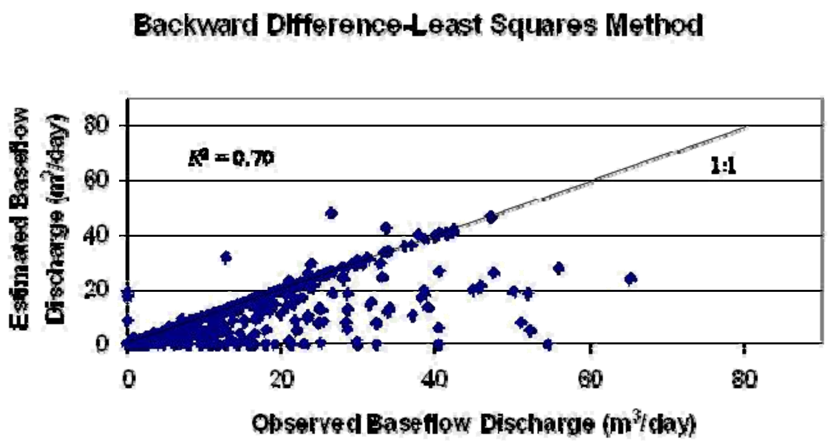


Figure 21. Observed Baseflow Discharge vs. Estimated Baseflow Using Backward Difference Approximation and Least Squares Method.

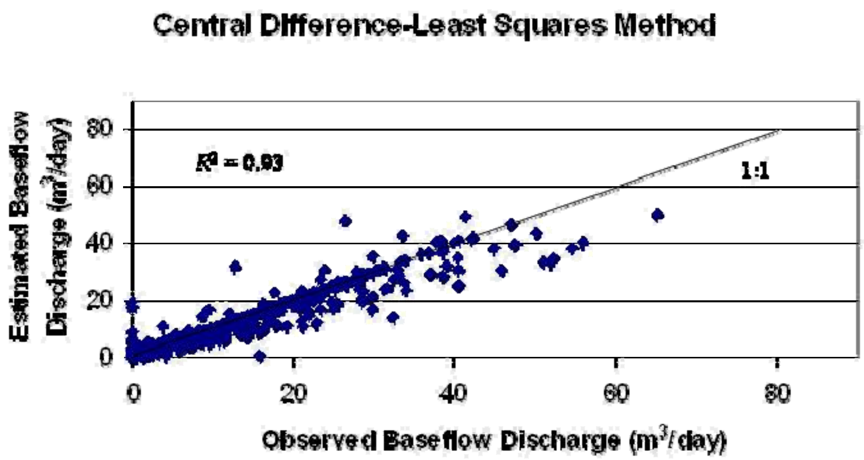


Figure 22. Observed Baseflow Discharge vs. Estimated Baseflow Using Central Difference Approximation and Least Squares Method.

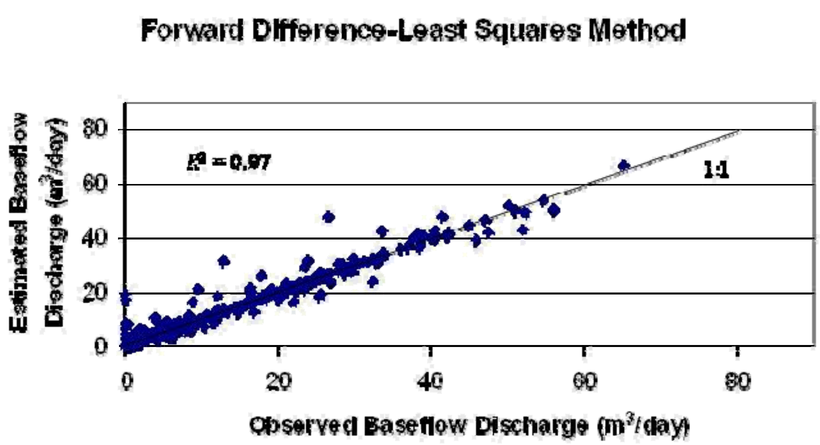


Figure 23. Observed Baseflow Discharge vs. Estimated Baseflow Using Forward Difference Approximation and Least Squares Method.

4.2.2.3 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 12. 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 (Appendix A.14).

Table 12. 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 42. However, our major goal here was to reach the maximum possible coefficient of determination in developing the regression equation and not performing optimization of the 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 12 (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:

$$\begin{cases} For \quad \alpha \le 0.5 \\ \qquad \alpha = -0.188 + 0.069Var_1 - 0.087Var_2 + 0.186Var_3 \\ \qquad\quad + 0.13Var_4 + 0.212Var_6 + 0.009Var_7 & (42-a) \\ For \quad \alpha > 0.5 \\ \qquad \alpha = 1.072 + 0.044Var_1 + 0.066Var_2 - 0.045Var_3 \\ \qquad\quad + 0.043Var_4 - 0.302Var_6 + 0.0004Var_7 & (42-b) \end{cases}$$

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 42 in predicting α values.

In order to select which of the two above equations to apply, it is necessary to have a 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 et al., 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 12), 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 ($Var6$), 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 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:

$$\begin{aligned} \alpha^* = & -2.826 - 0.733 \times Var_6 + 1.789 \times Var_3 \\ & + 0.13 \times Var_6^2 - 0.192 \times Var_3^2 + 0.041 \times Var_6 \times Var_3 \end{aligned} \qquad (43)$$

This equation, used by itself (without equation 42), 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 43 to identify initial α value, thus helping the user in deciding what piece of equation 42 to use in predicting a precise α value.

The accuracy with which the predictor-corrector equations (42)-(43) can predict alpha values was evaluated using 3 years (1976-1978) of the dataset. First, equation 43 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 (42-a) or (42-b) should be used for each event. The corresponding equation (42-a) or (42-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 24 compares estimated baseflow discharge values obtained by the above predictor-corrector method with observed baseflow discharge values. The coefficient of determination between estimated and observed baseflow 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.

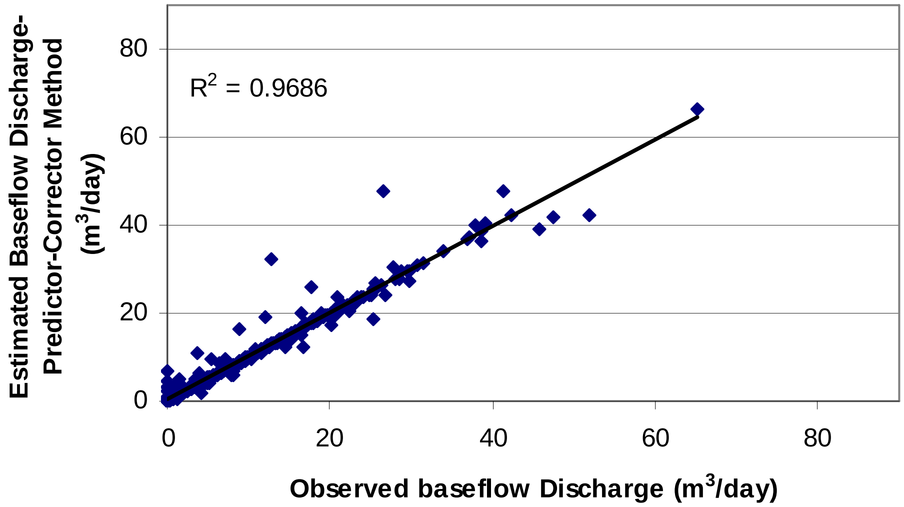


Figure 24. Observed Baseflow Discharge vs. Estimated Baseflow Using the Predictor-Corrector Method.

4.2.3 Conclusions

The main objective of this part of the study was to use climatological factors to improve estimation of streamflow partitioning techniques. Four different strategies were developed and evaluated to improve Boughton's method of daily baseflow 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 baseflow with coefficient of determination of up to R^2 = 0.97. Overall, this part of the 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 watersheds 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 baseflow 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.

4.3 Improvement in Hydrograph Separation Estimation by Incorporating Physical and Hydrologic Characteristics of Watersheds.

Evaluating the relative amounts of stored or moving water through the different components of the hydrological cycle is required for precise management and planning of water resources. A prior study evaluated forty different approaches for hydrograph-partitioning on a field scale watershed (station Z) in the Coastal Plain of the Southeastern United States and concluded that 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 a function of many physical and hydrologic characteristics of a watershed. In the previous section, the effect of climatological factors on hydrograph components estimation was examined. It was shown that proper estimation of the fraction coefficient, using climatological factors, can provide very accurate estimates of daily baseflow with a coefficient of determination of up to R^2 = 0.97. Overall, it was 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. The goal of this stage of study is to improve the α value estimation by developing a regression equation based on the watershed's physical and hydrologic characteristics (e.g. rainfall, infiltration, runoff).

4.3.1 Material and Methods

Several computer programs were developed using the Visual BASIC language to execute tasks involved in all steps in this study (Appendix A). These programs give one the ability to compute and compare different approaches in a small period of time. They also help to synthesize the hydrologic behavior of watersheds.

An extensive database was gathered for a wide range of different climatic conditions between 1970 and 1978. It is composed of independently measured surface and subsurface flow data, management practices (land use), soil type, and climatological data. These data were obtained from a small, field-sized watershed in the Coastal Plain physiographic region of Southeast United States. The time step for precipitation measurement is 5 minutes; however, all computations were performed on a daily time step. In addition, the output of all scenarios was constrained so that the sum of the separated flow components was not negative or greater than total flow. The following sections describe the methods used to analyze different physical and hydrologic parameters, which were later used to develop a multivariate regression model for estimating the α value.

4.3.1.1 Infiltration

The movement of water through the soil surface is known as infiltration. Infiltration plays a very significant role in the runoff process and accurate infiltration components are essential for physicaly-based hydrologic modeling. Infiltration is controlled by many factors including rainfall rate and soil properties both before ponding and after ponding. Many equations are available for estimating infiltration, amongst which are Richard's equation, the Green and Ampt model, the Horton Method, and the SCS curve number method are often used. In this study, the Green and Ampt model and the SCS curve number method were used to compute infiltration.

4.3.1.1.1 The Green and Ampt model

The Green and Ampt infilitration model (1911) continues to be a widely used method. Many current hydrologic models use some form of the Green and Ampt model to partition rainfall between runoff and infiltration components. The original equation was derived from Darcy's law for infiltration assuming ponded water at the soil surface at all times. The model assumes that the soil profile is homogenous with uniform initial water content. The model also assumes that at any time after the start of rainfall, the wetting front is located at a vertical distance from the ground surface and the soil above the wetting front is completely saturated (Serrano, 2001).

In its simplest form the Green and Ampt equation for infiltration rate, *f*, can be written as:

$$f = K_s \frac{dH}{dz} \tag{44}$$

where *dH*/*dz* is hydraulic gradient, K_s is saturated hydraulic conductivity (cm/h) and *f* is infiltration rate, and H is the total hydraulic head and is the sum of the matric potential (*h*) and position head (*z*)

The depth of the wetting front can be related to cumulative infiltration, *F* (cm), by:

$$F = Z_f(\theta_s - \theta_i) \tag{45}$$

where θ_s is the saturated moisture content (cm^3/cm^3) and θ_i is the initial moisture content before infiltration began in cm^3/cm^3 and Z_f is the depth of the wetting front in cm.

Rearranging Equation 45 to solve for Z_f and applying it to Equation 44, the infiltration rate equation, *f*(t), becomes:

$$\begin{cases} f(t) = K_s + K_s \dfrac{\psi_{mf}(\theta_s - \theta_i)}{F} & for \quad t > t_p \\ f(t) = P & for \quad t \le t_p \end{cases} \tag{46}$$

where *P* is the rainfall rate (cm/hr), ψ_{mf} = matric-suction at the wetting front (cm of water), and t_p is the time when water begins to pond on the surface (hr). The instantaneous time in the above equations can be estimated using the following expression (Walter, 2006):

$$t = t_p + \frac{1}{K_s}\left[F - F_p + \psi_{mf}(\theta_s - \theta_i)\ln\left(\frac{\psi_{mf}(\theta_s - \theta_i) + F_P}{\psi_{mf}(\theta_s - \theta_i) + F}\right)\right] \qquad (47)$$

where, F_p is the amount of water that infiltrates before water begins to pond at the surface (cm) and t_p is the time it takes to have water begin to pond at the soil surface (hr). The following are expressions of these quantities (Walter, 2006).

$$F_p = \frac{\psi_{mf} K_s(\theta_s - \theta_i)}{P - K_s} \qquad \text{for } t = t_p \text{ and } P > K_s \qquad (48)$$

$$t_p = \frac{F_p}{P} \qquad (49)$$

To determine the amount of infiltration from a rain storm of duration, t_r, and intensity P, one needs to first determine the time at which surface ponding occurs (Equations 48 and 49).

If $t_r \leq t_p$ or $P<K_s$ then the amount of infiltration, $F = Pt_r$ and the infiltration rate, $f = P$.

If $t_r>t_p$ then Equation 47 should be used where time of runoff initiation (t_r) may be found once predetermined surface depression storage is filled (Walter, 2006).

The major use and availability of the Green-Ampt method in agricultural hydrologic models has been limited to event based models, specific application models, and field-scale models. The availability of the Green-Ampt model in continuous-time agriculture watershed scale models has been limited due to its demand for detailed breakpoint rainfall data (Hann et al., 1982, and Maidment, 1993)

The above procedure was completely coded within the Visual BASIC language for estimating the cumulative amount of infiltration on a daily basis. The program can be used for calculating infiltration for one layer of soil and a single rainfall intensity (Appendix A.15) or for multiple soil layers and rainfall intensities (Appendix A.16).

a. Estimation of Green and Ampt Parameters

In this section, the parameters used to estimate infiltration by the Green and Ampt equation will be discussed. As addressed earlier, the representative soil of station Z is classified as Cowarts loamy sand (Table 13). The top 1 m of the soil profile was considered as the effective root zone depth. Therefore, averages of physical characteristics for the top 1 m of the soil profile were considered for estimating different parameters in the Green and Ampt equation (Table 15). Data presented in Table 15 were obtained from in-situ measurements and/or USDA recommendations for the Green and Ampt parameters based on the soil textural class (Table 14).

Table 13. Representative soil profile of Cowarts loamy sand (Rawls, 1976).

Horizon	Depth (m)	Description
Apcn	0-0.2	Dark, grayish brown (10YR-4/2) loamy sand; weak fine granular structure; very friable, non-sticky; many small hard iron pebbles 1/8 to ½ in. in diameter; many fine roots; strongly acid; abrupt smooth boundary.
Bltcn	0.2-0.36	Yellowish brown (10YR-5-8) sandy loam; weak medium granular structure; very friable, non-sticky; many small hard in pebbles; fine roots common; strongly acid; clear wavy boundary.
B21cn	0.36-0.94	Yellowish brown (7.5YR-5/8) sandy clay loam; moderate medium sub-angular blocky structure; friable, sticky; small hard iron pebbles common; few fine roots mostly in upper part; very strongly acid; gradual wavy boundary.
B22tcnpl	0.94-1.27	Yellowish brown (10YR-5/6) sandy clay loam; with common and medium distinct mottles of light yellowish brown (2.5YR-6/4) and red (2.5 YR-4/8); moderate medium sub-angular blocky structure; firm, sticky; few hard and soft iron pebbles; soft plinthite; very strongly acid; gradual wavy boundary.
B23tpl	1.27-1.65	Reticulately mottled, yellowish brown (10YR-518), light gray (10YR-7/1), red (2.5YR-418), and strong brown (7.5YR-5/8) sandy clay loam; moderate medium sub-angular structure; few patchy clay films on red faces; firm, sticky; soft plinthite; very strongly acid.

Table 14. USDA soil texture - Green and Ampt infiltration parameters (Maidment, 1993).

Soil Texture Class	Porosity θ cm^3/cm^3	Wetting front soil suction head $\psi_{mf,\ cm}$	Saturated hydraulic conductivity K_s^*, cm/h	Residual water content θ_r^{**} cm^3/cm^3
Sand	0.437 (0.374-0.500)	4.95 (0.97-25.36)	23.56	0.020 (0.001-0.039)
Loamy sand	0.437 (0.363-506)	6.13 (1.35-27.94)	5.98	0.035 (0.003-0.067)
Sandy loam	0.453 (0.351-0.555)	11.01 (2.67-45.47)	2.18	0.041 (-0.024-0.0106)
Loam	0.463 (0.375-0.551)	8.89 (1.33-59.38)	1.32	0.027 (-0.020-0.074)
Silt loam	0.501 (0.420-0.582)	16.68 (2.92-95.39)	0.68	0.015 (-0.028-0.058)
Sandy clay loam	0.398 (0.332-0.464)	21.85 (4.42-108.0)	0.30	0.068 (-0.001-0.137)
Clay loam	0.464 (0.409-0.519)	20.88 (4.79-91.10)	0.20	0.075 (-0.024-0.174)
Silty clay loam	0.471 (0.418-0.524)	27.30 (5.67-131.50)	0.20	0.040 (-0.038-0.118)
Sandy clay	0.430 (0.370-0.490)	23.90 (4.08-140.2)	0.12	0.109 (0.013-0.205)
Silty clay	0.479 (0.425-0.533)	29.22 (6.13-139.4)	0.10	0.056 (-0.024-0.136)
Clay	0.475 (0.427-0.523)	31.63 (6.39-156.5)	0.06	0.090 (-0.015-0.195)

* For bare ground conditions K can be taken as $K_s/2$.
** Rawls et al. 1982

Supplementary data, like breakpoint precipitation (5-minute interval), air temperatures, pan evaporation, water temperature, wind, and radiation, were collected during the study period by the U.S. Weather Bureau climatological station located at the Georgia Coastal Plain Experiment Station in Tifton, Georgia. This station is located 0.5 mile east of the study area (Rawls, 1976).

Table 15. Average physical characteristics of Cowarts loamy sand soil at station Z (Rawls, 1976).

Soil Physical property	Value/Notation	Computation method
Hydrologic Soil Group	C	
Percent of the Sand	84.3	SSURGO Georeferenced Database
Total Porosity θ_t (cm^3/cm^3)	0.3642	In-situ measurement
Effective Porosity $\theta_e = \theta_t - \theta_r$ (cm^3/cm^3)	0.3292	In-situ measurement & Table 14
Saturated Hydraulic Conductivity *K*ef (cm/hr)	7.239	In situ measurement
Hydraulic Conductivity for Fallow Condition *K*ef (cm/hr)	0.32	Table 16
Water Retained at Wilting Point θ_{WP} (cm^3/cm^3)	0.0625	In-situ measurement
Water Retained at Field Capacity θ_{FC} (cm^3/cm^3)	0.1776	In-situ measurement
Wetting front soil suction head ψ_{mf} (cm)	17	In-situ measurement & Table 14

b. Effective Hydraulic Conductivity

Nearing et al. (1996) performed a comprehensive study to quantitatively relate curve number to the Green and Ampt's effective hydraulic conductivity parameters, K_e, so that the information available on land uses, soil types, and management practices may be applied in predicting infiltration from rainfall data. In this method the curve number value should be adjusted for antecedent moisture conditions, based on the previous five day rainfall as outlined in the USDA-SCS National Engineering Handbook (NEH-4, 2004), before it can be employed in estimating effective hydraulic conductivity. Nearing et al. (1996) suggested relationships for curve number optimized hydraulic conductivity for the fallow conditions (K_{ef}) for different hydrologic soil groups (Table 16).

Table 16. Relationships for calculating curve number optimized Green and Ampt effective hydraulic conductivity values for fallow conditions, K*ef* (Nearing et al., 1996)

Hydrologic Soil Group	Formula K_{ef} (mm/h)
A	$K_{ef} = 14.18$
B	$K_{ef} = 1.17 + 0.072 \times \%$ Sand
C	$K_{ef} = 0.50 + 0.032 \times \%$ Sand
D	$K_{ef} = 0.34$

Optimized K_e values for cropped conditions were relatively consistent when they were expressed as a ratio of K_e for the cropped condition to effective conductivity for the fallow condition; K_{ef}. A nonlinear regression model was developed to relate K_e for the cropped conditions to curve number by the following equation (Nearing et al., 1996):

$$K_e = \frac{56.82 K_{ef}^{0.286}}{1 + 0.051 \exp(0.062 CN)} - 2 \qquad (50)$$

where *CN* is curve number for the given soil hydrologic group and cropping condition and K_e is effective hydraulic conductivity (mm/hr).

The Soil and Water Assessment Tool (SWAT) model incorporates the Nearing et al. (1996) approach for calculating effective hydraulic conductivity with a slight modification. In the SWAT model, hydraulic conductivity for the fallow condition, K_{ef}, was replaced by soil saturated hydraulic conductivity (SWAT, 2000).

The purpose of this stage of study is to investigate the relationships between curve number and effective hydraulic conductivity values for the Green and Ampt equation. In this regard, two scenarios were investigated: 1) K_{ef} is calculated based on formula provided by Nearing et al. in Table 16, 2) K_{ef} is replaced by saturated hydraulic conductivity, K_s (SWAT model approach).

c. Weighted Average Porosity

Shockley (1953) introduced a simplified procedure for determining the amount of moisture to be replaced within the effective root zone. In this method the effective root zone of any crop or soil profile is divided into quarters and the moisture extracted from each quarter is computed as a percentage of the total moisture extracted (Table 17, Appendix A.18). This pattern was used to calculate total porosity at station Z (Woodward et al., 1969).

Table 17. Basic moisture extraction pattern (Woodward, 1969)

Percent of Total Root Zone Depth	Percent of Total Moisture Extracted
25	40
50	70
75	90
100	100

4.3.1.1.2 The Soil Conservation Service (SCS) Equation

The Soil Conservation Service Curve Number (SCS-CN) method is a conceptual method, which is well supported by empirical data. It is simple because it relies only on curve number (CN), which is a function of the watershed cover and soils complex characteristics. The SCS-CN method was originally developed for agricultural watersheds. Therefore, the best result is usually obtained for agricultural watersheds and poorer results are obtained for forested sites. One of the biggest challenges in usage of the runoff curve number method is the proper selection of the curve number values, thus properly reflecting the effects of surface cover, management, land use, and antecedent soil moisture conditions. However, its use has been documented for different land uses (Shirmohammadi et al., 1997, Hawkins, 1978, and Mishra and Singh, 2003).

The curve number method combines infiltration losses, depression storage, and interception into a maximum soil water retention parameter called *S*. The accumulated runoff depth or rainfall excess (in), *Q,* and total infiltration depth (in), *F,* can be estimated by the following set of empirical relationships:

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \tag{51}$$

$$F = P - Q \tag{52}$$

$$S = \frac{1000}{CN} - 10 \tag{53}$$

where, *P* is the depth of 24 h precipitation (in) and *S* is the retention parameter (in). In this study, daily infiltration was computed by subtracting daily surface runoff (*Q*) from daily precipitation. There are no parameters to be calibrated, however, the amount of moisture present in the soil is known to affect the volume and the rate of runoff. The curve number varies for each storm event according to the 5-day antecedent rainfall that defines three antecedent soil moisture condition classes (dry, normal, and wet) according to the season (dormant season or growing season) (Chahinian et al., 2005).

Many studies (King et al. 1999, Mullem 1991) have shown that the Green-Ampt method results in more accurate runoff volume than the SCS-CN method. However, in the absence of break point rainfall data and proper soil hydraulic properties, this model is of little use. Therefore, the SCS-CN number and methods whose parameters are more empirical in nature and are easily estimated continue to be used more frequently (Smemoe et al., 2004).

In this study, a computer program was developed (Appendix A.17) to calculate total infiltration depth considering both antecedent soil moisture conditions and the seasonal factors according to the National Engineering Handbook (1972).

4.3.1.2 Water Movement in Soils

Water movement in soils is principally through the larger pore spaces and depends on the relative number and continuity of these pores. The rate of water movement in soils is termed the permeability of the soil. It depends to a large extent upon the interrelation of the soil itself, including texture, structure, water stability of aggregates, and nature of exchangeable ions. When rain or irrigation water is applied to the soil surface, both gravity and capillary potential cause its downward movement by infiltration. If the water table is close to the surface and sufficient water is supplied, the moisture may reach the water table and add to the groundwater. If the water table is deep or the applied water is insufficient, the moisture may never reach the groundwater as it may be removed by evapotranspiration before it reaches the water table. The presence of relatively impermeable subsoil (the Hawthorn Formation of Miocene Age at station Z) restricts the downward movement of the water (Rawls, 1976, Linsley et al. 1987, Woodward et al., 1969).

In this study, the amount of available water above field capacity (gravitational water) in each time step is considered as baseflow. It was assumed that this water will leave the study site; station Z, within a time period of 24 hours.

4.3.1.3 Soil Moisture Content

Despite the fact that soil moisture data were measured and are available at different depths (15, 30, 46, 61, 91, 122, and 137 cm) at station Z, a water balance approach was employed to update average soil moisture content within the root zone depth for each time step (Appendix A.18). A computer model was developed based on the following water balance assumption:

$$SW_t = SW_o + \sum_{i=1}^{t}(R_i - Q_i - P_i - ETc_i) \qquad (54)$$

where, SW_t is the final soil water content (cm) at time t, SW_o is the initial soil water content available for plant uptake on day i (defined as the initial soil water content minus the permanent wilting point water content (cm)), t is the simulation time (days), R_i is the amount of precipitation on day i (cm), Q_i is the amount of surface runoff on day i (cm), P_i is the amount of percolation below the root zone on day i, and ETc_i is the amount of evapotranspiration on day i (cm).

4.3.2 Results and Discussion

Results from section 4.2 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 a given watershed. The correlation matrix is used to present the correlation between pairs of variables used in the study (Table 18). The correlation matrix is developed based on 8 years of daily measurements and predictions. The correlations between variables are mostly below 0.3 with a largest correlation of 0.44 between α and the duration of surface runoff. The squares of predictor-criterion correlations indicate that the fraction of variance explained by individual variables ranges from 4.84×10^{-8} to 0.19. These results indicate that accurate prediction of α by regression will require the use of more than one predictor variable, or of a non-linear model.

Table 18. Correlation Matrix for the Fraction Variable.

	V1	V2	V3	V4	V5	V6	V7	V8	V9	V10	V11	V12	V13	V14	V15	α
V1(1)	1.00	0.11	-0.03	0.63	0.83	0.39	0.68	0.92	1.00	0.60	0.98	0.56	0.43	0.47	0.68	-0.00022
V2(2)		1.00	0.17	-0.11	0.14	-0.21	-0.12	0.14	0.11	-0.26	0.10	-0.27	-0.03	0.07	0.13	-0.31384
V3(3)			1.00	-0.45	0.04	-0.19	-0.16	0.06	-0.04	-0.15	-0.11	-0.18	-0.23	-0.27	0.28	-0.40891
V4(4)				1.00	0.45	0.39	0.52	0.43	0.63	0.47	0.68	0.49	0.56	0.52	0.17	0.32711
V5(5)					1.00	0.51	0.49	0.82	0.83	0.48	0.85	0.48	0.32	0.42	0.62	-0.10235
V6(6)						1.00	0.55	0.26	0.39	0.75	0.41	0.79	0.41	0.35	0.12	0.27519
V7(7)							1.00	0.58	0.68	0.72	0.64	0.69	0.41	0.36	0.40	0.21000
V8(8)								1.00	0.92	0.46	0.89	0.42	0.09	0.28	0.79	-0.17973
V9(9)									1.00	0.60	0.98	0.56	0.43	0.47	0.68	0.00008
V10(10)										1.00	0.58	0.98	0.43	0.33	0.32	0.25005
V11(11)											1.00	0.56	0.44	0.49	0.63	0.01999
V12(12)												1.00	0.44	0.34	0.29	0.27156
V13(13)													1.00	0.63	-0.05	0.43628
V14(14)														1.00	-0.22	0.12997
V15(15)															1.00	-0.19530
α(16)																1.00000

(1) Total rainfall during a storm event in (cm)
(2) Total evapotranspiration during a storm event (cm)
(3) Breakpoint rainfall intensity (cm/hr)
(4) Breakpoint rainfall duration (hr)
(5) Infiltration during storm event based on SCS curve number method (cm)
(6) Baseflow during storm event based on SCS curve number method (cm)
(7) Observed Total flow during storm event (cm)
(8) Rainfall / Duration of storm (cm/day)
(9) Infiltration during storm event using Green and Ampt equation, K_{ef} = saturated hydraulic conductivity (cm)
(10) Baseflow during storm event using Green and Ampt equation, K_{ef} = saturated hydraulic conductivity (cm)
(11) Infiltration during storm event using Green and Ampt equation, K_{ef} obtains from Table 16 (cm)
(12) Baseflow during storm event using Green and Ampt equation, K_{ef} obtains from Table 16 (cm)
(13) Duration of runoff storm event (day)
(14) Rainfall Duration (day)
(15) Daily Rainfall intensity (cm/day)
(16) The fraction coefficient

Scenario I:

Table 18 indicates interdependence among variables and so perhaps a principal components analysis of the variables or a stepwise regression should be used to eliminate redundant variables prior to the calculation of the regression relations. In this regard, after developing the multivariate linear regression equation, a forward stepwise regression method along with systematic elimination of variables were performed using STATISTICA software Version 4.3 (StatSoft, Inc), for eliminating redundancy and improving the coefficient of determination (Table 19).

Table 19. Summary of stepwise regression

Variables*	Variables included	Multiple R	Multiple R-Square	R-Square change
V13	1	0.83	0.68	0.68
V15	2	0.87	0.76	0.08
V3	3	0.90	0.81	0.05
V5	4	0.91	0.83	0.02

* Variables are defined as footnotes under Table 18.

The following stepwise regression equation was developed and calibrated for the period of 1971 through 1974.

$$\alpha = 0.302 \times V13 - 0.080 \times V15 - 0.137 \times V3 - 0.065 \times V5 \qquad (55)$$

If $\alpha > 1$, use $\alpha = 1$ and if $\alpha < 0$ use $\alpha = 0$

As shown in Table 19, the coefficient of determination using multiple parameters (i.e., four parameters) results in a zero intercept regression model with R^2 = 0.834. Figure 25 compares estimated baseflow discharge values obtained by Equation 54 with observed baseflow values. The coefficient of determination between estimated and observed baseflow discharge values is found to be 0.84. This result indicates that the developed multivariate regression equation can be used to predict α values based on physical and hydrologic characteristics of a watershed with significant accuracy for station Z.

Scenario II:

In the absence of breakpoint rainfall measurements, equation 55 can not be used for estimating alpha values during storm events; therefore, equation 56 was developed. This equation may be used for estimating alpha values when only daily rainfall measurement is available.

$$\alpha = 0.278 \times V13 - 0.113 \times V15 - 0.049 \times V5 \qquad (56)$$

If α >1, use α = 1 and if α < 0 use α = 0

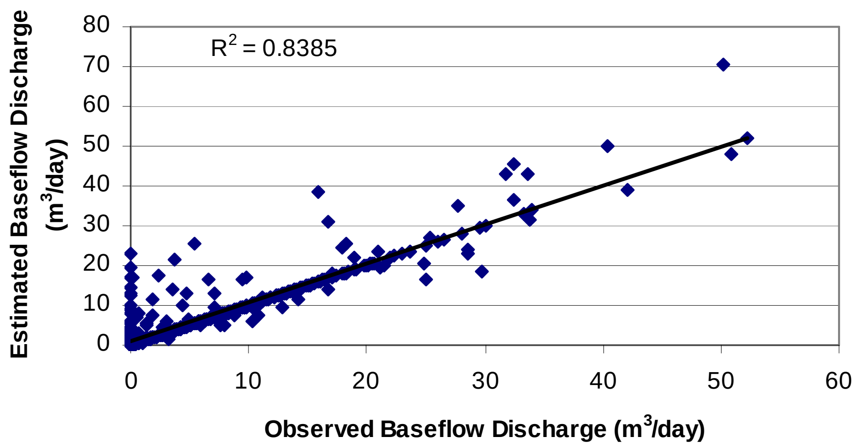


Figure 25. Observed baseflow discharge vs. estimated baseflow using equation 55

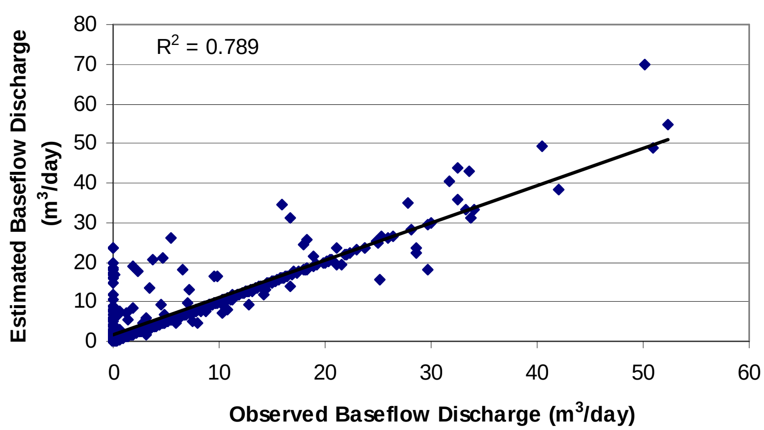


Figure 26. Observed baseflow discharge vs. estimated baseflow using equation 56

Figure 26 compares estimated baseflow discharge values obtained using α values computed by Equation 56 with observed baseflow values. Figure 26 indicates a reasonable agreement between estimated and observed baseflow values with a R^2 (coefficient of determination) value of 0.789. In this case, the coefficient of determination is lower than the one obtained using equation 55. However, this result indicates that the developed multivariate regression equation can be recommended to predict α values.

In general, a single evaluation measure can indicate that a model is a good predictor, when in reality it is not. Because of these limitations, additional evaluation criteria, such as relative percent error (E_r), coefficient of efficiency (E), and root mean square error ($RMSE$), have been proposed by different researchers to assess model performance. Therefore, in the following section additional statistical criteria will be discussed for a more detailed evaluation of the accuracy of predictions (Chinkuyu et al., 2004).

The fit between model results on baseflow discharge obtained under Scenario I or Scenario II and observed values for individual storm events can be quantified in terms of coefficient of efficiency or modeling efficiency (Nash and Sutcliff, 1970). The coefficient of efficiency, E, is computed as:

$$E = 1 - \left[\frac{\sum (Q_{obs} - Q_{pred})^2}{\sum (Q_{obs} - Q_{mean})^2} \right] \tag{57}$$

where, Q_{obs} is the observed baseflow discharge, Q_{pred} is the estimated baseflow discharge, and Q_{mean} is the mean observed baseflow discharge. The coefficient of model efficiency is the proportion of the initial variance in the observed values, which is explained by the model, where initial variance is relative to the mean value of all the observations. Thus, E may range from 1 to $-\infty$. If $E = 1$, the model is estimating exactly the observed baseflow discharge for every storm. A value of $E = 0$ would indicate that the sum of squares of the difference between the observed and the estimated is equal to the sum of the squares of the difference between the observed values and the mean of the observed values (Nearing et al., 1996). In this study, coefficients of efficiencies were computed for both scenarios. For the model developed under scenario I, $E = 0.802$ and for the model developed under Scenario II, $E = 0.736$.

The last criteria, which will be examined here is the ratio of standard error of estimates to the standard deviation. Generally, a smaller arithmetic ratio of these parameters (*Se/Sy*) is an indication of higher accuracy in model estimation. This ratio (*Se/Sy*) was found to be 0.398 and 0.482 for Senarios I and II, respectively (Table 20).

Table 20. Summary of statistical test for baseflow analysis (1971-1978)

Baseflow	$\overline{Q}$ Mean (m^3/day)	*Sy* Standard Deviation (m^3/day)	R^2 Coefficient of Determination	*Se* Standard Error of Estimate (m^3/day)	*Se/Sy*	*E* Model efficiency (Nash-Sutcliffe)
Measured	7.3182	8.2163				
Scenario I	8.2704	8.7594	0.8385	3.6486	0.398	0.802
Scenario II	8.5194	8.7551	0.7890	4.2160	0.482	0.736

A model may be considered to have performed well when: (i) the ratio of standard error of estimation to standard deviation is less than 0.5 (ii) modeling efficiency is greater than 0.50, and (iii) R^2 is greater than 0.5. These benchmark values were chosen based on other studies that gave similar "acceptable" values showing good model performance. As it is shown in Table 20, both scenarios satisfy all criteria to be considered as a good model performance (Bakhsh et al., 2000; Hanson et al., 1999; Ma et al., 2000, and Chinkuyu et al., 2004).

4.3.3 Summary and Conclusions

The main objective of this study was to examine the effect of physical and hydrologic characteristics of watersheds to improve estimation of streamflow partitioning techniques. Among numerous factors, which may affect the ratio of hydrograph components to the total runoff, fifteen parameters were selected for further investigation.

A multivariate linear regression equation was developed to relate these parameters to the fraction value (Boughton, 1988). In the next stage, the forward stepwise regression method along with systematic elimination of variables was performed to identify the more sensitive parameters in calculation of the α fraction values. In the real world scenario, breakpoint rainfall and runoff measurements are not commonly available for all watersheds; therefore, two sets of equations were developed. The first set of equations using breakpoint rainfall intensity data for calculating α values and the second set of equation estimating α values based on daily rainfall data. However, in both cases the physical and hydrologic characteristics of watersheds were incorporated into the decision making process.

Eight years of data were collected and computed for the field scale watershed, station Z in Tifton Georgia. These data were used for the model calibration and validation. Next, three statistical criteria including coefficient of determination, Nash-

Sutcliff coefficient of efficiency, and the ratio of standard error of estimaties to the standard deviation were employed to test the accuracy and performance of both case scenarios. The results of this section showed that a higher statistical score was obtained for the first case scenario, while both methods were classified as good performance models.

Overall, this study demonstrated that incorporating physical and hydrologic characteristics of watersheds can significantly improve the accuracy of hydrograph separation techniques when used jointly with enhanced recession limb analysis, calibration approach, and time-discretization method.

The next step of this study involves deploying this method within a GIS environment in order to access spatial contribution of surface and subsurface flow in total flow hydrographs.

4.4 Data Acquisition

As mentioned before, the Little River Watershed in Tifton, Georgia was selected for the model implementation. In this stage of study, the GIS-Based data including land use, soil type, digital elevation model, river network along with long term streamflow and precipitation data were acquired and compiled. Data (1968-2000) for the Coastal Plain physiographic region is available through USDA-ARS Watershed Research Laboratory in Tifton, Georgia.

4.4.1 Little River Watershed

4.4.1.1 Study Area and Hydrologic Instrumentation

The USDA-ARS Southeast Watershed Research Laboratory (SEWRL) is in charge of collecting and developing hydrologic databases on the Little River Experimental Watershed (LRW). The LRW is an agricultural watershed with an area of 334 km^2 (Figure 27). The watershed was selected as an experimental watershed and represents the Tifton-Vidalia Upland of the Gulf-Atlantic Coastal Plain region in the southeastern United States. Before establishment of the SEWRL, comprehensive hydrologic data was not available for the region. This deficiency originated from associated costs, low-gradient stream, and its heavily vegetated condition. The first series of hydrologic monitoring instrumentation, which was installed in the LRW in 1967 included 52 raingages, eight stream stage sites, and three groundwater stage stations within the stream channel alluvial aquifer system. The motivation for such an effort was the evaluation of Coastal Plain hydrologic behavior, which helps hydrologists to assess existing methods and develop new approaches for predicting hydrologic processes. The obtained data is also useful for water resources management and environmental research (Sheridan et al., 1995).

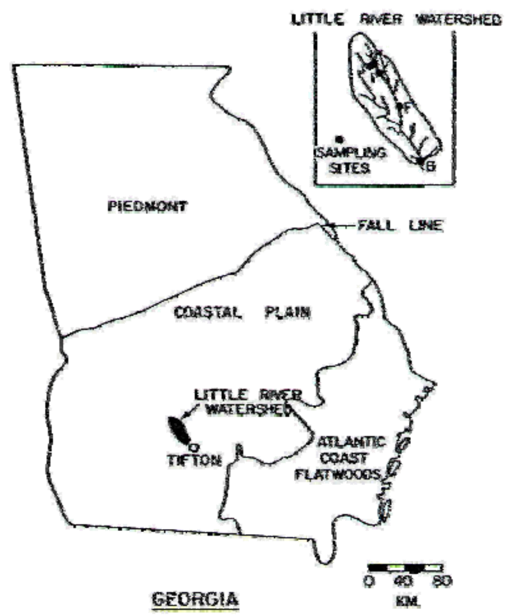


Figure 27. Location of the Little River Watershed in the State of Georgia (Asmussen et al., 1979)

4.4.1.1.1 Precipitation Measurement

Most of the precipitation in the LRW is in the form of rainfall, and other forms of precipitation such as snow and freezing rain are hydrologically negligible. The accuracy of rainfall measurement is 0.1 inches (2.54 mm), which is recorded every five minutes. The raingage network consists of Fisher-Porter weighing, binary-coded, and digital punch gages, which are spread throughout the watershed at approximately two to eight kilometer intervals (Figure 28). Raingages recorded cumulative precipitation based on 16-channel paper tape upon punch mechanism. The number of raingages was increased from 52 in 1967 to 58 in 1981 (Sheridan et al., 1995). Precipitation data was initially analyzed through LRW and daily precipitation values were reported for each subwatershed within the study area.

4.4.1.1.2 Streamflow Measurement

An intensive streamflow measurement program was initiated on the LRW control structures in the early 1970s. Measurement of streamflow in the Coastal Plain region of the southeastern United States is not a simple task. This problem originates from low-gradient drainage systems. Most of the channels within the watershed have slopes less than 1%. Therefore, the region can be generally considered as broad floodplains with poorly defined streams. The low-steepness and heavily vegetated characteristics of the floodplains, cause water to spread out several hundred meters during moderate to high flow conditions. This makes highway bridges and culverts proper places for streamflow measurement. Table 21 gives detailed information concerning flow measurement structures on LRW (Sheridan et al., 1995). A Virginia V-notch weir is mostly used throughout the watershed for flow measurement. In addition, water levels in both upstream and downstream stations were continuously recorded (on proper tape at 5-min intervals) in selected locations within the watershed (Figure 28). In this study, ten years of daily streamflow data (1972-1981) were used as the model input. This period was selected to match the data period for station Z where the streamflow partitioning method developed in this study was both calibrated and validated.

4.4.1.1.3 Alluvial Groundwater Measurement

Three observation wells were drilled into floodplain alluvial material near flow measurement sites. The groundwater levels were continuously recorded from 1969 to 1981. The output format of groundwater measurement was the same as stream stage recorders (Sheridan et al., 1995).

Table 21. Details on flow measurement structures on Little River watershed (Sheridan et al., 1995)

Watershed	Control Location	Drainage Area		Total Structure Width (m)		Notch Depth		25-year Design Flow Rate*	
		(km^2)	(acre)	(m)	(ft)	(m)	(ft)	(m^3/s)	(ft^3/s)
B	Dual Bridges	334.3	82,600	92.3	302.8	0.93	3.05	191.4	6,759
F	Single Bridge	114.9	28,790	43.1	141.4	0.61	2.00	81.9	2,892
I	Single Bridge	49.9	12,330	26.6	87.3	0.50	1.64	41.6	1,469
J	4-Barrel Culvert	22.1	5,460	16.8	55.1	0.47	1.54	20.8	735
K	4-Barrel Culvert	16.7	4,130	17.8	58.4	0.44	1.44	16.5	583
M	2-Barrel Culvert	2.6	640	3.6	11.8	0.19	0.62	4.0	141
N	3-Barrel Culvert	15.7	3,880	14.8	48.6	0.62	2.03	15.4	544
O	3-Barrel Culvert	15.9	3,930	14.8	48.6	0.62	2.03	14.5	512

* Design flow rates based on preliminary estimates of watershed drainage areas.

4.4.1.1.4 Hydrologic Network Reduction

Regarding the hydrologic network reduction policy in early 1982, data collection and processing programs dropped significantly after 14 years. The number of raingages decreased to 29 digital recorders. However, the dense raingage network on the headwater study area was kept intact. This decision minimized the impact of raingage reduction on the study of the small watershed hydrology. Furthermore, as a part of this policy, monitoring of the streamflow for two small watersheds (O, N) and the groundwater stage observation program were terminated (Sheridan et al., 1995).

4.4.1.1.5 Replacement of Hydrologic Instrumentation

High repair service costs were incurred in late 1992 and early 1993, after approximately 25 years. Digital punch raingages and streamflow recorders were replaced by electronic recorders (Sheridan et al., 1995).

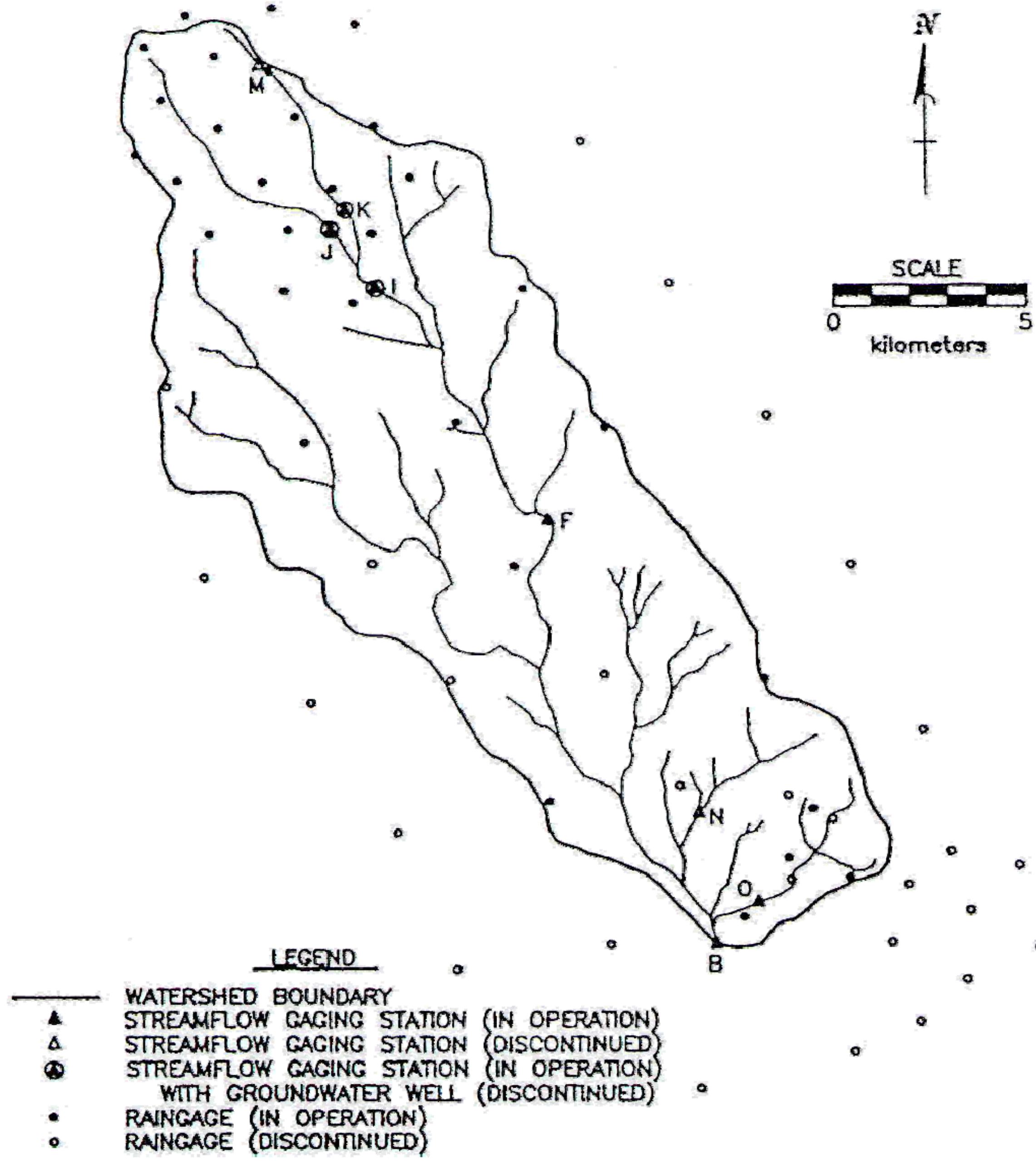


Figure 28. Little River Watershed with raingages, stream stage, and alluvial groundwater well sites (Sheridan et al., 1995).

4.4.2 Georeferenced Databases

The question of which resolution suffices for hydrologic purposes is answered in part by testing the quantity of information contained in a database as a function of resolution. As discussed earlier, section 4.1.6, data from the field scale watershed (station Z) located in the Little River Watershed near Tifton, Georgia were used for model calibration and validation. Therefore, it seems logical to choose a cell size, which is consistent with the size of the study area. In this regard, 60 m cell size was selected as a baseline for further analysis.

4.4.2.1 Projection

All geographic data were projected in the same coordinate system – NAD83, UTM Zone 17, meters.

4.4.2.2 Soil Data

Both SSURGO and STATSGO data set were provided through SEWRL. Comparing the SSURGO and STATSGO databases shows that STATSGO grossly underrepresented soil coverage under assigned resolution (60m). Therefore, SSURGO database was selected as the soil database for modeling purpose.

4.4.2.3 Land Use Date

The land use data coverage was created by processing the classified Landsat imagery for July 20, 2003 into grid format. The classified Landsat data is a thematic image. The land use data had 60 m resolution and were available for two years (1980, 1990).

4.4.2.4 Drainage Network Date

Digital Elevation Model (DEM) resolution has a direct influence on the total drainage length and slope. These effects on hydrograph response may be compensating; shorter drainage length accelerates arrival times at the outlet, whereas flatter slopes delay the response. In order to minimize the effect of DEM resolution for developing the drainage network, the National Hydrography Dataset (NHD) was used. The National Hydrography Dataset (NHD) is a comprehensive set of digital spatial data that contains information about surface water features such as lakes, ponds, streams, rivers, springs and wells (NHD, 2006; Vieux, 2001).

The “model streams” coverage include the streams as defined by USGS on the 7.5 minute quadrangle maps that have been edited to show no gaps or breaks.

4.5 Model Simulation

Model simulation for different scenarios (e.g., soils, land use, etc.) was performed. In this regard, the acquired data such as rainfall, soils, land use, topography, and other attributes (section 4.4) were incorporated into the developed model to make the model more versatile and interactive with the georeferenced data. This will allow the examination of “what if” scenarios with the model. In this section three scenarios were investigated and compared as follow:

- Scenario I (Empirical Based Model – Modified Boughton's Method): Estimating the α value based on the modified Boughton's method (forward difference approximation)
- Scenario II (Physical Based Model – Weighted Average Curve Number Method): Estimating the α value considering physical and hydrologic characteristics of a watershed. In this approach, infiltration was computed based on an average curve number value for each subwatershed
- Scenario III (Physical Based model – Weighted Discharge Method): Estimating the α value considering physical and hydrologic characteristics of a watershed. In this approach, infiltration was computed based on curve number values for all cells within each subwatershed

All steps identified in this study were programmed using the Visual BASIC language (Appendix A). Ten years of streamflow measurement and precipitation data (1972-1981) were used for the model's implementation. These data were collected from eight subwatersheds within the Little River Watershed in the Coastal Plain physiographic region of Southeast United States (Figure 29). The time interval for all computations is one day because both precipitation and runoff data are based on a daily time step. For all scenarios, the output of the model 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 scenarios:

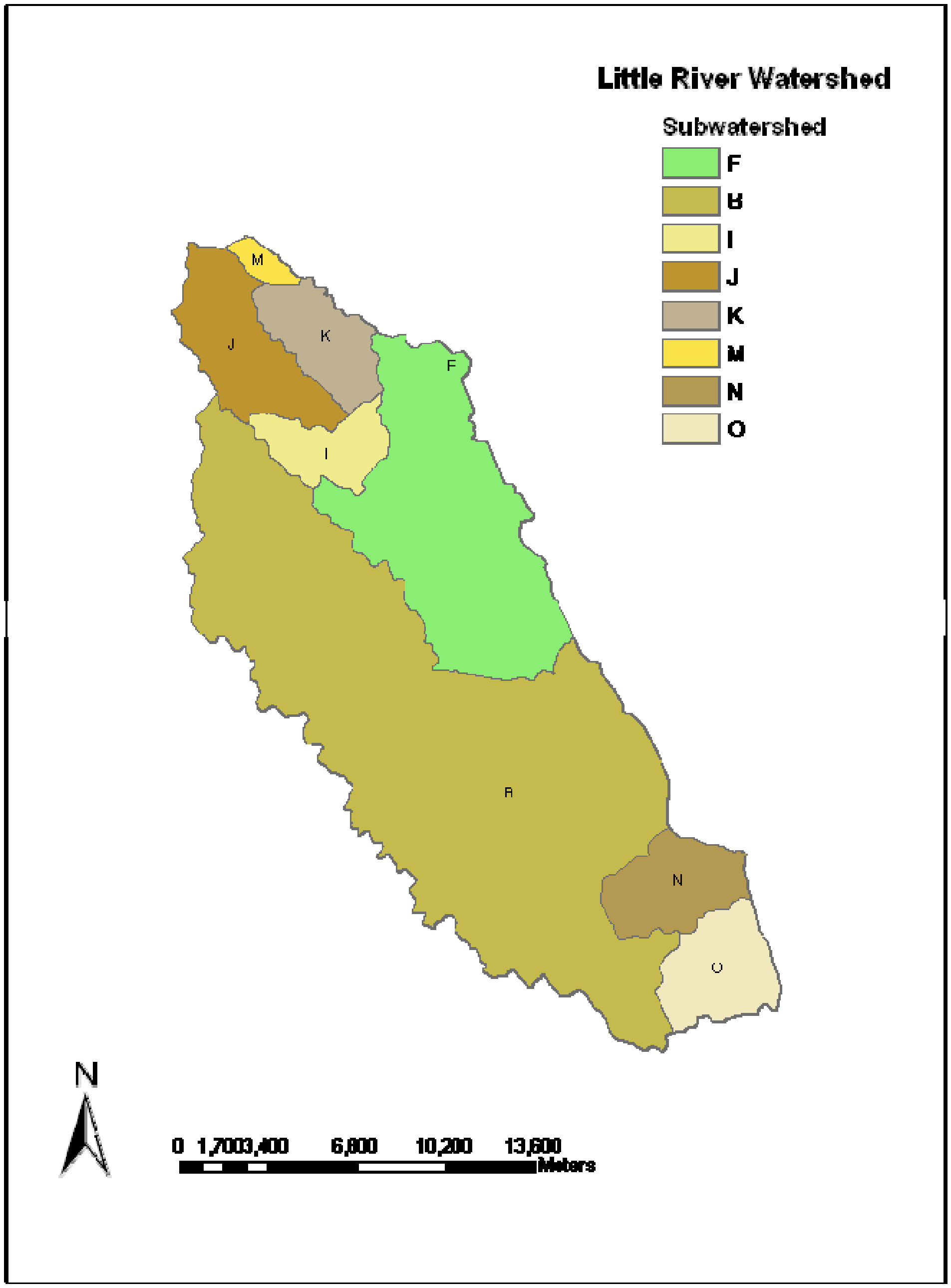


Figure 29. Subwatersheds of Little River Watershed

4.5.1 Scenario I (Empirical Based Model – Modified Boughton's Method)

As discussed earlier (4.2.1.2.1), the modified Boughton's method (forward difference approximation) can be used as the approximate streamflow partitioning method. This method uses daily streamflow measurement for estimating α values during storm events.

In this method, 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 baseflow on the previous time step (Equation 41). For this scenario, the developed program is able to identify the end of the surface runoff for all storm events throughout the 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 baseflow increases to equal the total flow at the specified point at the end of the separation process.

In the previous study, the modified Boughton's method (forward difference) for streamflow separation was tested using separately measured surface and subsurface flow data from the field scale watershed Z for the period of 1970 through 1981. Results showed that the coefficient of determination (R^2) value for the forward difference approximation approach is 0.87. The comparative study showed that despite the simplicity of the forward difference approximation, it produced reasonably accurate results.

In this stage of the study, ten years of total streamflow data (1972-1981) were used for the model implementation. The developed program (Appendix A.19) was run for all subwatersheds within the Little River Watershed.

4.5.2 Scenario II (Physical Based Model – Weighted Average Curve Number Method)

A better understanding and improvement of existing methods for streamflow partitioning is the initial motivation for this study. While many hydrological model software packages are currently available, no model has been developed for examining watershed characteristics for the purpose of hydrograph separation. Therefore, developing and assessing the new hydrological model using physical and hydrologic characteristics of a mixed land use watershed is the ultimate goal of this research.

In this stage of the study, the developed method under section 4.3.2 was implemented for the eight subwatersheds within the Little River Watershed. This was accomplished by incorporating different physical and hydrologic characteristics of watersheds. This model will use different georeferenced data such as digital elevation model, soil type, land use, ground network precipitation records, and total streamflow as its input data. This kind of approach should be more robust and capable of providing timely predictions. The following steps were performed in the implementation phase of this scenario:

1. A computer program capable of distinguishing the starting and ending points of surface runoff was developed (Appendix A.19). In this program, the starting point of surface runoff can be identified as the first point on the rising limb of a hydrograph. Also in order to identify the end point of surface runoff, the second derivative of all points on the recession limb of each hydrograph was calculated. The inflection point or the end of surface

runoff was defined as the point on the recession limb of the hydrograph where the second derivative is zero (Nejadhashemi et al., 2005).

2. As discussed (section 4.3.2), in the absence of breakpoint rainfall measurements, a multivariate regression equation (equation 56) can be used for estimating α values during storm events.

$$\alpha = 0.278 \times V13 - 0.113 \times V15 - 0.049 \times V5 \quad (56)$$

where, *V5* is infiltration during storm event obtained based on SCS curve number method in cm, V*13* is duration of runoff event in days, and *V15* is daily rainfall intensity in cm/day.

3. In the next step, the duration of storm event and daily rainfall intensity fix with each storm was computed (Appendix A.19).
4. Before computing infiltration during storm events based on the SCS curve number method, a computer program was developed (Appendix A.17) to account for both antecedent soil moisture conditions and the seasonal factor according to USDA-SCS National Engineering Handbook (1972).
5. Another computer program was developed to compute composite curve numbers from land use (Figure 30), soil type (Figure 31), and basin boundary shape files (Figure 29). Besides the three layers used to compute CN, a lookup table was embedded within the program (Appendix A.20, Figure 32) to relate land use and soil ID to curve numbers for hydrologic soil groups A, B, C, and D.

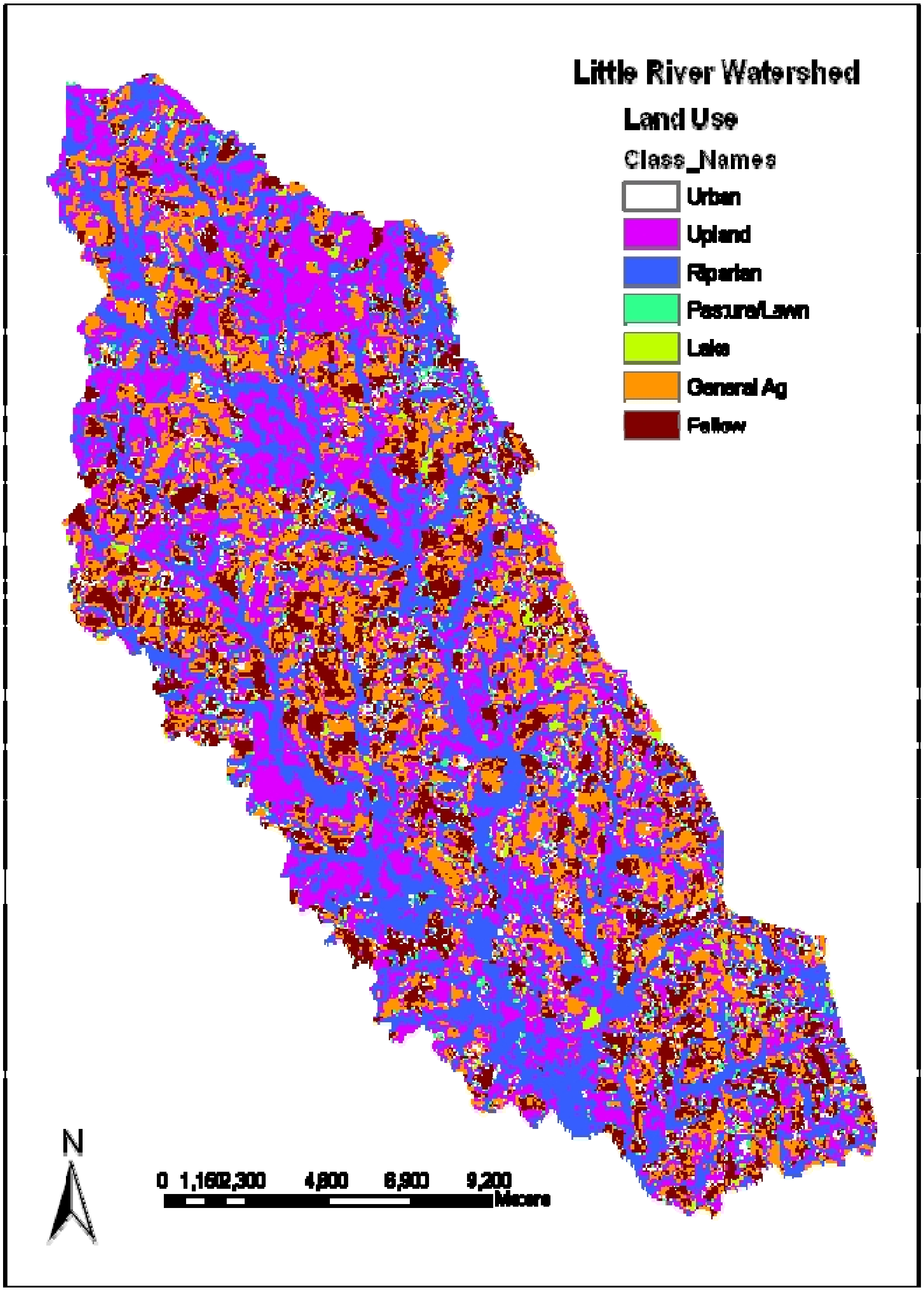


Figure 30. Land use classes - the Little River Watershed

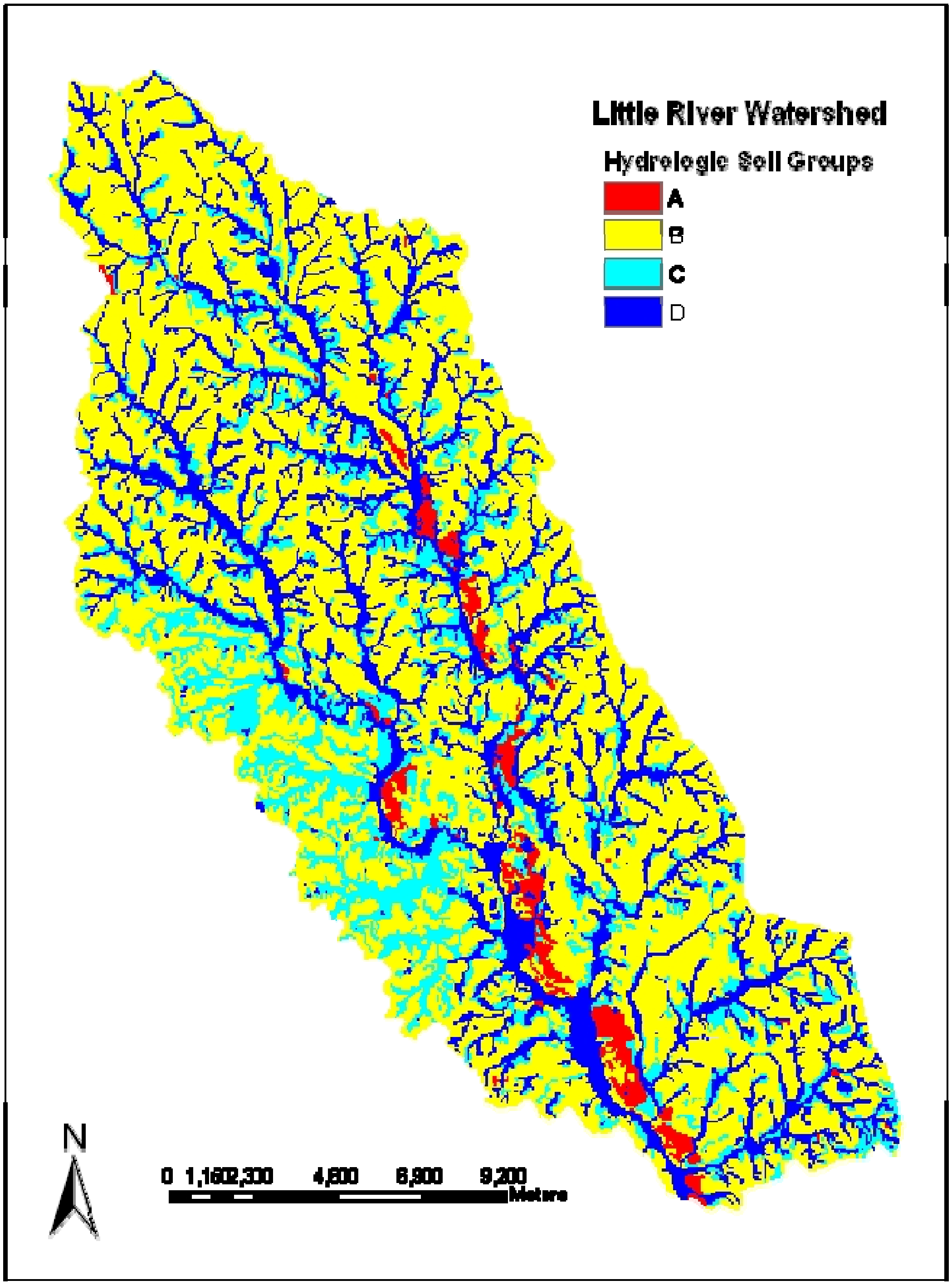


Figure 31. Hydrologic soil groups - the Little River Watershed

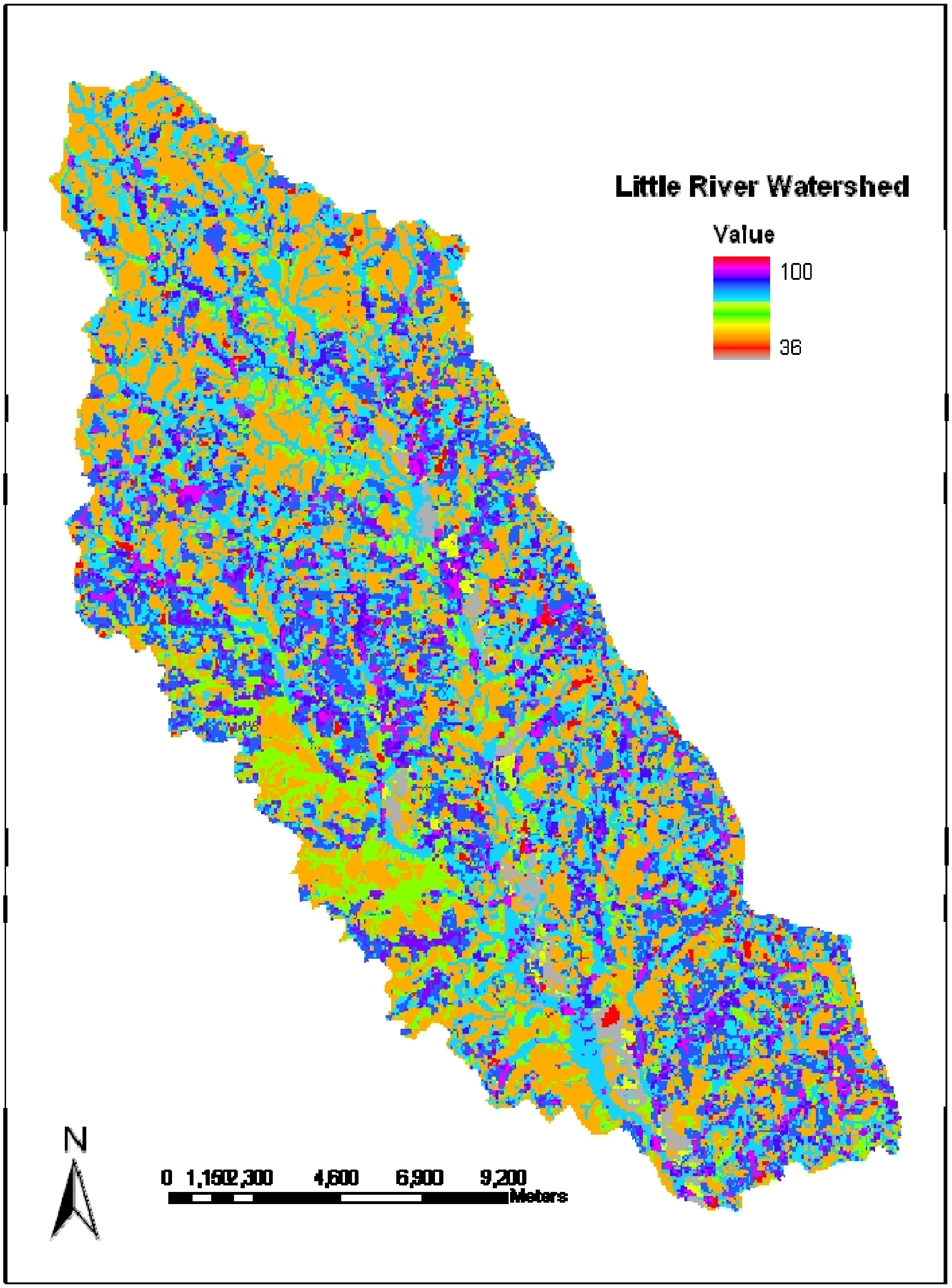


Figure 32. Curve number variation - the Little River Watershed

Table 22. Summary of CN values in the Little River Watershed Tifton, GA

Watershed	Mean	Min.	Max	Standard Deviation
B	73.8	36	100	12.59
F	73.0	36	100	12.25
I	71.3	36	100	11.21
J	71.7	36	100	11.19
K	69.8	60	100	10.94
M	69.0	60	100	11.31
N	77.2	36	100	11.69
O	76.6	36	100	12.07
Little River	73.8	36	100	12.59

6. In order to simplify the process, an average curve number was computed for each subwatershed (Table 22). These values were further adjusted for antecedent runoff condition and seasonal factor for the period of study (Appendix A.17).
7. Infiltration during the storm events was obtained based on the SCS curve number method (Appendix A.21 and A.22).
8. All computed parameters (total infiltration, duration of runoff, and daily rainfall intensity) were incorporated into equation 56 to calculate α values (Appendix A.23). These values were used to separate overland flow from baseflow during each storm event.

4.5.3 Scenario III (Physical Based Model – Weighted Discharge Method)

Sheridan et al. (1986) evaluated the curve number procedure for estimating storm runoff for use in Coastal Plain watersheds. They concluded that for effective modeling or prediction of storm runoff volumes considering average curve number values even after correction for antecedent runoff-producing conditions was not effective. This is caused by specific characteristics of Coastal Plain with low gradient channels and aquifer systems and considerable potential for rainfall runoff storage. They recommended that for the Coastal Plain and other watersheds with similar characteristics, computation of storm runoff volumes should be made separately for the upland and lowland runoff-producing zones (Sheridan et al., 1986).

As indicated in National Engineering Handbook: Section 4 – Hydrology (NEH-4, 2004), a single watershed weighted average curve number does not produce accurate estimates of runoff for watersheds with widely varied curve number values. For this case, the method of weighted discharge always gives the correct result (in terms of the given data), but it requires more work than the weighted curve number method especially when a watershed has many complex features (NEH-4, 2004).

In this section the weighted discharge method was performed, however, the first four steps of the procedure were exactly the same as for the weighted curve number method. Therefore only the rest of the procedure will be discussed here:

5. The original curve number map (Figure 32) was used as a starting point. However, because of the memory limitation of current computers, each subwatershed was simulated separately for the period of the study. In the first step, several curve number maps were produced and the number cells within

each subwatershed were adjusted based on the antecedent rainfall conditions and the seasonal factor (Figure 33, Appendix A.24).

6. The curve number varies on a daily basis according to the 5-day antecedent rainfall and the seasonal factor (dormant season or growing season). This causes the infiltration rate to change correspondingly (Figure 34, Appendix A.24).

7. Weighted average infiltration was computed for each day and this value along with duration of the runoff storm and daily rainfall intensity were used to compute α values (Equation 56, Appendix A.25). These values were further used to separate overland flow from baseflow during each storm event (Appendix A.26).

Figure 33. Variation of curve number on a daily basis for watershed M.

Figure 33. Variation of curve number on a daily basis for watershed M (continued).

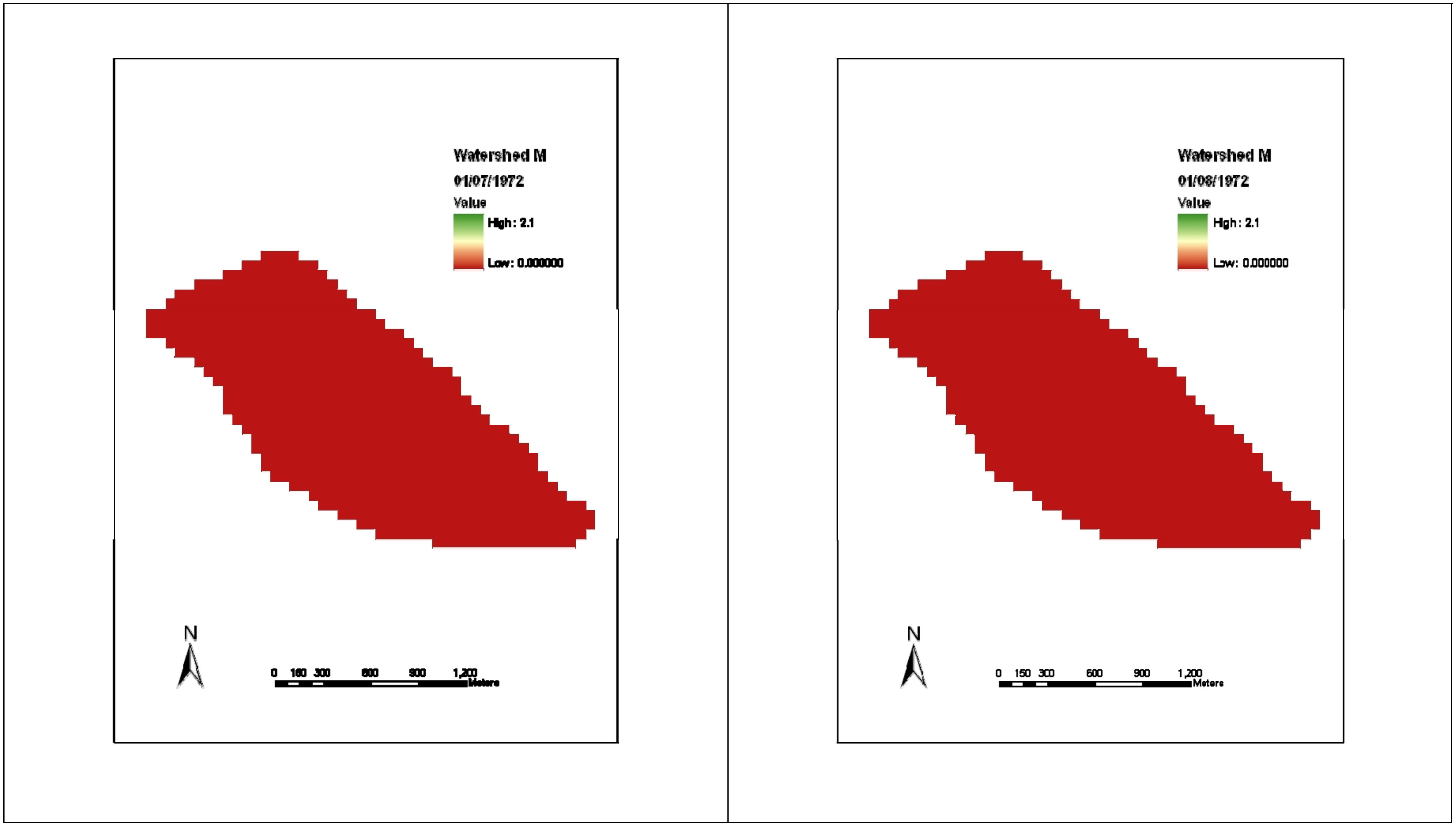


Figure 34. Total infiltration in cm on a daily basis for watershed M.

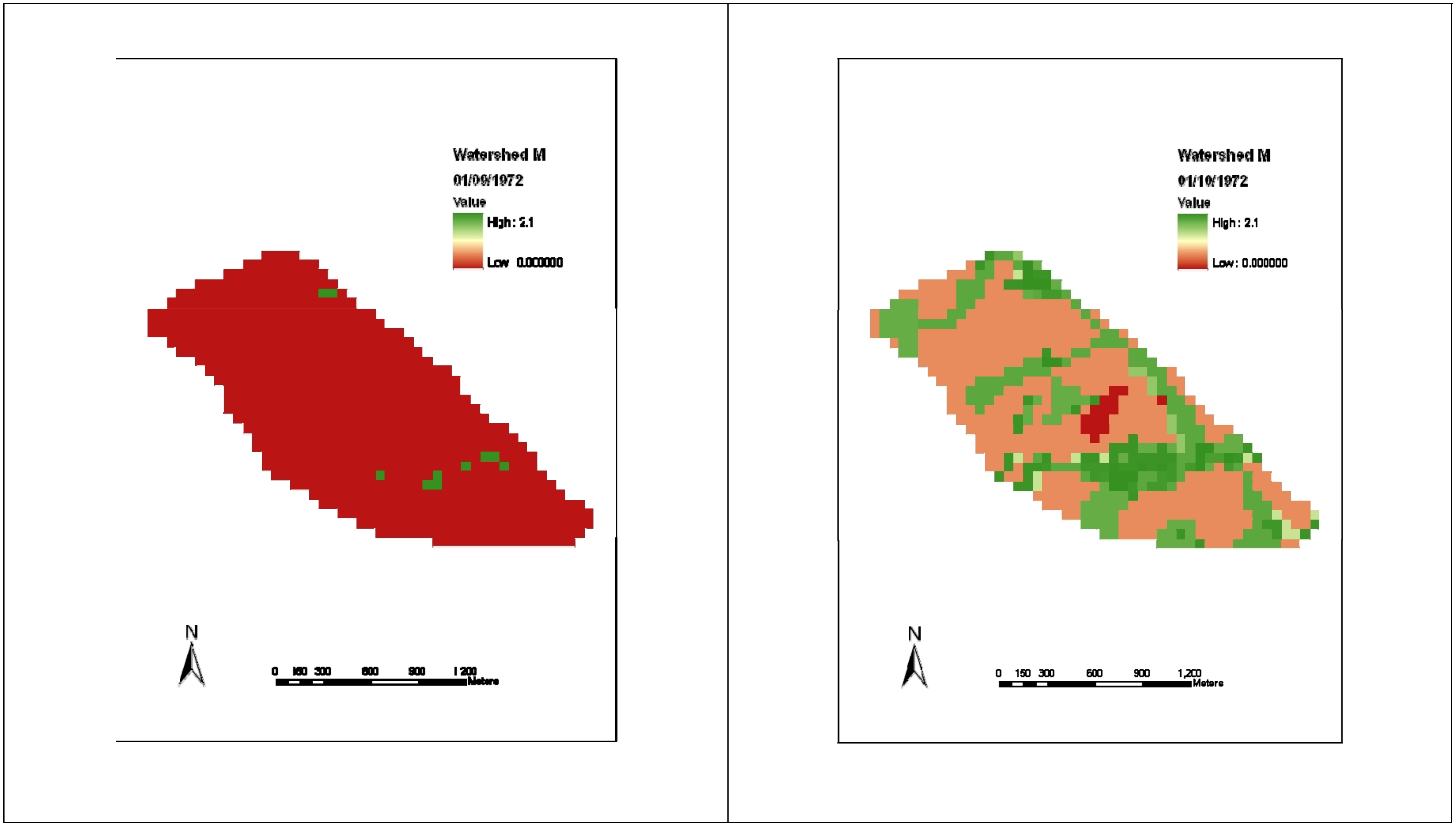


Figure 34. Total infiltration in cm on a daily basis for watershed M (continued)

4.5.4 Results and Discussion

Three scenarios (modified Boughton's method, weighted average curve number method, and weighted discharge method) for streamflow separation were implemented using measured total flow data from eight subwatersheds (B, F, I, J, K, M, N, and O) within the Little River Watershed for the period of 1972 through 1981. All three scenarios were programmed using the 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 (Appendix A). The program developed based on the modified Boughton's method also automatically calibrates and calculates the fraction (α) values based on an estimated inflection point on the hydrograph, which marks the end of surface runoff. However, in two other programs (weighted average curve number method and weighted discharge method), α values were calculated based on physical and hydrologic characteristics of the watersheds.

The goal at this stage is to simulate and implement the previously developed models (for streamflow partitioning within a field scale watershed) to large scale watersheds. Results showed that the coefficients of determination (R^2) for the α values computed from the scenario I (modified Boughton's method) and two other scenarios (weighted average curve number method, and weighted discharge method) are very low (less than 6 percent). However, as expected, the coefficient of determination for the α values between weighted average curve number method and weighted discharge method are high and vary from 0.68 to 1. The lower range of R^2 was computed for complex watersheds in terms of land use, soil type and management practice, and the higher range of (R^2) is for less complex watersheds.

Therefore, the weighted average curve number method is not recommended for a watershed with a high level of complexity in land use and soil type. In this condition, the weighted average curve number method either under- or over-estimated the amount of infiltration (NEH-4, 2004).

Table 23. Summary of correlation between the α values computed for different scenarios

Watershed	Drainage Area (km^2)	Period of Study (year)	Number of Storm Events	R^2 α Scenario * I vs. II	R^2 **α** Scenario* I vs. III	R^2 **α** Scenario* II vs. III
B	334.3	10	362	0.0134	0.0272	0.8350
F	114.9	10	404	0.0280	0.0002	0.6813
I	49.9	10	415	0.0181	0.0015	0.6946
J	22.1	10	403	0.0344	0.0309	0.9988
K	16.7	10	480	0.0090	0.0083	0.9990
M	2.6	10	514	0.0525	0.0483	0.9990
N	15.7	10	485	0.0482	0.0432	0.9987
O	15.9	10	644	0.0201	0.0169	0.9987

* Scenario I: Modified Boughton's method
Scenario II: Weighted average curve number method
Scenario III: Weighted discharge method

In addition to the above test, another set of coefficients of determination values was computed between estimated baseflow values for the three scenarios (Table 24). The overall evaluation showed that on the average, the coefficient of determination between Scenarios II and III are higher than the coefficients of determination between Scenarios I and II and Scenarios I and III. Comparison of R^2 between Tables 23 and 24 also showed that a very high or very low correlation between computed ***α*** values are not linearly reflected in R^2 between computed baseflow discharge values. For example, for subwatershed B, the coefficient of determination for estimated ***α*** values between Scenarios I and II is about 1%, however, based on the results (Table 24) R^2 is 90%. This showed the importance of baseflow contribution to average annual water yield and also the importance of accurate hydrograph separation in the context of low-flow conditions, which are becoming an increasing concern given the potential for climate change and greater climate variability.

Table 24. Summary of correlation between baseflow discharge values computed through different scenarios for the period of 1972-1981.

Watershed	B	F	I	J	K	M	N	O
R^2 Baseflow Scenario * I vs. II	0.8957	0.8446	0.8578	0.8278	0.7625	0.8741	0.7620	0.7582
R^2 Baseflow Scenario I vs. III	0.8313	0.6806	0.6802	0.7531	0.6713	0.7903	0.7025	0.7116
R^2 Baseflow Scenario II vs. III	0.9443	0.8224	0.8735	0.9405	0.9226	0.9303	0.9437	0.9599

* Scenario I: Modified Boughton's method
Scenario II: Weighted average curve number method
Scenario III: Weighted discharge method

The next series of tests were performed to determine if there is a significant difference between daily average baseflow values within these three scenarios. In this regard, eight series of ANOVA tests were conducted (Table 25). The results showed that average daily values of computed baseflow in each scenario are significantly different at a 5% level of significance from the other scenarios. One potential drawback to the ANOVA test is that the test does not specify which pair or pairs of means are unequal. To test this, a post-hoc comparison method (Tukey Test) was performed to find out where the differences are or which groups are significantly different from each other and which are not. Results showed that for all three scenarios, estimated daily baseflow values are significantly different for all pairs of scenarios. Unfortunately, because separately measured surface and subsurface flow data are not available for the Little River Watershed and its subwatersheds, no conclusion can be drawn about accuracy of the methods' outputs.

Regarding the scaling issue and extrapolating the results from a field scale watershed (station Z) to the large scale watershed (Little River Watershed), for the Scenario I, no strategy was considered. Therefore, it can be expected that the results of the model will be distorted (Shirmohammadi, et al., 2005). However, in the case of Scenarios II and III, similar area was considered for the cell size as the experimental field (station Z). By implementing this strategy, low level of distortion can be expected on results obtained from Scenarios II and III than the Scenario I. Another concern about the scaling issue can be drawn from the fact that the original methods, which were used on all three scenarios, were developed under the assumption that the time of concentration for the study area is one day. In the case that the time of concentration for a study area is more than a day, distortion should be expected in the model outputs. However, by considering all of these limitations, it is reasonable to assume that the application of these models to large-scale watersheds with proper input data may provide reasonable estimate of surface and subsurface flow components.

4.5.5 Conclusion

At this stage of study, the developed methods under sections 4.2 and 4.3 were implemented for the large scale watershed (Little River Watershed). The implementation phase involved incorporating different physical and hydrologic characteristics of watersheds. In this regard, three scenarios were considered; a) Scenario I: Empirical Based Model – Modified Boughton's Method, Scenario II: Physical Based Model – Weighted Average Curve Number Method, and Scenario III: Physical Based Model – Weighted Discharge Method.

Table 25. Summary of ANOVA test for all three scenarios

Watershed	Scenarios I, II, and III are significantly different at 5% level of significance
B	Yes $F_{computed} > F_{critical}$ 3.810 > 2.997 p-level =0.022
F	Yes $F_{computed} > F_{critical}$ 8.029 > 2.997 p-level =0.000328
I	Yes $F_{computed} > F_{critical}$ 8.496 > 2.997 p-level =0.000206
J	Yes $F_{computed} > F_{critical}$ 5.647 > 2.997 p-level =0.003542
K	Yes $F_{computed} > F_{critical}$ 7.346 > 2.997 p-level =0.00065
M	Yes $F_{computed} > F_{critical}$ 6.973 > 2.997 p-level =0.000943
N	Yes $F_{computed} > F_{critical}$ 7.400 > 2.997 p-level =0.000615
O	Yes $F_{computed} > F_{critical}$ 5.054 > 2.997 p-level =0.006401

In addition, different georeferenced data sets were used such as digital elevation model, soil type, land use, river network, and ground network precipitation records as models' input values.

The Scenario I only uses daily streamflow values as input data. This scenario is among the methods that proved to have the highest accuracy in predicting baseflow values within a field scale watershed (Nejadhashemi et al., 2005). However, scaling is a major concern and may distort the accuracy of this method when it is used in large scale watersheds.

The Scenario II is a physical based model. However, this method estimates physical and hydrologic characteristics of watersheds in a simplified form (the weighted average curve number method).

The Scenario III has the same structure as the Scenario II in regard to the governing model equation. However, in this scenario, more refinement and detailed strategy were employed for the model implementation. Therefore, it is reasonable to assume that the results obtained using Scenario III should provide more accurate prediction in terms of baseflow estimation. In addition, in order to minimize the scaling distortion factor in the α value estimation, the cell size within the GIS environment was selected in a way that it replicates the original size of the study area (station Z) in Scenarios II and III.

Originally, all of these methods were developed and calibrated for a watershed with a time of concentration of less than one day. Therefore, in order to prevent misuses of the models, its use is not recommended for watersheds with times of concentration longer than a day. However, these models still can be used if one splits a large watershed into small subwatersheds with shorter times of concentration and perform the separation techniques for each subwatershed.

Statistical analysis of the eighty years worth of data (eight subwatersheds were tested for 10 years) showed that these scenarios are significantly different at a 5% level of significance when compared of daily average estimated baseflow values. However, because of the lack of separately measured surface and subsurface flow data the results are inconclusive in terms of which scenarios can simulate the real world conditions better.

Tables B.1 through B.24 (Appendix B) show monthly and annual averages of the α values obtained from the Scenarios I, II, and III along with annual standard deviation for the period of the study. For a better comparison of these results, Figures 35 through 37 were constructed. Interestingly, for all three scenarios, even though average α values are different for each subwatershed during the period of the study, they all seem to follow the same trend. This phenomenon can explain the importance of considering the physical and hydrologic characteristics of a watershed in predicting α values. Therefore, it can be expected that another relationship may be derived to relate the results of small watershed observation to a large scale watershed if they can be classified to be within a similar physiographic region. Figure 38 shows that annual average α values obtained for the three scenarios are very similar in their trends. In addition, the annual average for Scenarios II and III are almost identical. However, the α value for Scenario I, is always less than Scenarios II and III with an average difference of about 0.24. This is because physical and hydrologic characteristics of watersheds play an important role in computation of α values using equation 55.

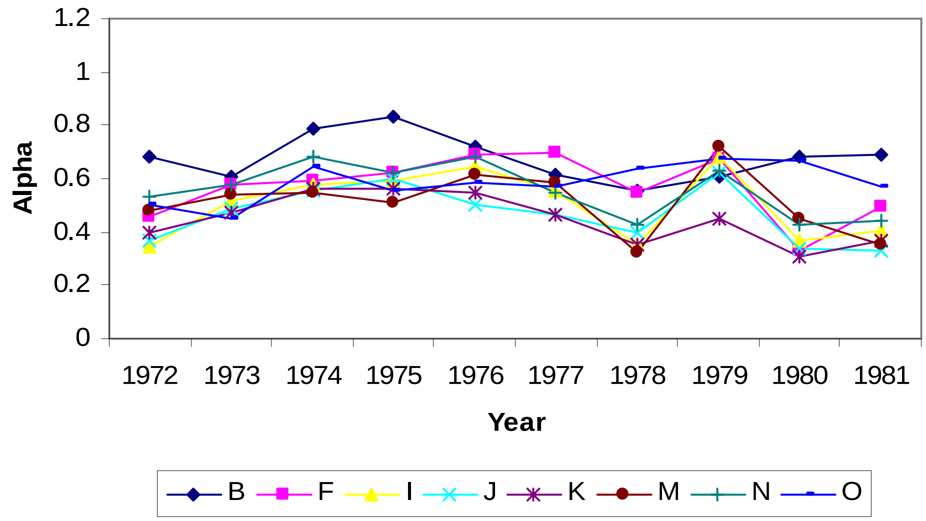


Figure 35. α value variation calculated from Scenario I for subwatersheds B through O (1972-1981).

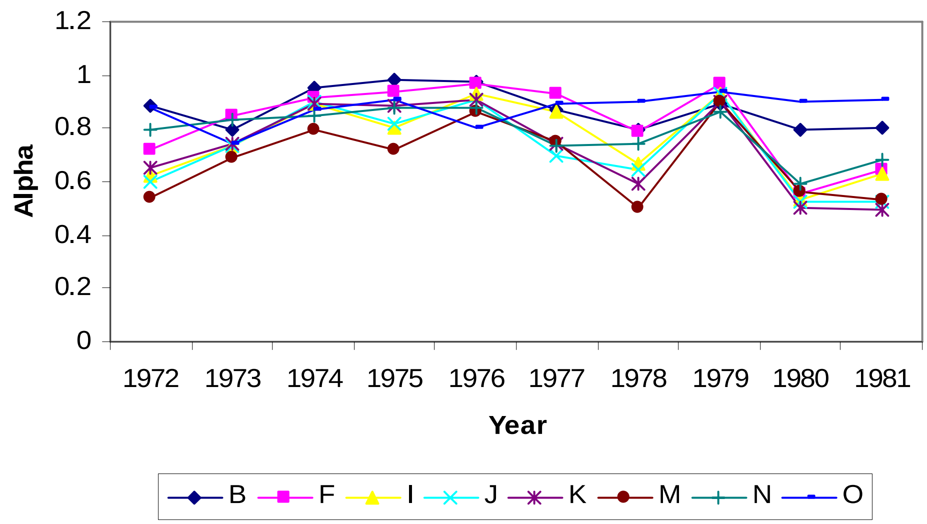


Figure 36. α value variation calculated from Scenario II for subwatersheds B through O (1972-1981).

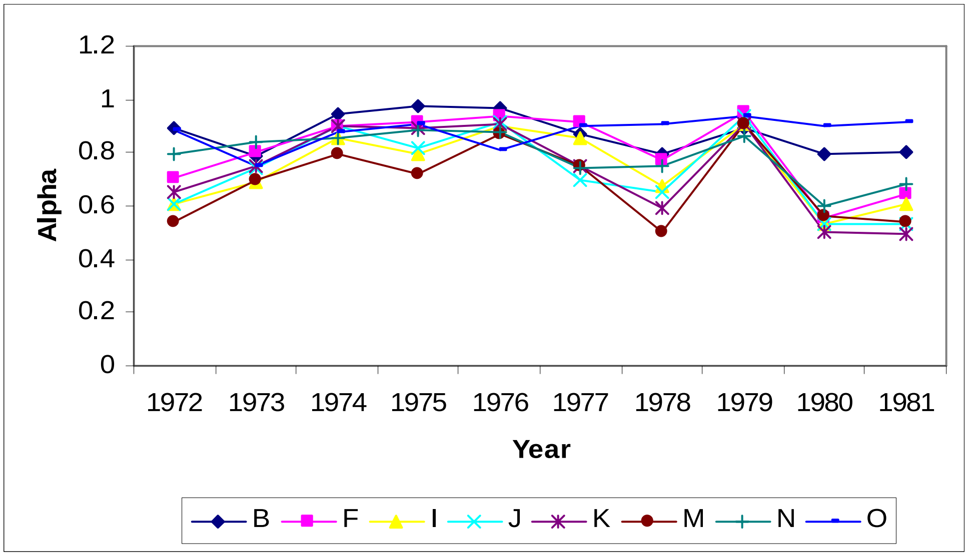


Figure 37. ***α*** value variation calculated from Scenario III for subwatersheds B through O (1972-1981).

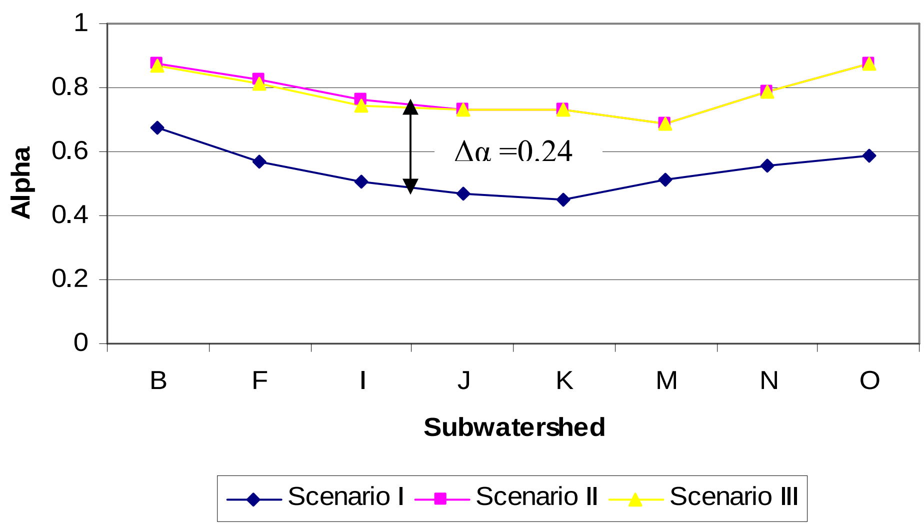


Figure 38. Annual average α value variation for subwatersheds B through O obtained from the Scenarios I, II and III for the period of 1972-1981

Chapter 5: SUMMARY AND CONCLUSION

The aim of this study is to separate the storm runoff hydrograph into its components, thus being able to infer about sources and hydrological pathways. While many hydrological model software packages are currently available, no model has been developed for examining watershed characteristics on hydrograph separation estimation. Therefore, developing and assessing the new hydrological model using physical and hydrologic characteristics of a mixed land use watershed is the ultimate goal of this research.

The large number of existing techniques and high level of subjectivity in separating baseflow from streamflow indicates that the problem is not fully understood. Forty different streamflow partitioning methods were reviewed, and classified into three-component, analytical, empirical, graphical, geochemical and automated methods. Their advantages and disadvantages were highlighted for appropriate use and avoiding of their misuses and five methods (a. Wittenberg and Sivapalan, 1999, Wittenberg; 1999: b. Nathan and T.A. McMahon; 1990. Mugo and Sharma; 1999, and Eckhardt; 2005, c. Boughton's constant coefficient; 1988, d. Boughton's fraction coefficient; 1988, and e. Sloto and Crouse, 1996) were identified as being the most relevant and least input intensive.

The performance of these methods were tested against twelve years (1970-1981) 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 method with fraction coefficient (α) performed the best. However, its accuracy depends upon the proper estimation of the "fraction" coefficient that is based on many physical and hydrologic characteristics of a watershed.

The next 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 Boughton's method of daily baseflow 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 baseflow with a coefficient of determination (R^2) of up to 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.

Incorporating both physical and hydrologic characteristics of a watershed in hydrograph separation estimation and evaluation were the next step in this study. Among numerous factors, which may affect the ratio of hydrograph components to the total runoff, fifteen parameters were selected. A multivariate linear regression equation was developed to relate these parameters to the fraction value (Boughton, 1988). In the next stage, a forward stepwise regression method along with systematic elimination of variables was performed to identify the more sensitive parameters in calculation of the ***α*** fraction values. Two sets of regression equation were calibrated and validated against eight years of collected data for the field scale watershed, station Z, in Tifton, Georgia. Next, three statistical criteria including the coefficient of determination, Nash-Sutcliff coefficient of efficiency, and the ratio of standard error of estimation to standard deviation were employed to test the accuracy and performance of both case scenarios. The results of this section showed that a higher statistical score was obtained for the first case scenario, while both methods can be classified as good performance models.

The next step involves deploying this method within the GIS environment in order to assess the spatial contribution of surface and subsurface flow in total flow hydrographs. In this stage of study, the developed method under section 4.3.2 and 4.2.1.2.1 were implemented for the eight subwatersheds within the Little River Watershed. Three scenarios were considered under the implementation phase. Scenario I (Modified Boughton), Scenario II (Weighted Average Curve Number), and Scenario III (Weighted Discharge Method). Scenario I is a pure empirical method which operates on a daily base streamflow measurement. This model performed well for an experimental field scale watershed extrapolating the small-scale analysis to a large scale can distort the model results, especially because the model is empirically based. Scenario II uses the weighted average curve number for predicting the fraction coefficient (α) values. As indicated in National Engineering Handbook: Section 4 – Hydrology (NEH-4), a single watershed weighted average curve number does not produce accurate estimates of runoff for complex watersheds. Therefore, it is expected that the results of this method will be distorted when the level of complexity in land use, soil type and management practices are high. However, scaling effects were minimized for Scenarios II and III by selecting similar cell size in the GIS for computation of (α) values. Finally Scenario III uses the weighted discharge method. This method was recommended by the National Engineering Handbook (NEH-4, 2004) as the most accurate method among different approaches in estimating discharge from the NRCS curve number method. In addition, as mentioned earlier, negative scaling effects were minimized in this method as well (the cell size within the GIS environment was selected in a way that it replicates the original size of the study area). Therefore, it is expected that this model may provide a reasonable estimate of surface and subsurface flow components if proper input data are provided.

In terms of predicting the (α) value or hydrograph components estimation, results of this study showed that correlation between Scenario II and III are the highest. However, based on the results from ANOVA-Tukey test, these three scenarios are significantly different at the 5% level of significance. In addition, the use of these methods is limited to watersheds having a time of concentration of less than one day.

Overall, this study demonstrated that incorporating the physical and hydrologic characteristics of watersheds can significantly improve the accuracy of hydrograph separation techniques.

5.1 Recommendations

1) Scenario I is suggested to be used in field scale watersheds because it does not handle mixed land use or soils conditions.

2) Scenario II is applicable to large watersheds because it uses variable hydrologic and physical data, thus accommodating the heterogeneity in the watershed due to mixed land use and soils conditions.

3) Scenario III is superior to the other two methods because it divides the watershed into small field scale pixels and treats each pixel separately, thus mimicking the field scale station Z conditions where the method was successfully applied.

5.2 Future Work

Natural phenomena can be explained and understood through appropriate models. These mathematical or physical systems are able to furnish an estimation of behavior in the form of deterministic or probabilistic schemes under certain conditions (Shirmohammadi et al., 2002). Hydrologic and nonpoint source pollution models have been used as assessment tools for decades. However, misuse or violation of models' limitations magnifies the amount of error/uncertainty in making an appropriate management decision. Therefore, in future studies, one or more hydrologic and nonpoint source pollution models should be selected for comparison and tested using techniques from this research for estimation of overland and/or subsurface flow and its effects on improvement of contaminant transport assessment.

In addition, the performance of the developed models can be examined with shorter time steps using hourly rainfall measurements. It can be expected that the current models developed in this study may not be good representative of real world conditions if used for time interval shorter than a day. Therefore, new series of equations should be developed to represent such conditions.

Appendix A

List of Computer Programs

(A.1) Iterative least squares method to calibrate both parameters *a* and *b* for Wittenberg and Sivapalan method.

Input: discharge in mm/day.

Output: *a* and *b* for Wittenberg and Sivapalan method. *a* is in mm^{1-b}/day^{b} and *b* is dimensionless.

```
Dim T(100), Q(100) As Double
Dim i As Integer
Dim er As Double
Private Sub Command1_Click()
cd2.ShowSave
yy = cd2.FileName
Open yy For Output As #2
For j = 0 To i
Write #2, Q(j)
Next j
Close 2
End Sub
Private Sub Computation_Click()
dt = 1 ' time increment, which define in day
Q(0) = T(0)
aa = 0
bb = 0
ww = 1E+300
For b = 0.001 To 1 Step 0.001
s = 0
m = 0
For k = 1 To i
s = s + (T(k - 1) + T(k))
m = m + ((T(k - 1) ^ b) - (T(k) ^ b))
Next k
a = (s * dt) / (2 * m)
For v = 1 To i
d = ((1 - b) * v / (a * b)) * Q(0) ^ (1 - b)
Q(v) = Q(0) * (1 + d) ^ (1 / (b - 1))
Next v
er = 0
For vv = 0 To i
er = er + (Q(vv) - T(vv)) ^ 2
Next vv
```

```
If er < ww Then
aa = a
bb = b
ww = er
End If
Next b
For vc = 1 To i
d = ((1 - bb) * vc / (aa * bb)) * Q(0) ^ (1 - bb)
Q(vc) = Q(0) * (1 + d) ^ (1 / (bb - 1))
Next vc
Text1.Text = aa
Text2.Text = bb
End Sub
Private Sub Open_Click()
CD1.ShowOpen
yy = CD1.FileName
i = -1
Open yy For Input As #1
Do Until (EOF(1) = True)
i = i + 1
Input #1, T(i)
Loop
Close 1
End Sub
```

(A.2) Wittenberg and Sivapalan method.

Input: average *a* value in mm^{1-b}/day^{b}, average *b* value which is dimensionless, total discharge in mm/day.

Output: surface discharge in mm/day, subsurface disharge in mm/day.

```
Dim aa, bb, d, n, w As Double
Dim i As Integer
Dim T(4800), b(4800), s(4800), ht(2000), hday(2000), st(2000), sday(2000),
Iday(2000) As Double
Private Sub Command2_Click()
b(i) = T(i)
b(0) = T(0)
h = -1
For k = 1 To i - 1
If T(k) > T(k - 1) And T(k) > T(k + 1) Then
h = h + 1
ht(h) = T(k)
hday(h) = k
End If
Next k
h1 = -1
For k1 = 1 To i - 1
If T(k1) <= T(k1 - 1) And T(k1) < T(k1 + 1) Then
h1 = h1 + 1
st(h1) = T(k1)
sday(h1) = k1
End If
Next k1
sh = h
sh1 = h1
n = 0
dt = 1
h2 = -1
sday(h1 + 1) = i
For kk = i - 1 To 1 Step -1
If kk > hday(h) And kk < sday(h1 + 1) Then
w = (T(kk + 1) - 2 * T(kk) + T(kk - 1)) / dt
If (w >= 0 And n >= 0) Or (w <= 0 And n <= 0) Then
GoTo 555
Else
h2 = h2 + 1
```

```
Iday(h2) = kk + 1
h1 = h1 - 1
h = h - 1
n = 0
If h = -1 Then
GoTo 45
End If
End If
555         n = w
End If
Next kk
45 ali = 0
jj = 0
For v = i To 1 Step -1
If sh = -1 Then
GoTo 100
End If
If v >= Iday(jj) And v < sday(sh1 + 1) Then
b(v) = T(v)
'GoTo 20
End If
If v > hday(sh) And v <= Iday(jj) Then
d = (T(v) ^ (bb - 1)) + (bb - 1) * (v - hday(sh)) / (aa * bb) 'b
b(v - 1) = (d) ^ (1 / (bb - 1))
If b(v - 1) > T(v - 1) Then
b(v - 1) = T(v - 1)
End If
'GoTo 20
End If
If v >= sday(sh1) And v <= hday(sh) Then
100         d = ((1 - bb) * 1 / (aa * bb)) * T(v - 1) ^ (1 - bb) 'b
b(v) = T(v - 1) * (1 + d) ^ (1 / (bb - 1)) 'b
If b(v) > T(v) Then
b(v) = T(v)
End If
' GoTo 20
 End If
If v = sday(sh1) Then
jj = jj + 1
sh = sh - 1
sh1 = sh1 - 1
End If
If sh1 = -1 Then
GoTo 50
End If
20 ali = 0
```

```
If b(v) > T(v) Then
b(v) = T(v)
End If
Next v
50 ali = 0
For kk = 0 To i
s(kk) = T(kk) - b(kk)
Next kk
End Sub
Private Sub Command3_Click()
cd2.ShowSave
yy = cd2.FileName
Open yy For Output As #2
For j = 0 To i
Write #2, s(j)
Next j
Close 2
End Sub
Private Sub Command4_Click()
cd3.ShowSave
yy = cd3.FileName
Open yy For Output As #3
For j = 0 To i
Write #3, b(j)
Next j
Close 3
End Sub
Private Sub Enter_Click()
aa = Text1.Text
bb = Text2.Text
End Sub
Private Sub Total_Click()
CD1.ShowOpen
yy = CD1.FileName
i = -1
Open yy For Input As #1
Do Until (EOF(1) = True)
i = i + 1
Input #1, T(i)
Loop
Close 1
End Sub
```

(A.3) Nathan & Mugo method

Part I: Estimation of average filter parameter for Nathan & Mugo method

Input: total flow and baseflow in mm/day

Output: average filter parameter for Nathan & Mugo method which is dimensionless.

```
Dim i, ll As Integer
Dim t(4800), b(4800), s(4800), alpha(4800) As Double
Private Sub Command1_Click()
CD1.ShowOpen
yy = CD1.FileName
i = -1
Open yy For Input As #1
Do Until (EOF(1) = True)
i = i + 1
Input #1, t(i)
Loop
Close 1
End Sub
Private Sub Command2_Click()
CD4.ShowOpen
yy = CD4.FileName
k = -1
Open yy For Input As #4
Do Until (EOF(4) = True)
k = k + 1
Input #4, b(k)
Loop
Close 4
End Sub
Private Sub Command3_Click()
Dim a1, a2, ww, q As Double
For h = 0 To i
s(h) = t(h) - b(h)
Next h
k = -1
For w = 1 To i
'If t(w) = 0 Or (2 * s(w - 1) + t(w) - t(w - 1)) Then
If t(w) = 0 Then
ali = 0
Else
a1 = 2 * s(w) - t(w) + t(w - 1)
```

```
a2 = 2 * s(w - 1) + t(w) - t(w - 1)
k = k + 1
alpha(k) = a1 / a2
End If
Next w
ww = 0
For ff = 0 To k
ww = ww + alpha(ff)
Next ff
q = ww / k
Text1.Text = q
ll = k
End Sub
Private Sub Command4_Click()
cd2.ShowSave
yy = cd2.FileName
Open yy For Output As #2
For j = 0 To ll
Write #2, alpha(j)
Next j
Close 2
End Sub
```

(A.3) Nathan & Mugo method

Part II: Estimation of baseflow and surface flow from Nathan & Mugo method

Input: total flow in mm/day, average filter parameter for Nathan & Mugo method which is dimensionless, surface flow in mm/day

Output: surface flow and baseflow in mm/day

```
Dim aa As Double
Dim t(4800), b(4800), s(4800) As Double
Dim i As Integer
Private Sub Command1_Click()
cd4.ShowOpen
yy = cd4.FileName
k = -1
Open yy For Input As #4
Do Until (EOF(4) = True)
k = k + 1
Input #4, s(k)
Loop
Close 4
End Sub
Private Sub Command2_Click()
For j = 1 To i
s(j) = aa * s(j - 1) + ((1 + aa) * 0.5) * (t(j) - t(j - 1))
If s(j) < 0 Then
s(j) = 0
End If
If s(j) > t(j) Then
s(j) = t(j)
End If
Next j
For j2 = i To 1 Step -1
s(j2 - 1) = (1 / aa) * (s(j2) - 0.5 * (1 + aa) * (t(j2) - t(j2 - 1)))
If s(j2 - 1) < 0 Then
s(j2 - 1) = 0
End If
If s(j2 - 1) > t(j2 - 1) Then
s(j2 - 1) = t(j2 - 1)
End If
Next j2
For j1 = 1 To i
```

```
s(j1) = aa * s(j1 - 1) + ((1 + aa) * 0.5) * (t(j1) - t(j1 - 1))
If s(j1) < 0 Then
s(j1) = 0
End If
If s(j1) > t(j1) Then
s(j1) = t(j1)
End If
Next j1
For jk = 0 To i
b(jk) = t(jk) - s(jk)
Next jk
End Sub
Private Sub Command3_Click()
cd2.ShowSave
yy = cd2.FileName
Open yy For Output As #2
For j = 0 To i
Write #2, s(j)
Next j
Close 2
End Sub
Private Sub Command4_Click()
cd3.ShowSave
yy = cd3.FileName
Open yy For Output As #3
For j = 0 To i
Write #3, b(j)
Next j
Close 3
End Sub
Private Sub Enter_Click()
aa = Text1.Text
End Sub
Private Sub Total_Click()
CD1.ShowOpen
yy = CD1.FileName
i = -1
Open yy For Input As #1
Do Until (EOF(1) = True)
i = i + 1
Input #1, t(i)
Loop
Close 1
End Sub
```

(A.4) Boughton constant based method

Input: constat alpha value which is dimensionless and total flow in mm/day

Output: baseflow in mm/day

```
Dim y, t(4800), s(4800), b(4800), tt, bb, ss As Double
Dim I As Integer
Private Sub Command1_Click()
y = Text1.Text
End Sub
Private Sub Command2_Click()
CD1.ShowOpen
yy = CD1.FileName
I = -1
Open yy For Input As #1
Do Until (EOF(1) = True)
I = I + 1
Input #1, t(I)
Loop
Close 1
End Sub
Private Sub Computation_Click()
b(0) = t(0)
s(0) = t(0) - b(0)
tt = t(0)
bb = b(0)
ss = s(0)
For j = 1 To I
If (t(j) > (b(j - 1) + y)) Then
b(j) = b(j - 1) + y
s(j) = t(j) - b(j)
tt = tt + t(j)
bb = bb + b(j)
ss = ss + s(j)
Else
b(j) = t(j)
s(j) = 0
tt = tt + t(j)
bb = bb + b(j)
ss = ss + s(j)
End If
Next j
Label7.Caption = ss
Label8.Caption = bb
```

```
End Sub
Private Sub Exit_Click()
Unload Me
End
End Sub
Private Sub Save_Base_Click()
CD3.ShowSave
yy = CD3.FileName
Open yy For Output As #3
For j = 0 To I
Write #3, b(j)
Next j
Close 3
End Sub
Private Sub Save_Surface_Click()
CD2.ShowSave
yy = CD2.FileName
Open yy For Output As #2
For j = 0 To I
Write #2, s(j)
Next j
Close 2
End Sub
```

(A.5) Boughton fraction based method

Part I:

Input: total flow in mm/day

Output: the alpha value from the Boughton fraction based method

---

```
' This section calculate the Fraction value, which is
' later import in Part II for separation.
Dim T(4800), b(4800), s(4800) As Double
Dim f, h As Double
Dim i As Integer
Private Sub Command1_Click()
CD2.ShowSave
Y = CD2.FileName
Open Y For Append As #2
'For j = 0 To i
'Write #2, T(j), b(j), s(j)
'Next j
'Close 2
End Sub
Private Sub Command2_Click()
f = Text1.Text
End Sub
Private Sub Exit_Click()
Unload Me
End
End Sub
Private Sub OpenFile_Click()
CD1.ShowOpen
Y = CD1.FileName
i = -1
Open Y For Input As #1
Do Until (EOF(1) = True)
i = i + 1
Input #1, T(i)
Loop
Close 1
End Sub
Private Sub Result_Click()
b(0) = T(0)
s(0) = 0
For j = 1 To i
If T(j) > b(j - 1) Then
```

```
b(j) = (T(j) - b(j - 1)) * f + b(j - 1)
s(j) = T(j) - b(j)
Else
b(j) = T(j)
s(j) = 0
End If
Next j
End Sub
Private Sub Save_Base_Click()
CD3.ShowSave
yy = CD3.FileName
Open yy For Output As #3
For j = 0 To i
Write #3, b(j)
Next j
Close 3
End Sub
Private Sub Save_Surface_Click()
CD2.ShowSave
yy = CD2.FileName
Open yy For Output As #2
For j = 0 To i
Write #2, s(j)
Next j
Close 2
End Sub
```

(A.5) Boughton fraction based method

Part II:

Input: total flow in mm/day and the alpha value from the Boughton fraction based method

Output: baseflow in mm/day

```
Dim t(4800), b(4800), s(4800) As Double
Dim f, h As Double
Dim i As Integer
Private Sub Computation_Click()
b(0) = t(0)
s(0) = 0
f = 0
Do
f = f + 0.001
For j = 1 To i
If t(j) > b(j - 1) Then
b(j) = (t(j) - b(j - 1)) * f + b(j - 1)
s(j) = t(j) - b(j)
Else
b(j) = t(j)
s(j) = 0
End If
Next j
h = t(i) - b(i)
Write #2, f, h, t(i), b(i)
Loop Until Abs(h) < 0.1
End Sub
Private Sub Exit_Click()
Unload Me
End
End Sub
Private Sub Open_Click()
CD1.ShowOpen
yy = CD1.FileName
i = -1
Open yy For Input As #1
Do Until (EOF(1) = True)
i = i + 1
Input #1, t(i)
Loop
```

```
Close 1
End Sub
Private Sub Save_Click()
CD2.ShowSave
Y = CD2.FileName
Open Y For Append As #2
End Sub
```

(A.6) Smoothed Minima Technique

Input: total flow in mm/day

Output: baseflow and overland flow in mm/day

```
Dim t(4800), g(4800), bb(4800), b(4800), s(4800) As Double
Dim bday(4800), day(4800) As Double
Dim i, kk As Integer
Dim c As Double
Private Sub Command1_Click()
For n = 0 To kk
Label2.Caption = "pp"
Next n
End Sub
Private Sub c1_Click()
CD2.ShowSave
yy = CD2.FileName
Open yy For Output As #2
For j = 0 To i
Write #2, s(j)
Next j
Close 2
End Sub
Private Sub C2_Click()
CD3.ShowSave
yy = CD3.FileName
Open yy For Output As #3
For j = 0 To i
Write #3, b(j)
Next j
Close 3
End Sub
Private Sub Computation_Click()
g(0) = t(0)
day(0) = 0
kk = 0
For w = 0 To i Step 5
kk = kk + 1
If t(w) <= t(w + 1) And t(w) <= t(w + 2) And t(w) <= t(w + 3) And t(w) <= t(w + 4)
Then
g(kk) = t(w)
day(kk) = w
End If
```

```
If t(w + 1) <= t(w) And t(w + 1) <= t(w + 2) And t(w + 1) <= t(w + 3) And t(w + 1)
<= t(w + 4) Then
g(kk) = t(w + 1)
day(kk) = w + 1
End If
If t(w + 2) <= t(w) And t(w + 2) <= t(w + 1) And t(w + 2) <= t(w + 3) And t(w + 2)
<= t(w + 4) Then
g(kk) = t(w + 2)
day(kk) = w + 2
End If
If t(w + 3) <= t(w) And t(w + 3) <= t(w + 2) And t(w + 3) <= t(w + 1) And t(w + 3)
<= t(w + 4) Then
g(kk) = t(w + 3)
day(kk) = w + 3
End If
If t(w + 4) <= t(w) And t(w + 4) <= t(w + 2) And t(w + 4) <= t(w + 3) And t(w + 4)
<= t(w + 1) Then
g(kk) = t(w + 4)
day(kk) = w + 4
End If
Next w
kk = kk + 1
g(kk) = t(i)
day(kk) = i
jj = 0
bb(0) = t(0)
bday(0) = 0
For hh = 1 To kk - 1
If (1.1 * g(hh)) < g(hh + 1) And (1.1 * g(hh)) < g(hh - 1) Then
jj = jj + 1
bday(jj) = day(hh)
bb(jj) = g(hh)
End If
Next hh
If bday(jj) = i Then
ali = 0
Else
jj = jj + 1
bb(jj) = t(i)
bday(jj) = i
End If
'Label2.Caption = bday(2)
b(0) = t(0)
For gh = 1 To jj - 1
c = (bb(gh) - bb(gh - 1)) / (bday(gh) - bday(gh - 1))
For dos = bday(gh - 1) To bday(gh) - 1
```

```
b(dos + 1) = b(dos) + c
Next dos
Next gh
c = (t(i) - bb(jj - 1)) / (i - bday(jj - 1))
For dos1 = bday(jj - 1) To i
b(dos1 + 1) = b(dos1) + c

Next dos1
For ss = 0 To i
If b(ss) > t(ss) Then
b(ss) = t(ss)
s(ss) = 0
Else
s(ss) = t(ss) - b(ss)
End If
Next ss
End Sub
Private Sub Open_Click()
CD1.ShowOpen
yy = CD1.FileName
i = -1
Open yy For Input As #1
Do Until (EOF(1) = True)
i = i + 1
Input #1, t(i)
Loop
Close 1
End Sub
```

(A.7) Computing end of surface runoff

Input: date, total flow in mm/day, measured baseflow in mm/day

Output: date associated with end of surface runoff both based on measured values and calculated from second derivative of discharge function

---

```
'd means date and tf means total flow
'srun means start of runoff value an sday means start day of runoff
'maxrun means max runoff and maxday means day regarding max runoff
' Fd means second derivative
'erun mean end of surface runoff and eday means the day that surface runoff end
'hydno means the day storm event started, alpha means alpha value for that event
' base means baseflow
'endbase means end day of surface runoff based on observed data
Dim d(10000), tf(10000), fd(10000) As Double
Dim srun(10000), sday(10000) As Double
Dim erun(10000), eday(10000) As Double
Dim base(10000), hydno(15000), alpha(15000) As Double
Dim maxrun(10000), maxday(10000) As Double
Dim endbase(10000) As Double
Dim i, k, kk, kkk, zz As Long
Private Sub CD1_Click()
CC1.ShowOpen
yy = CC1.FileName
i = 0
Open yy For Input As #1
Do Until (EOF(1) = True)
i = i + 1
Input #1, d(i), tf(i), base(i)
Loop
Close 1
End Sub
Private Sub CD2_Click()
k = 0
For k1 = 2 To i - 1
If (tf(k1) <= tf(k1 - 1)) And (tf(k1) < tf(k1 + 1)) Then
k = k + 1
srun(k) = tf(k1)
sday(k) = k1
End If
Next k1
kk = 0
For k1 = 2 To i - 1
```

```
If (tf(k1) > tf(k1 - 1)) And (tf(k1) > tf(k1 + 1)) Then
kk = kk + 1
maxrun(kk) = tf(k1)
maxday(kk) = k1
End If
Next k1
dt = 1
fd(1) = 0
fd(i) = 0
For k1 = 2 To i - 1
fd(k1) = (tf(k1 - 1) - 2 * tf(k1) + tf(k1 + 1)) / dt ^ 2
Next k1
ww = 1
kkk = 0
For k1 = 1 To i - 1
If (fd(k1) < 0) And (fd(k1 + 1) > 0) Then
If k1 >= maxday(ww) And k1 <= sday(ww + 1) Then
ww = ww + 1
kkk = kkk + 1
erun(kkk) = tf(k1 + 1)
eday(kkk) = k1 + 1
If ww + 1 > k Then GoTo 10
End If
End If
10    If k1 > maxday(kk) Then
kkk = kkk + 1
erun(kkk) = tf(k1)
eday(kkk) = k1
GoTo 45
End If
Next k1
45 hh = 0
zz = 0
For k1 = 3 To i
If (base(k1) = tf(k1)) And (base(k1 - 1) <> tf(k1 - 1)) Then
zz = zz + 1
endbase(zz) = k1
End If
Next k1
End Sub
Private Sub CD3_Click()
CC2.ShowSave
yy = CC2.FileName
Open yy For Output As #2
For j = 1 To kkk
Print #2, eday(j), base(j), endbase(j), tf(j)
```

```
Next j
Close 2
End Sub
Private Sub Command1_Click()
Unload Final
End
End Sub
'Private Sub Command2_Click()
'CC3.ShowSave
'yy = CC3.FileName
'Open yy For Output As #3
'For j = 1 To i
'Print #3, base(j)
'Next j
'Close 3
'End Sub
```

(A.8) Boughton – backward difference method

Input: date and total flow in mm/day

Output: alpha value (dimensionless) and baseflow in mm/day

```
'd means date and tf means total flow
'srun means start of runoff value an sday means start day of runoff
'maxrun means max runoff and maxday means day regarding max runoff
' Fd means second derivative
'erun mean end of surface runoff and eday means the day that surface runoff end
'hydno means the day storm event started, alpha means alpha value for that event
' base means baseflow
Dim d(10000), tf(10000), fd(10000) As Double
Dim srun(10000), sday(10000) As Double
Dim erun(10000), eday(10000) As Double
Dim base(10000), hydno(15000), alpha(15000) As Double
Dim maxrun(10000), maxday(10000) As Double
Dim i, k, kk, kkk As Long
Private Sub CD1_Click()
CC1.ShowOpen
yy = CC1.FileName
i = 0
Open yy For Input As #1
Do Until (EOF(1) = True)
i = i + 1
Input #1, d(i), tf(i)
Loop
Close 1
End Sub
Private Sub CD2_Click()
k = 0
For k1 = 2 To i - 1
If (tf(k1) <= tf(k1 - 1)) And (tf(k1) < tf(k1 + 1)) Then
k = k + 1
srun(k) = tf(k1)
sday(k) = k1
End If
Next k1
kk = 0
For k1 = 2 To i - 1
If (tf(k1) > tf(k1 - 1)) And (tf(k1) > tf(k1 + 1)) Then
kk = kk + 1
maxrun(kk) = tf(k1)
maxday(kk) = k1
```

```
End If
Next k1
dt = 1
fd(1) = 0
fd(i) = 0
For k1 = 2 To i - 1
fd(k1) = (tf(k1 - 1) - 2 * tf(k1) + tf(k1 + 1)) / dt ^ 2
Next k1
ww = 1
kkk = 0
For k1 = 1 To i - 1
If (fd(k1) < 0) And (fd(k1 + 1) > 0) Then
If k1 >= maxday(ww) And k1 <= sday(ww + 1) Then
ww = ww + 1
kkk = kkk + 1
erun(kkk) = tf(k1 + 1)
eday(kkk) = k1 + 1
If ww + 1 > k Then GoTo 10
End If
End If
10    If k1 > maxday(kk) Then
kkk = kkk + 1
erun(kkk) = tf(k1)
eday(kkk) = k1
GoTo 45
End If
Next k1
45 hh = 0
For k3 = 1 To i
For k1 = 2 To k
For k2 = 1 To kkk
If sday(k1 - 1) < eday(k2) And sday(k1) > eday(k2) Then
If k3 >= eday(k2) And k3 <= sday(k1) Then
base(k3) = tf(k3)
End If
End If
If k3 <= sday(1) Or k3 >= eday(kkk) Then
base(k3) = tf(k3)
End If
Next k2
Next k1
Next k3
For k2 = 1 To k
mm = 1E+100
For k3 = 0 To 1 Step 0.001
For k1 = 1 To i
```

```
If k1 > sday(k2) And k1 <= eday(k2) Then
base(k1) = base(k1 - 1) + k3 * (tf(k1 - 1) - base(k1 - 1))
If k1 = eday(k2) Then
delta = Abs(tf(k1) - base(k1))
If delta < mm Then
mm = delta
alpha(k2) = k3
hydno(k2) = sday(k2)
End If
End If
End If
Next k1
Next k3
Next k2
For k1 = 1 To i
For k2 = 1 To k
If k1 > sday(k2) And k1 <= eday(k2) Then
base(k1) = base(k1 - 1) + alpha(k2) * (tf(k1 - 1) - base(k1 - 1))
End If
Next k2
Next k1
For k3 = 1 To i
For k1 = 1 To k
For k2 = 1 To kkk
If k3 = eday(k2) Then
base(k3) = tf(k3)
End If
If k3 = sday(k2) Then
base(k3) = tf(k3)
End If
If base(k3) > tf(k3) Then
base(k3) = tf(k3)
End If
Next k2
Next k1
Next k3
End Sub
Private Sub CD3_Click()
CC2.ShowSave
yy = CC2.FileName
Open yy For Output As #2
For j = 1 To k
Print #2, alpha(j), hydno(j), eday(j)
Next j
Close 2
End Sub
```

```
Private Sub Command1_Click()
Unload Final
End
End Sub

Private Sub Command2_Click()
CC3.ShowSave
yy = CC3.FileName
Open yy For Output As #3
For j = 1 To i
Print #3, j, base(j)
Next j
Close 3
End Sub
```

(A.9) Boughton – central difference method

Input: date and total flow in mm/day

Output: alpha value (dimensionless) and baseflow in mm/day

```
'd means date and tf means total flow
'srun means start of runoff value an sday means start day of runoff
'maxrun means max runoff and maxday means day regarding max runoff
' Fd means second derivative
'erun mean end of surface runoff and eday means the day that surface runoff end
'hydno means the day storm event started, alpha means alpha value for that event
' base means baseflow
Dim d(10000), tf(10000), fd(10000) As Double
Dim srun(10000), sday(10000) As Double
Dim erun(10000), eday(10000) As Double
Dim base(10000), hydno(15000), alpha(15000) As Double
Dim maxrun(10000), maxday(10000) As Double
Dim i, k, kk, kkk As Long
Private Sub CD1_Click()
CC1.ShowOpen
yy = CC1.FileName
i = 0
Open yy For Input As #1
Do Until (EOF(1) = True)
i = i + 1
Input #1, d(i), tf(i)
Loop
Close 1
End Sub
Private Sub CD2_Click()
k = 0
For k1 = 2 To i - 1
If (tf(k1) <= tf(k1 - 1)) And (tf(k1) < tf(k1 + 1)) Then
k = k + 1
srun(k) = tf(k1)
sday(k) = k1
End If
Next k1
kk = 0
For k1 = 2 To i - 1
If (tf(k1) > tf(k1 - 1)) And (tf(k1) > tf(k1 + 1)) Then
kk = kk + 1
maxrun(kk) = tf(k1)
maxday(kk) = k1
```

```
End If
Next k1
dt = 1
fd(1) = 0
fd(i) = 0
For k1 = 2 To i - 1
fd(k1) = (tf(k1 - 1) - 2 * tf(k1) + tf(k1 + 1)) / dt ^ 2
Next k1
ww = 1
kkk = 0
For k1 = 1 To i - 1
If (fd(k1) < 0) And (fd(k1 + 1) > 0) Then
If k1 >= maxday(ww) And k1 <= sday(ww + 1) Then
ww = ww + 1
kkk = kkk + 1
erun(kkk) = tf(k1 + 1)
eday(kkk) = k1 + 1
If ww + 1 > k Then GoTo 10
End If
End If
10    If k1 > maxday(kk) Then
kkk = kkk + 1
erun(kkk) = tf(k1)
eday(kkk) = k1
GoTo 45
End If
Next k1
45 hh = 0
For k3 = 1 To i
For k1 = 2 To k
For k2 = 1 To kkk
If sday(k1 - 1) < eday(k2) And sday(k1) > eday(k2) Then
If k3 >= eday(k2) And k3 <= sday(k1) Then
base(k3) = tf(k3)
End If
End If
If k3 <= sday(1) Or k3 >= eday(kkk) Then
base(k3) = tf(k3)
End If
Next k2
Next k1
Next k3
For k2 = 1 To k
mm = 1E+100
For k3 = 0 To 1 Step 0.001
For k1 = 1 To i
```

```
If k1 > sday(k2) And k1 <= eday(k2) Then
base(k1) = base(k1 - 1) + k3 * (0.5 * (tf(k1 - 1) + tf(k1)) - base(k1 - 1))
If k1 = eday(k2) Then
delta = Abs(tf(k1) - base(k1))
If delta < mm Then
mm = delta
alpha(k2) = k3
hydno(k2) = sday(k2)
End If
End If
End If
Next k1
Next k3
Next k2
For k1 = 1 To i
For k2 = 1 To k
If k1 > sday(k2) And k1 <= eday(k2) Then
base(k1) = base(k1 - 1) + alpha(k2) * (0.5 * (tf(k1 - 1) + tf(k1)) - base(k1 - 1))
End If
Next k2
Next k1
For k3 = 1 To i
For k1 = 1 To k
For k2 = 1 To kkk
If k3 = eday(k2) Then
base(k3) = tf(k3)
End If
If k3 = sday(k2) Then
base(k3) = tf(k3)
End If
If base(k3) > tf(k3) Then
base(k3) = tf(k3)
End If
Next k2
Next k1
Next k3
End Sub
Private Sub CD3_Click()
CC2.ShowSave
yy = CC2.FileName
Open yy For Output As #2
For j = 1 To k
Print #2, alpha(j), hydno(j), eday(j)
Next j
Close 2
End Sub
```

```
Private Sub Command1_Click()
Unload Final
End
End Sub
Private Sub Command2_Click()
CC3.ShowSave
yy = CC3.FileName
Open yy For Output As #3
For j = 1 To i
Print #3, j, base(j)
Next j
Close 3
End Sub
```

(A.10) Boughton – forward difference method

Input: date and total flow in mm/day

Output: alpha value (dimensionless) and baseflow in mm/day

```
'd means date and tf means total flow
'srun means start of runoff value an sday means start day of runoff
'maxrun means max runoff and maxday means day regarding max runoff
' Fd means second derivative
'erun mean end of surface runoff and eday means the day that surface runoff end
'hydno means the day storm event started, alpha means alpha value for that event
' base means baseflow
Dim d(10000), tf(10000), fd(10000) As Double
Dim srun(10000), sday(10000) As Double
Dim erun(10000), eday(10000) As Double
Dim base(10000), hydno(15000), alpha(15000) As Double
Dim maxrun(10000), maxday(10000) As Double
Dim i, k, kk, kkk As Long
Private Sub CD1_Click()
CC1.ShowOpen
yy = CC1.FileName
i = 0
Open yy For Input As #1
Do Until (EOF(1) = True)
i = i + 1
Input #1, d(i), tf(i)
Loop
Close 1
End Sub
Private Sub CD2_Click()
k = 0
For k1 = 2 To i - 1
If (tf(k1) <= tf(k1 - 1)) And (tf(k1) < tf(k1 + 1)) Then
k = k + 1
srun(k) = tf(k1)
sday(k) = k1
End If
Next k1
kk = 0
For k1 = 2 To i - 1
If (tf(k1) > tf(k1 - 1)) And (tf(k1) > tf(k1 + 1)) Then
kk = kk + 1
maxrun(kk) = tf(k1)
maxday(kk) = k1
```

```
End If
Next k1
dt = 1
fd(1) = 0
fd(i) = 0
For k1 = 2 To i - 1
fd(k1) = (tf(k1 - 1) - 2 * tf(k1) + tf(k1 + 1)) / dt ^ 2
Next k1
ww = 1
kkk = 0
For k1 = 1 To i - 1
If (fd(k1) < 0) And (fd(k1 + 1) > 0) Then
If k1 >= maxday(ww) And k1 <= sday(ww + 1) Then
ww = ww + 1
kkk = kkk + 1
erun(kkk) = tf(k1 + 1)
eday(kkk) = k1 + 1
If ww + 1 > k Then GoTo 10
End If
End If
10    If k1 > maxday(kk) Then
kkk = kkk + 1
erun(kkk) = tf(k1)
eday(kkk) = k1
GoTo 45
End If
Next k1
45 hh = 0
For k3 = 1 To i
For k1 = 2 To k
For k2 = 1 To kkk
If sday(k1 - 1) < eday(k2) And sday(k1) > eday(k2) Then
If k3 >= eday(k2) And k3 <= sday(k1) Then
base(k3) = tf(k3)
End If
End If
If k3 <= sday(1) Or k3 >= eday(kkk) Then
base(k3) = tf(k3)
End If
Next k2
Next k1
Next k3
For k2 = 1 To k
mm = 1E+100
For k3 = 0 To 1 Step 0.001
For k1 = 1 To i
```

```
If k1 > sday(k2) And k1 <= eday(k2) Then
base(k1) = base(k1 - 1) + k3 * (tf(k1) - base(k1 - 1))
If k1 = eday(k2) Then
delta = Abs(tf(k1) - base(k1))
If delta < mm Then
mm = delta
alpha(k2) = k3
hydno(k2) = sday(k2)
End If
End If
End If
Next k1
Next k3
Next k2
For k1 = 1 To i
For k2 = 1 To k
If k1 > sday(k2) And k1 <= eday(k2) Then
base(k1) = base(k1 - 1) + alpha(k2) * (tf(k1) - base(k1 - 1))
End If
Next k2
Next k1
For k3 = 1 To i
For k1 = 1 To k
For k2 = 1 To kkk
If k3 = eday(k2) Then
base(k3) = tf(k3)
End If
If k3 = sday(k2) Then
base(k3) = tf(k3)
End If
If base(k3) > tf(k3) Then
base(k3) = tf(k3)
End If
Next k2
Next k1
Next k3
End Sub
Private Sub CD3_Click()
CC2.ShowSave
yy = CC2.FileName
Open yy For Output As #2
For j = 1 To k
Print #2, alpha(j), hydno(j), eday(j)
Next j
Close 2
End Sub
```

```
Private Sub Command1_Click()
Unload Final
End
End Sub

Private Sub Command2_Click()
CC3.ShowSave
yy = CC3.FileName
Open yy For Output As #3
For j = 1 To i
Print #3, j, base(j)
Next j
Close 3
End Sub
```

(A.11) Boughton – backward difference – least squares method

Input: date and total flow in mm/day, observed baseflow in mm/day

Output: alpha value (dimensionless) and baseflow in mm/day

```
'd means date and tf means total flow
'srun means start of runoff value an sday means start day of runoff
'maxrun means max runoff and maxday means day regarding max runoff
' Fd means second derivative
'erun mean end of surface runoff and eday means the day that surface runoff end
'hydno means the day storm event started, alpha means alpha value for that event
' base means baseflow
' basereal means real baseflow data
Dim d(10000), tf(10000), fd(10000) As Double
Dim srun(10000), sday(10000) As Double
Dim erun(10000), eday(10000) As Double
Dim base(10000), hydno(15000), alpha(15000) As Double
Dim maxrun(10000), maxday(10000) As Double
Dim basereal(10000) As Double
Dim i, k, kk, kkk As Long
Private Sub CD1_Click()
CC1.ShowOpen
yy = CC1.FileName
i = 0
Open yy For Input As #1
Do Until (EOF(1) = True)
i = i + 1
Input #1, d(i), tf(i), basereal(i)
Loop
Close 1
End Sub
Private Sub CD2_Click()
k = 0
For k1 = 2 To i - 1
If (tf(k1) <= tf(k1 - 1)) And (tf(k1) < tf(k1 + 1)) Then
k = k + 1
srun(k) = tf(k1)
sday(k) = k1
End If
Next k1
kk = 0
For k1 = 2 To i - 1
If (tf(k1) > tf(k1 - 1)) And (tf(k1) > tf(k1 + 1)) Then
kk = kk + 1
```

```
maxrun(kk) = tf(k1)
maxday(kk) = k1
End If
Next k1
dt = 1
fd(1) = 0
fd(i) = 0
For k1 = 2 To i - 1
fd(k1) = (tf(k1 - 1) - 2 * tf(k1) + tf(k1 + 1)) / dt ^ 2
Next k1
ww = 1
kkk = 0
For k1 = 1 To i - 1
If (fd(k1) < 0) And (fd(k1 + 1) > 0) Then
If k1 >= maxday(ww) And k1 <= sday(ww + 1) Then
ww = ww + 1
kkk = kkk + 1
erun(kkk) = tf(k1 + 1)
eday(kkk) = k1 + 1
If ww + 1 > k Then GoTo 10
End If
End If
10    If k1 > maxday(kk) Then
kkk = kkk + 1
erun(kkk) = tf(k1)
eday(kkk) = k1
GoTo 45
End If
Next k1
45 hh = 0
For k3 = 1 To i
For k1 = 2 To k
For k2 = 1 To kkk
If sday(k1 - 1) < eday(k2) And sday(k1) > eday(k2) Then
If k3 >= eday(k2) And k3 <= sday(k1) Then
base(k3) = tf(k3)
End If
End If
If k3 <= sday(1) Or k3 >= eday(kkk) Then
base(k3) = tf(k3)
End If
Next k2
Next k1
Next k3
For k2 = 1 To k
mm = 1E+100
```

```
For k3 = 0 To 1 Step 0.001
zz = 0
For k1 = 1 To i
If k1 > sday(k2) And k1 <= eday(k2) Then
base(k1) = base(k1 - 1) + k3 * (tf(k1 - 1) - base(k1 - 1))
zz = (basereal(k1) - base(k1)) ^ 2 + zz
If k1 = eday(k2) Then
delta = zz
If delta < mm Then
mm = delta
alpha(k2) = k3
hydno(k2) = sday(k2)
End If
End If
End If
Next k1
Next k3
Next k2
For k1 = 1 To i
For k2 = 1 To k
If k1 > sday(k2) And k1 <= eday(k2) Then
base(k1) = base(k1 - 1) + alpha(k2) * (tf(k1 - 1) - base(k1 - 1))
End If
Next k2
Next k1
For k3 = 1 To i
For k1 = 1 To k
For k2 = 1 To kkk
If k3 = eday(k2) Then
base(k3) = tf(k3)
End If
If k3 = sday(k2) Then
base(k3) = tf(k3)
End If
If base(k3) > tf(k3) Then
base(k3) = tf(k3)
End If
Next k2
Next k1
Next k3
End Sub
Private Sub CD3_Click()
CC2.ShowSave
yy = CC2.FileName
Open yy For Output As #2
For j = 1 To k
```

```
Print #2, alpha(j), hydno(j), eday(j)
Next j
Close 2
End Sub

Private Sub Command1_Click()
Unload Final
End
End Sub
Private Sub Command2_Click()
CC3.ShowSave
yy = CC3.FileName
Open yy For Output As #3
For j = 1 To i
Print #3, j, base(j)
Next j
Close 3
End Sub
```

(A.12) Boughton – central difference – least squares method

Input: date and total flow in mm/day, observed baseflow in mm/day

Output: alpha value (dimensionless) and baseflow in mm/day

```
'd means date and tf means total flow
'srun means start of runoff value an sday means start day of runoff
'maxrun means max runoff and maxday means day regarding max runoff
' Fd means second derivative
'erun mean end of surface runoff and eday means the day that surface runoff end
'hydno means the day storm event started, alpha means alpha value for that event
' base means baseflow
' basereal means real baseflow data
Dim d(10000), tf(10000), fd(10000) As Double
Dim srun(10000), sday(10000) As Double
Dim erun(10000), eday(10000) As Double
Dim base(10000), hydno(15000), alpha(15000) As Double
Dim maxrun(10000), maxday(10000) As Double
Dim basereal(10000) As Double
Dim i, k, kk, kkk As Long
Private Sub CD1_Click()
CC1.ShowOpen
yy = CC1.FileName
i = 0
Open yy For Input As #1
Do Until (EOF(1) = True)
i = i + 1
Input #1, d(i), tf(i), basereal(i)
Loop
Close 1
End Sub
Private Sub CD2_Click()
k = 0
For k1 = 2 To i - 1
If (tf(k1) <= tf(k1 - 1)) And (tf(k1) < tf(k1 + 1)) Then
k = k + 1
srun(k) = tf(k1)
sday(k) = k1
End If
Next k1
kk = 0
For k1 = 2 To i - 1
If (tf(k1) > tf(k1 - 1)) And (tf(k1) > tf(k1 + 1)) Then
kk = kk + 1
```

```
maxrun(kk) = tf(k1)
maxday(kk) = k1
End If
Next k1
dt = 1
fd(1) = 0
fd(i) = 0
For k1 = 2 To i - 1
fd(k1) = (tf(k1 - 1) - 2 * tf(k1) + tf(k1 + 1)) / dt ^ 2
Next k1
ww = 1
kkk = 0
For k1 = 1 To i - 1
If (fd(k1) < 0) And (fd(k1 + 1) > 0) Then
If k1 >= maxday(ww) And k1 <= sday(ww + 1) Then
ww = ww + 1
kkk = kkk + 1
erun(kkk) = tf(k1 + 1)
eday(kkk) = k1 + 1
If ww + 1 > k Then GoTo 10
End If
End If
10    If k1 > maxday(kk) Then
kkk = kkk + 1
erun(kkk) = tf(k1)
eday(kkk) = k1
GoTo 45
End If
Next k1
45 hh = 0
For k3 = 1 To i
For k1 = 2 To k
For k2 = 1 To kkk
If sday(k1 - 1) < eday(k2) And sday(k1) > eday(k2) Then
If k3 >= eday(k2) And k3 <= sday(k1) Then
base(k3) = tf(k3)
End If
End If
If k3 <= sday(1) Or k3 >= eday(kkk) Then
base(k3) = tf(k3)
End If
Next k2
Next k1
Next k3
For k2 = 1 To k
mm = 1E+100
```

```
For k3 = 0 To 1 Step 0.001
zz = 0
For k1 = 1 To i
If k1 > sday(k2) And k1 <= eday(k2) Then
base(k1) = base(k1 - 1) + k3 * (0.5 * (tf(k1 - 1) + tf(k1)) - base(k1 - 1))
zz = (basereal(k1) - base(k1)) ^ 2 + zz
If k1 = eday(k2) Then
delta = zz
If delta < mm Then
mm = delta
alpha(k2) = k3
hydno(k2) = sday(k2)
End If
End If
End If
Next k1
Next k3
Next k2
For k1 = 1 To i
For k2 = 1 To k
If k1 > sday(k2) And k1 <= eday(k2) Then
base(k1) = base(k1 - 1) + alpha(k2) * (0.5 * (tf(k1 - 1) + tf(k1)) - base(k1 - 1))
End If
Next k2
Next k1
For k3 = 1 To i
For k1 = 1 To k
For k2 = 1 To kkk
If k3 = eday(k2) Then
base(k3) = tf(k3)
End If
If k3 = sday(k2) Then
base(k3) = tf(k3)
End If
If base(k3) > tf(k3) Then
base(k3) = tf(k3)
End If
Next k2
Next k1
Next k3
End Sub
Private Sub CD3_Click()
CC2.ShowSave
yy = CC2.FileName
Open yy For Output As #2
For j = 1 To k
```

```
Print #2, alpha(j), hydno(j), eday(j)
Next j
Close 2
End Sub
Private Sub Command1_Click()
Unload Final
End
End Sub
Private Sub Command2_Click()
CC3.ShowSave
yy = CC3.FileName
Open yy For Output As #3
For j = 1 To i
Print #3, j, base(j)
Next j
Close 3
End Sub
```

(A.13) Boughton – forward difference – least squares method

Input: date and total flow in mm/day, observed baseflow in mm/day

Output: alpha value (dimensionless) and baseflow in mm/day

```
'd means date and tf means total flow
'srun means start of runoff value an sday means start day of runoff
'maxrun means max runoff and maxday means day regarding max runoff
' Fd means second derivative
'erun mean end of surface runoff and eday means the day that surface runoff end
'hydno means the day storm event started, alpha means alpha value for that event
' base means baseflow
' basereal means real baseflow data
Dim d(10000), tf(10000), fd(10000) As Double
Dim srun(10000), sday(10000) As Double
Dim erun(10000), eday(10000) As Double
Dim base(10000), hydno(15000), alpha(15000) As Double
Dim maxrun(10000), maxday(10000) As Double
Dim basereal(10000) As Double
Dim i, k, kk, kkk As Long
Private Sub CD1_Click()
CC1.ShowOpen
yy = CC1.FileName
i = 0
Open yy For Input As #1
Do Until (EOF(1) = True)
i = i + 1
Input #1, d(i), tf(i), basereal(i)
Loop
Close 1
End Sub
Private Sub CD2_Click()
k = 0
For k1 = 2 To i - 1
If (tf(k1) <= tf(k1 - 1)) And (tf(k1) < tf(k1 + 1)) Then
k = k + 1
srun(k) = tf(k1)
sday(k) = k1
End If
Next k1
kk = 0
For k1 = 2 To i - 1
If (tf(k1) > tf(k1 - 1)) And (tf(k1) > tf(k1 + 1)) Then
kk = kk + 1
```

```
maxrun(kk) = tf(k1)
maxday(kk) = k1
End If
Next k1
dt = 1
fd(1) = 0
fd(i) = 0
For k1 = 2 To i - 1
fd(k1) = (tf(k1 - 1) - 2 * tf(k1) + tf(k1 + 1)) / dt ^ 2
Next k1
ww = 1
kkk = 0
For k1 = 1 To i - 1
If (fd(k1) < 0) And (fd(k1 + 1) > 0) Then
If k1 >= maxday(ww) And k1 <= sday(ww + 1) Then
ww = ww + 1
kkk = kkk + 1
erun(kkk) = tf(k1 + 1)
eday(kkk) = k1 + 1
If ww + 1 > k Then GoTo 10
End If
End If
10    If k1 > maxday(kk) Then
kkk = kkk + 1
erun(kkk) = tf(k1)
eday(kkk) = k1
GoTo 45
End If
Next k1
45 hh = 0
For k3 = 1 To i
For k1 = 2 To k
For k2 = 1 To kkk
If sday(k1 - 1) < eday(k2) And sday(k1) > eday(k2) Then
If k3 >= eday(k2) And k3 <= sday(k1) Then
base(k3) = tf(k3)
End If
End If
If k3 <= sday(1) Or k3 >= eday(kkk) Then
base(k3) = tf(k3)
End If
Next k2
Next k1
Next k3
For k2 = 1 To k
mm = 1E+100
```

```
For k3 = 0 To 1 Step 0.001
zz = 0
For k1 = 1 To i
If k1 > sday(k2) And k1 <= eday(k2) Then
base(k1) = base(k1 - 1) + k3 * (tf(k1) - base(k1 - 1))
zz = (basereal(k1) - base(k1)) ^ 2 + zz
If k1 = eday(k2) Then
delta = zz
If delta < mm Then
mm = delta
alpha(k2) = k3
hydno(k2) = sday(k2)
End If
End If
End If
Next k1
Next k3
Next k2
For k1 = 1 To i
For k2 = 1 To k
If k1 > sday(k2) And k1 <= eday(k2) Then
base(k1) = base(k1 - 1) + alpha(k2) * (tf(k1) - base(k1 - 1))
End If
Next k2
Next k1
For k3 = 1 To i
For k1 = 1 To k
For k2 = 1 To kkk
If k3 = eday(k2) Then
base(k3) = tf(k3)
End If
If k3 = sday(k2) Then
base(k3) = tf(k3)
End If
If base(k3) > tf(k3) Then
base(k3) = tf(k3)
End If
Next k2
Next k1
Next k3
End Sub
Private Sub CD3_Click()
CC2.ShowSave
yy = CC2.FileName
Open yy For Output As #2
For j = 1 To k
```

```
Print #2, alpha(j), hydno(j), eday(j)
Next j
Close 2
End Sub

Private Sub Command1_Click()
Unload Final
End
End Sub
Private Sub Command2_Click()
CC3.ShowSave
yy = CC3.FileName
Open yy For Output As #3
For j = 1 To i
Print #3, j, base(j)
Next j
Close 3
End Sub
```

(A.14) Improvement in the fraction (α) value estimation by incorporating climatological factors

Input: total rainfall during a storm event in cm, total evapotranspiration during a storm event in cm, duration of runoff storm event in day, average soil moisture (cm/cm) in top 137 cm of soil, total rainfall during storm event divided by the duration of surface runoff in cm/day, daily rainfall intensity in cm/day

Output: alpha value (dimensionless)

```
'd means date and tf means total flow
'srun means start of runoff value an sday means start day of runoff
'maxrun means max runoff and maxday means day regarding max runoff
' Fd means second derivative
'erun mean end of surface runoff and eday means the day that surface runoff end
'hydno means the day storm event started, alpha means alpha value for that event
' base means baseflow
' basereal means real baseflow data
' var1 means Sum of Rainfall for each Single Event(cm)
' var2 means Sum of ETc for a Single Event (cm)
' var3 means Duration of Storm (day)
' var4 means Average Soil Moisture
' var6 rainfall/duration of storm cm/day
' var7 rainfall/duration of rain cm/day
'evar6 estimated var6
Dim var1(500), var2(500), var3(500), var4(500), var6(500), var7(500) As Double
Dim alpha(500), alpha_a(500), alpha_b(500)
Dim i, k, kk, kkk As Long
Private Sub CD1_Click()
CC1.ShowOpen
yy = CC1.FileName
i = 0
Open yy For Input As #1
Do Until (EOF(1) = True)
i = i + 1
Input #1, var1(i), var2(i), var3(i), var4(i), var6(i), var7(i)
Loop
Close 1
End Sub
Private Sub CD2_Click()
```

```
For j = 1 To i
alpha_a(j) = -0.187771 + 0.069254 * var1(j) - 0.086849 * var2(j) + 0.030729 *
var3(j) + 0.129997 * var4(j) - 0.212351 * var6(j) + 0.009239 * var7(j)
alpha_b(j) = 1.071991 + 0.043917 * var1(j) + 0.065553 * var2(j) - 0.044798 * var3(j)
+ 0.042783 * var4(j) - 0.30195 * var6(j) + 0.000449 * var7(j)
Next j
w1 = 0
w2 = 0
z1 = 0
z2 = 0
For k = 1 To i
z1 = (alpha_a(k) - 0.004031) / 0.06426
z2 = (1.043544 - alpha_b(k)) / 0.123973
'If z1 < 0 Then z1 = 0
'If z1 > 1 Then z1 = 1
w1 = Abs(z1 - var6(k))
w2 = Abs(z2 - var6(k))
If w1 < w2 Then
alpha(k) = alpha_a(k)
End If
If alpha(k) > 0.5 And w1 < w2 Then
alpha(k) = (alpha_b(k) + alpha_a(k)) / 2
End If
If w1 > w2 Then
alpha(k) = alpha_b(k)
End If
If alpha(k) < 0.5 And w1 > w2 Then
alpha(k) = (alpha_b(k) + alpha_a(k)) / 2
End If
Next k
End Sub
Private Sub CD3_Click()
CC2.ShowSave
yy = CC2.FileName
Open yy For Output As #2
For k1 = 1 To i
Print #2, alpha(k1)
Next k1
Close 2
End Sub
Private Sub Command1_Click()
Unload Final
End
End Sub
```

(A.15) Green-Ampt method developed one layer soil and single rainfall intensity

Input: day, date, rainfall duration in hr, rainfall intensity in cm/hr, saturated hydraulic conductivity, average soil moisture in top 122 cm of soil in cm, effective porosity, matric-suction at the wetting front in cm, daily evapotranspiration in cm, adjusted curve number value for antecedent moisture condition, AMC.

Output: Average soil moisture content for top 100 cm of soil, cumulative amount of infiltration in cm, the amount of water that infiltrates before water begins to pond at the surface in cm, the time it takes to have water begin to pond at the surface in hr.

```
' day means day
' da means date
' dur means rainfall duration in hr
' inten means intensity in cm/hr
' CN means CN after considering 5 days antecedent soil moisture
' ks means saturated hydraulic conductivity calculated from book 112 cm/hr
' tetai means average soil moisture in top 48" of soil
' tetae means effective porosity from book 112
' suy means matric-suction at the wetting front in cm page 112
' base mean subsurface flow generation in cm
Dim day(10000), da(10000), dur(10000), inten(10000), CN(10000), ks(10000) As
Double
Dim tetai(10000), tetae(10000), suy(10000), ETc(10000) As Double
Dim w, Fp(10000), tp(100000), F(100000), ff(100000), t(100000), wf(10000) As
Double
Dim base(10000) As Double
Dim i, k, kk As Long
Private Sub CD1_Click()
CC1.ShowOpen
yy = CC1.FileName
i = 0
Open yy For Input As #1
Do Until (EOF(1) = True)
i = i + 1
Input #1, day(i), da(i), dur(i), inten(i), CN(i), ks(i), tetae(i), suy(i), ETc(i)
Loop
Close 1
End Sub
```

```
Private Sub CD2_Click()
F(0) = 0
tetai(1) = 0.243363833
For k1 = 1 To i
If k1 > 1 Then
If tetai(k1 - 1) > 0.177616 Then
base(k1 - 1) = tetai(k1 - 1) - 0.177616
tetai(k1 - 1) = 0.177616
Else
base(k1 - 1) = 0
End If
tetai(k1) = tetai(k1 - 1) + (F(k1 - 1) - ETc(k1 - 1)) / 100
If tetai(k1) < 0.0625 Then tetai(k1) = 0.0625
If tetai(k1) > (tetae(k1) - 0.002) Then tetai(k1) = tetae(k1) - 0.002
End If
If dur(k1) = 0 Or inten(k1) = 0 Then
tp(k1) = 0
Fp(k1) = 0
F(k1) = 0
ks(k1) = (((56.82 * (10 * ks(k1)) ^ 0.286) / (1 + 0.051 * Exp(0.062 * CN(k1)))) - 2) /
10
GoTo 100
Else
ks(k1) = (((56.82 * (10 * ks(k1)) ^ 0.286) / (1 + 0.051 * Exp(0.062 * CN(k1)))) - 2) /
10
Fp(k1) = (suy(k1) * ks(k1) * (tetae(k1) - tetai(k1))) / (inten(k1) - ks(k1))
tp(k1) = Fp(k1) / inten(k1)
If Fp(k1) < 0 Then
Fp(k1) = 0
tp(k1) = 0
F(k1) = inten(k1) * dur(k1)
Else
' Fp>0
kk = 0
For k2 = 0 To 5000 Step 0.01
kk = kk + 1
ff(kk) = k2
If ff(kk) < Fp(k1) Then
t(kk) = ff(kk) / inten(k1)
wf(kk) = inten(k1)
F(k1) = ff(kk)
Else
w = Log((suy(k1) * (tetae(k1) - tetai(k1)) + Fp(k1)) / (suy(k1) * (tetae(k1) - tetai(k1))
+ ff(kk)))
t(kk) = tp(k1) + (1 / ks(k1)) * (ff(kk) - Fp(k1) + suy(k1) * (tetae(k1) - tetai(k1)) * w)
wf(kk) = ks(k1) + ks(k1) * (suy(k1) * (tetae(k1) - tetai(k1))) / ff(kk)
```

```
F(k1) = k2
End If
If t(kk) > dur(k1) Then
F(k1) = ff(kk - 1)
GoTo 100
End If
Next k2
End If
End If
100 Next k1
End Sub
Private Sub CD3_Click()
CC2.ShowSave
yy = CC2.FileName
Open yy For Output As #2
For j = 1 To i
Print #2, day(j), da(j), dur(j), inten(j), CN(j), ks(j), tetai(j), tetae(j), suy(j), F(j), Fp(j),
tp(j), ETc(j), base(j)
Next j
Close 2
End Sub
Private Sub Command1_Click()
Unload Final
End
End Sub
```

(A.16) Green-Ampt method developed for multiple layers soil and rainfall intensities.

Input: layer number, depth of each layer in cm, mean saturated moisture content, initial moisture content, saturated hydraulic conductivity, average capillarity potential in cm, rain ID, year, month, day, and time from the start of rainfall.

Output: time, depth of wetting front in cm, rainfall intensity in cm/hr, cumulative rainfall infiltration in cm, infiltration rate in cm

---

```
' t means time (hour)
' f means the cumulative amount of water that has infiltrated
' ff means infiltration rate (cm/hr)
' zf means depth of the wetting front
' tp means time to ponding
Dim t(191500), F(191500), ff(191500), Zf(191500)  As Double
Dim rainid(90000), yr(90000), mo(90000), da(90000), inten(90000), tfsr(90000) As
Double
Dim LayNo(6), Depth(6), tetas(6), tetai(6), ks(6), suyf(6)  As Double
Dim intenc(5000, 50), tfsrc(5000, 50), shomareh(5000) As Double
Dim i, k, kk  As Long
'LayNo means soil layer number
'Depth menas bottom soil depth in (cm)
'tetas means saturated moisture content
'tetai means initial moisture content
'ks means effective saturated conductivity (cm/hr) equal of 0.5
'suyf means average capilarity potential in (cm)
Private Sub CD1_Click()
CC1.ShowOpen
yy = CC1.FileName
i = 0
Open yy For Input As #1
Do Until (EOF(1) = True)
i = i + 1
Input #1, LayNo(i), Depth(i), tetas(i), tetai(i), ks(i), suyf(i)
Loop
Close 1
End Sub
Private Sub CD2_Click(Index As Integer)
ww = 0
rainid(0) = 0
For xx = 1 To k
If rainid(xx) <> rainid(xx - 1) And rainid(xx) <> rainid(xx + 1) Then
```

```
intenc(rainid(xx), 1) = inten(xx)
tfsrc(rainid(xx), 1) = tfsr(xx)
shomareh(rainid(xx)) = 1
Else
If rainid(xx) = rainid(xx + 1) Or rainid(xx) = rainid(xx - 1) Then
If rainid(xx) <> rainid(xx - 1) Then ww = 0
ww = ww + 1
intenc(rainid(xx), ww) = inten(xx)
tfsrc(rainid(xx), ww) = tfsr(xx)
shomareh(rainid(xx)) = ww
Else
ww = 0
End If
End If
Next xx
For raincounter = 1 To rainid(k)
For intcounter = 1 To shomareh(raincounter)
Depth(0) = 0
h = 0.001
ff(0) = intenc(raincounter, 1)
F(0) = 0
Zf(0) = 0
ff(1) = intenc(raincounter, 1)
F(1) = h * ff(1)
Zf(1) = F(1) / (tetas(1) - tetai(1))
kk = 1
tfsrc(raincounter, 0) = 0
For zz = (2 * h) To 500 Step h
For tt = 0 To k - 1
If (zz >= tfsrc(raincounter, tt)) And (zz <= tfsrc(raincounter, tt + 1)) Then
ffff = intenc(raincounter, tt + 1)
End If
Next tt
If Depth(0) < Zf(kk) And Zf(kk) <= Depth(1) Then
aks = ks(1)
Asuyf = suyf(1)
Atetas = tetas(1)
Atetai = tetai(1)
End If
If i = 1 Then GoTo 555
If Zf(kk) > Depth(1) And Zf(kk) <= Depth(2) Then
d = Zf(kk) - Depth(1)
aks = Zf(kk) / ((d / ks(2)) + (Depth(1) / ks(1)))
Asuyf = suyf(2)
Atetas = tetas(2)
Atetai = tetai(2)
```

```
End If
If i = 2 Then GoTo 555
If Zf(kk) > Depth(2) And Zf(kk) <= Depth(3) Then
d = Zf(kk) - Depth(2)
aks = Zf(kk) / ((d / ks(3)) + ((Depth(2) - Depth(1)) / ks(2)) + (Depth(1) / ks(1)))
Asuyf = suyf(3)
Atetas = tetas(3)
Atetai = tetai(3)
End If
If i = 3 Then GoTo 555

If Zf(kk) > Depth(3) And Zf(kk) <= Depth(4) Then
d = Zf(kk) - Depth(3)
aks = Zf(kk) / ((d / ks(4)) + ((Depth(3) - Depth(2)) / ks(2)) + ((Depth(2) - Depth(1)) /
ks(2)) + (Depth(1) / ks(1)))
Asuyf = suyf(4)
Atetas = tetas(4)
Atetai = tetai(4)
End If
If i = 4 Then GoTo 555
If i > 4 Then
imm = MsgBox("You can not simulate more than 4 layer of soils", vbSystemModal +
vbOKOnly, "warning")
End
End If
555 ali = 0
kk = kk + 1
w1 = ffff
w2 = aks * (1 + (Asuyf / Zf(kk - 1)))
If w1 < w2 Then
Zf(kk) = Zf(kk - 1) + h * ffff / (Atetas - Atetai)
F(kk) = (Zf(kk) - Zf(kk - 1)) * (Atetas - Atetai) + F(kk - 1)
ff(kk) = ffff
Else
w2 = w2 / (Atetas - Atetai)
k1 = h * w2
k2 = (h * aks / (Atetas - Atetai)) * (1 + (Asuyf / (Zf(kk - 1) + 0.5 * k1)))
k3 = (h * aks / (Atetas - Atetai)) * (1 + (Asuyf / (Zf(kk - 1) + 0.5 * k2)))
k4 = (h * aks / (Atetas - Atetai)) * (1 + (Asuyf / (Zf(kk - 1) + k3)))
Zf(kk) = Zf(kk - 1) + (1 / 6) * (k1 + 2 * k2 + 2 * k3 + k4)
F(kk) = (Zf(kk) - Zf(kk - 1)) * (Atetas - Atetai) + F(kk - 1)
ff(kk) = (F(kk) - F(kk - 1)) / h
'ff(kk) = aks * (1 + Asuyf * (Atetas - Atetai) / F(kk))
End If
If zz > tfsrc(rainid(k), shomareh(raincounter)) Then GoTo 222
Next zz
```

```
Next intcounter
Next raincounter
222 ali = 0
End Sub
Private Sub CD3_Click()
CC2.ShowSave
yy = CC2.FileName
Open yy For Output As #2
For dd = 1 To rainid(k)
For j = 0 To kk
zzz = j / 1000
Print #2, rainid(dd), zzz, Zf(j), F(j), ff(j)
Next j
Next dd
Close 2
End Sub
Private Sub Command1_Click()
Unload Final
End
End Sub
' rainid means rain ID
' yr means year
' mo menas month
' da means day
' inten means intensity of rainfall (cm/hr)
' tsfr means time from start of rainfall for this event
Private Sub Command2_Click()
CC3.ShowOpen
yy = CC3.FileName
k = 0
Open yy For Input As #3
Do Until (EOF(3) = True)
k = k + 1
Input #3, rainid(k), yr(k), mo(k), da(k), z1, z2, z3, inten(k), tfsr(k)
Loop
Close 3
End Sub
```

(A.17) Calculate total infiltration based on SCS Curve Number considering both antecedent soil moisture conditions and the seasonal factor

Input: day, date, curve number, growing season, rainfall, curve number lookup table for account of soil moisture conditions.

Output: adjusted curve number, rainfall infiltration in cm.

```
'Day means day number
'Da means date
'CN means curve number
'grow means growing season yes =1 no =0
'asm means antecedent rainfall 5-days total
' rain means rainfall in cm
' CN_I, CN_II, CN_III mean Cn for dry, medium and wet conditions
Dim day(10000), da(10000), CN(10000), grow(10000), rain(10000) As Double
Dim CN_I(100), CN_II(100), CN_III(100) As Double
Dim asm(10000) As Double
Dim i, ii, k, kk As Long
Private Sub CD1_Click()
CC1.ShowOpen
yy = CC1.FileName
i = 0
Open yy For Input As #1
Do Until (EOF(1) = True)
i = i + 1
Input #1, day(i), da(i), CN(i), grow(i), rain(i)
Loop
Close 1
End Sub
Private Sub CD2_Click()
For k0 = 1 To 5
asm(k0) = 0
Next k0
For k1 = 6 To i
asm(k1) = rain(k1 - 5) + rain(k1 - 1) + rain(k1 - 2) + rain(k1 - 3) + rain(k1 - 4)
Next k1
For k2 = 6 To i
If grow(k2) = 0 Then
Select Case asm(k2)
Case Is < 1.27:
For ii1 = 1 To ii
If CN(k2) < CN_II(ii1) Then
```

```
CN(k2) = CN_I(ii1) - 0.2 * (CN_II(ii1) - CN(k2)) * (CN_I(ii1) - CN_I(ii1 - 1))
GoTo 100
End If
Next ii1
Case Is > 2.8:
For ii1 = 1 To ii
If CN(k2) < CN_II(ii1) Then
CN(k2) = CN_III(ii1) - 0.2 * (CN_II(ii1) - CN(k2)) * (CN_III(ii1) - CN_III(ii1 - 1))
GoTo 100
End If
Next ii1
Case Else: CN(k2) = CN(k2)
End Select
End If
If grow(k2) = 1 Then
Select Case asm(k2)
Case Is < 3.56:
For ii1 = 1 To ii
If CN(k2) < CN_II(ii1) Then
CN(k2) = CN_I(ii1) - 0.2 * (CN_II(ii1) - CN(k2)) * (CN_I(ii1) - CN_I(ii1 - 1))
GoTo 100
End If
Next ii1
Case Is > 5.33:
For ii1 = 1 To ii
If CN(k2) < CN_II(ii1) Then
CN(k2) = CN_III(ii1) - 0.2 * (CN_II(ii1) - CN(k2)) * (CN_III(ii1) - CN_III(ii1 - 1))
GoTo 100
End If
Next ii1
Case Else: CN(k2) = CN(k2)
End Select
End If
00 Next k2
End Sub
Private Sub CD3_Click()
CC2.ShowSave
yy = CC2.FileName
Open yy For Output As #2
For j = 1 To i
Print #2, day(j), da(j), CN(j), grow(j), rain(j), asm(j)
Next j
Close 2
End Sub
Private Sub Command1_Click()
Unload Final
```

```
End
End Sub
Private Sub Command2_Click()
CC3.ShowOpen
yy = CC3.FileName
ii = 0
Open yy For Input As #1
Do Until (EOF(1) = True)
ii = ii + 1
Input #1, CN_II(ii), CN_I(ii), CN_III(ii)
Loop
Close 1
End Sub
```

(A.18) Estimating average soil moisture content based on measured values

Input: day, soil moisture measurements at 15.24, 30.48, 45.72, 60.96, 76.20, 91.44, and 106.68 cm.

Output: average soil moisture content

```
Dim start(10000), eday(10000), zz As Double
Dim day(10000), d6(10000), d12(10000), d18(10000), d24(10000), d30(10000),
d36(10000), d42(10000) As Double
Dim i, k, kk, ll As Long
Private Sub CD1_Click()
CC1.ShowOpen
yy = CC1.FileName
i = 0
Open yy For Input As #1
Do Until (EOF(1) = True)
i = i + 1
Input #1, day(i), d6(i), d12(i), d18(i), d24(i), d30(i), d36(i), d42(i)
Loop
Close 1
End Sub
Private Sub CD2_Click()
ll = 0
For k1 = 1 To i
If d6(k1) <> 9999 Then
ll = ll + 1
eday(ll) = k1
start(ll) = d6(k1)
End If
Next k1
zz = 0
For k2 = 1 To ll - 1
zz = (start(k2 + 1) - start(k2)) / (eday(k2 + 1) - eday(k2))
For k3 = 2 To i
If k3 > eday(k2) And k3 < eday(k2 + 1) Then
d6(k3) = d6(k3 - 1) + zz
End If
Next k3
Next k2
ll = 0
For k1 = 1 To i
If d12(k1) <> 9999 Then
```

```
ll = ll + 1
eday(ll) = k1
start(ll) = d12(k1)
End If
Next k1
zz = 0
For k2 = 1 To ll - 1
zz = (start(k2 + 1) - start(k2)) / (eday(k2 + 1) - eday(k2))
For k3 = 2 To i
If k3 > eday(k2) And k3 < eday(k2 + 1) Then
d12(k3) = d12(k3 - 1) + zz
End If
Next k3
Next k2
ll = 0
For k1 = 1 To i
If d18(k1) <> 9999 Then
ll = ll + 1
eday(ll) = k1
start(ll) = d18(k1)
End If
Next k1
zz = 0
For k2 = 1 To ll - 1
zz = (start(k2 + 1) - start(k2)) / (eday(k2 + 1) - eday(k2))
For k3 = 2 To i
If k3 > eday(k2) And k3 < eday(k2 + 1) Then
d18(k3) = d18(k3 - 1) + zz
End If
Next k3
Next k2
ll = 0
For k1 = 1 To i
If d24(k1) <> 9999 Then
ll = ll + 1
eday(ll) = k1
start(ll) = d24(k1)
End If
Next k1
zz = 0
For k2 = 1 To ll - 1
zz = (start(k2 + 1) - start(k2)) / (eday(k2 + 1) - eday(k2))
For k3 = 2 To i
If k3 > eday(k2) And k3 < eday(k2 + 1) Then
d24(k3) = d24(k3 - 1) + zz
End If
```

```
Next k3
Next k2
ll = 0
For k1 = 1 To i
If d30(k1) <> 9999 Then
ll = ll + 1
eday(ll) = k1
start(ll) = d30(k1)
End If
Next k1
zz = 0
For k2 = 1 To ll - 1
zz = (start(k2 + 1) - start(k2)) / (eday(k2 + 1) - eday(k2))
For k3 = 2 To i
If k3 > eday(k2) And k3 < eday(k2 + 1) Then
d30(k3) = d30(k3 - 1) + zz
End If
Next k3
Next k2
ll = 0
For k1 = 1 To i
If d36(k1) <> 9999 Then
ll = ll + 1
eday(ll) = k1
start(ll) = d36(k1)
End If
Next k1
zz = 0
For k2 = 1 To ll - 1
zz = (start(k2 + 1) - start(k2)) / (eday(k2 + 1) - eday(k2))
For k3 = 2 To i
If k3 > eday(k2) And k3 < eday(k2 + 1) Then
d36(k3) = d36(k3 - 1) + zz
End If
Next k3
Next k2
ll = 0
For k1 = 1 To i
If d42(k1) <> 9999 Then
ll = ll + 1
eday(ll) = k1
start(ll) = d42(k1)
End If
Next k1
zz = 0
For k2 = 1 To ll - 1
```

```
zz = (start(k2 + 1) - start(k2)) / (eday(k2 + 1) - eday(k2))
For k3 = 2 To i
If k3 > eday(k2) And k3 < eday(k2 + 1) Then
d42(k3) = d42(k3 - 1) + zz
End If
Next k3
Next k2
End Sub
Private Sub CD3_Click()
CC2.ShowSave
yy = CC2.FileName
Open yy For Output As #2
For j = 1 To i
Print #2, day(j), d6(j), d12(j), d18(j), d24(j), d30(j), d36(j), d42(j)
Next j
Close 2
End Sub
Private Sub Command1_Click()
Unload Final
End
End Sub
```

(A.19) Empirical Based Model – Modified Boughton's Method

Input: day, rainfall in cm, totalflow in cm/day

Output: baseflow in cm/day

```
'd means date and tf means total flow
'srun means start of runoff value an sday means start day of runoff
'maxrun means max runoff and maxday means day regarding max runoff
' Fd means second deravative
'erun mean end of surface runoff and eday means the day that surface runoff end
'hydno means the day storm event started, alpha means alpha value for that event
' base means baseflow
' rain means daily rainfall in cm
' rr means total amount of rain per storm
' dr means rainy days
' ddrain means intensity of rainfall during storm (cm/day)
' duration means duration of storm
Dim d(10000), tf(10000), fd(10000) As Double
Dim srun(10000), sday(10000) As Double
Dim erun(10000), eday(10000) As Double
Dim base(10000), hydno(10000), alpha(10000) As Double
Dim maxrun(10000), maxday(10000) As Double
Dim rain(10000), rr(10000), dr(10000), ddrain(10000) As Double
Dim duration(10000) As Double
Dim i, k, kk, kkk As Long
Private Sub CD1_Click()
CC1.ShowOpen
yy = CC1.FileName
i = 0
Open yy For Input As #1
Do Until (EOF(1) = True)
i = i + 1
Input #1, d(i), rain(i), tf(i)
Loop
Close 1
End Sub
Private Sub CD2_Click()
For ss = 1 To i - 1
If tf(ss) <> 0 And tf(ss) = tf(ss + 1) Then
tf(ss + 1) = tf(ss + 1) + 0.000001
End If
Next ss
k = 0
For k1 = 2 To i - 1
```

```
If (tf(k1) <= tf(k1 - 1)) And (tf(k1) < tf(k1 + 1)) Then
k = k + 1
srun(k) = tf(k1)
sday(k) = k1
End If
Next k1
kk = 0
For k1 = 2 To i - 1
If (tf(k1) > tf(k1 - 1)) And (tf(k1) > tf(k1 + 1)) Then
kk = kk + 1
maxrun(kk) = tf(k1)
maxday(kk) = k1
End If
Next k1
dt = 1
fd(1) = 0
fd(i) = 0
For k1 = 2 To i - 1
fd(k1) = (tf(k1 - 1) - 2 * tf(k1) + tf(k1 + 1)) / dt ^ 2
Next k1
For k1 = 1 To i - 1
For k2 = 1 To k - 1
If (fd(k1) < 0) And (fd(k1 + 1) > 0) Then
If k1 >= maxday(k2) And k1 <= sday(k2 + 1) Then
erun(k2) = tf(k1 + 1)
eday(k2) = k1 + 1
End If
End If
If k1 > maxday(k2 + 1) Then
If (fd(k1) < 0) And (fd(k1 + 1) > 0) Then
erun(k) = tf(k1 + 1)
eday(k) = k1 + 1
End If
End If
Next k2
Next k1
45 hh = 0
For k3 = 1 To i
For k1 = 2 To k
For k2 = 1 To kkk
If sday(k1 - 1) < eday(k2) And sday(k1) > eday(k2) Then
If k3 >= eday(k2) And k3 <= sday(k1) Then
base(k3) = tf(k3)
End If
End If
If k3 <= sday(1) Or k3 >= eday(kkk) Then
```

```
base(k3) = tf(k3)
End If
Next k2
Next k1
Next k3
For k2 = 1 To k
mm = 1E+100
For k3 = 0 To 1 Step 0.001
For k1 = 1 To i
If k1 > sday(k2) And k1 <= eday(k2) Then
base(k1) = base(k1 - 1) + k3 * (tf(k1) - base(k1 - 1))
If k1 = eday(k2) Then
delta = Abs(tf(k1) - base(k1))
If delta < mm Then
mm = delta
alpha(k2) = k3
hydno(k2) = sday(k2)
End If
End If
End If
Next k1
Next k3
Next k2
For k1 = 1 To i
For k2 = 1 To k
If k1 > sday(k2) And k1 <= eday(k2) Then
base(k1) = base(k1 - 1) + alpha(k2) * (tf(k1) - base(k1 - 1))
End If
Next k2
Next k1
For k3 = 1 To i
For k1 = 1 To k
For k2 = 1 To kkk
If k3 = eday(k2) Then
base(k3) = tf(k3)
End If
If k3 = sday(k2) Then
base(k3) = tf(k3)
End If
If base(k3) > tf(k3) Then
base(k3) = tf(k3)
End If
Next k2
Next k1
Next k3
For www = 1 To i
```

```
For zzz = 1 To k
If www >= sday(zzz) And www <= eday(zzz) And rain(www) <> 0 Then
dr(zzz) = dr(zzz) + 1
rr(zzz) = rr(zzz) + rain(www)
End If
Next zzz
Next www
For zzz1 = 1 To k
If dr(zzz1) <> 0 Then
ddrain(zzz1) = rr(zzz1) / dr(zzz1)
Else
222 ddrain(zzz1) = 0
End If
Next zzz1
For zzz2 = 1 To k
duration(zzz2) = eday(zzz2) - sday(zzz2) + 1
Next zzz2
End Sub
Private Sub CD3_Click()
CC2.ShowSave
yy = CC2.FileName
Open yy For Output As #2
For j = 1 To k
Print #2, sday(j), maxday(j), eday(j), alpha(j), ddrain(j), duration(j)
Next j
Close 2
End Sub
Private Sub Command1_Click()
Unload Final
End
End Sub
Private Sub Command2_Click()
CC3.ShowSave
yy = CC3.FileName
Open yy For Output As #3
For j = 1 To i
Print #3, j, base(j)
Next j
Close 3
End Sub
```

(A. 20) Calculating curve number for the GIS environment

Input: land use, soil type

Output: curve number

```
Dim soil(1000000), LandUse(1000000) As Double
Dim CN(1000000) As Double
Dim i, k, kk  As Long
Private Sub CD1_Click()
CC1.ShowOpen
yy = CC1.FileName
i = 0
Open yy For Input As #1
Do Until (EOF(1) = True)
i = i + 1
Input #1, soil(i)
Loop
Close 1
End Sub
Private Sub CD2_Click(Index As Integer)
For c = 1 To i
If soil(c) = -9999 Or LandUse(c) = -9999 Then CN(c) = -9999
If soil(c) = 2 Then
Select Case LandUse(c)
Case 0: CN(c) = 92
Case 1: CN(c) = 79
Case 3: CN(c) = 79
Case 4: CN(c) = 84
Case 5: CN(c) = 100
Case 6: CN(c) = 89
Case 7: CN(c) = 93.5
End Select
End If
If soil(c) = 4 Then
Select Case LandUse(c)
Case 0: CN(c) = 77
Case 1: CN(c) = 36
Case 3: CN(c) = 36
Case 4: CN(c) = 49
Case 5: CN(c) = 100
Case 6: CN(c) = 67
Case 7: CN(c) = 76.5
End Select
End If
```

```
If soil(c) = 1 Then
Select Case LandUse(c)
Case 0: CN(c) = 85
Case 1: CN(c) = 60
Case 3: CN(c) = 60
Case 4: CN(c) = 69
Case 5: CN(c) = 100
Case 6: CN(c) = 78
Case 7: CN(c) = 85.5
End Select
End If
If soil(c) = 3 Then
Select Case LandUse(c)
Case 0: CN(c) = 90
Case 1: CN(c) = 73
Case 3: CN(c) = 73
Case 4: CN(c) = 79
Case 5: CN(c) = 100
Case 6: CN(c) = 85
Case 7: CN(c) = 90.5
End Select
End If
Next c
End Sub
Private Sub CD3_Click()
CC2.ShowSave
yy = CC2.FileName
Open yy For Output As #2
For j = 1 To i
Print #2, CN(j)
Next j
Close 2
End Sub
Private Sub Command1_Click()
Unload Final
End
End Sub
Private Sub Command2_Click()
CC3.ShowOpen
yy = CC3.FileName
k = 0
Open yy For Input As #3
Do Until (EOF(3) = True)
k = k + 1
Input #3, LandUse(k)
Loop
```

```
Close 3
End Sub
```

(A.21) Computing infiltration based on weighted average curve number method

Input: day, date, curve number, rainfall in cm

Output: surface runoff in cm/day, infiltration in cm/day

```
' day means day
' da means date
' CN menas curve number
' rain means daily rainfall in cm
' Q means surface runoff as cm
Dim day(10000), da(10000), CN(10000), rain(10000), Q(10000), infilt(10000) As
Double
Dim S, P As Double
Dim i As Long
Private Sub CD1_Click()
CC1.ShowOpen
yy = CC1.FileName
i = 0
Open yy For Input As #1
Do Until (EOF(1) = True)
i = i + 1
Input #1, day(i), da(i), CN(i), rain(i)
Loop
Close 1
End Sub
Private Sub CD2_Click()
For k1 = 1 To i
If rain(k1) = 0 Then
Q(k1) = 0
Else
S = (1000 / CN(k1)) - 10
P = rain(k1) / 2.54
Q(k1) = 2.54 * (((P - 0.2 * S) ^ 2) / (P + 0.8 * S))
P = P * 2.54
If Q(k1) > P Then Q(k1) = P
infilt(k1) = P - Q(k1)
End If
Next k1
End Sub
Private Sub CD3_Click()
CC2.ShowSave
yy = CC2.FileName
Open yy For Output As #2
For j = 1 To i
```

```
Print #2, day(j), da(j), CN(j), rain(j), Q(j), infilt(j)
Next j
Close 2
End Sub
Private Sub Command1_Click()
Unload Final
End
End Sub
```

(A.22) Computing total infiltration for each storm event

Input: start of storm event, end of storm event, daily infiltration in cm

Output: total infiltration for each storm event

```
' sday means start of the runoff
' eday means end of the runoff
'daily means day
' infday means infilitration based on SCS curve number method in cm
Dim sday(10000), eday(10000) As Double
Dim daily(10000), infday(100000), SCS(10000) As Double
Dim asm(10000) As Double
Dim i, ii, k, kk As Long
Private Sub CD1_Click()
CC1.ShowOpen
yy = CC1.FileName
i = 0
Open yy For Input As #1
Do Until (EOF(1) = True)
i = i + 1
Input #1, sday(i), eday(i)
Loop
Close 1
End Sub
Private Sub CD2_Click()
For k1 = 1 To ii
For k2 = 1 To i
If daily(k1) >= sday(k2) And daily(k1) <= eday(k2) Then
SCS(k2) = SCS(k2) + infday(k1)
End If
Next k2
Next k1
End Sub
Private Sub CD3_Click()
CC2.ShowSave
yy = CC2.FileName
Open yy For Output As #2
For j = 1 To i
Print #2, sday(j), eday(j), SCS(j)
Next j
Close 2
End Sub
Private Sub Command1_Click()
Unload Final
```

```
End
End Sub
Private Sub Command2_Click()
CC3.ShowOpen
yy = CC3.FileName
ii = 0
Open yy For Input As #1
Do Until (EOF(1) = True)
ii = ii + 1
Input #1, daily(ii), infday(ii)
Loop
Close 1
End Sub
```

(A.23) Estimating alpha value based on weighted average curve number method

Input: infiltration during storm event obtained from SCS curve number method in cm, duration of runoff event in days, daily rainfall intensity in cm/day

Output: alpha value

```
'sday means start of the surface runoff
' eday means end of the surface runoff
' alphaem means alpha obtained from imperical method
' duration means storm duration in day
' infSCS means total infiltration during storm event in cm
' alphaeq means alpha obtained from the equation
' rain means rainfall intensity in cm/day
Dim sday(10000), eday(10000), alphaem(10000), infSCS(10000) As Double
Dim alphaeq(10000), rain(100000) As Double
Dim i, k, kk, kkk, duration(10000) As Long
Private Sub CD1_Click()
CC1.ShowOpen
yy = CC1.FileName
i = 0
Open yy For Input As #1
Do Until (EOF(1) = True)
i = i + 1
Input #1, sday(i), eday(i), alphaem(i), rain(i), duration(i), infSCS(i)
Loop
Close 1
End Sub
Private Sub CD2_Click()
For k2 = 1 To i
alphaeq(k2) = -0.048773 * infSCS(k2) + 0.277548 * duration(k2) - 0.113226 *
rain(k2)
If alphaeq(k2) > 1 Then alphaeq(k2) = 1
If alphaeq(k2) < 0 Then alphaeq(k2) = 0
5000 Next k2
End Sub
Private Sub Command1_Click()
Unload Final
End
End Sub
Private Sub Command2_Click()
CC3.ShowSave
yy = CC3.FileName
```

```
Open yy For Output As #3
For j = 1 To i
Print #3, sday(j), eday(j), alphaem(j), alphaeq(j)
Next j
Close 3
End Sub
```

(A.24) Computing infiltration values for each cell for GIS environment

Input: day, date, growing season (yes/no), rainfall in cm, start day of storm event, end day of storm event, rainfall intensity in cm/day, duration of storm in days, curve number table for different soil moisture conditions, initial curve number value for soil moisture condition II

Output: infiltration values for each cell within the GIS in cm

---

```
'Day means day number
'Da means date
'CN means curve number
'grow means growing season yes =1 no =0
'asm means antecedent rainfall 5-days total
' rain means rainfall in cm
' CN_I, CN_II, CN_III mean Cn for dry, medium and wet conditions
' sady means start of the storm
' eday means end of the the storm
' rinten means rainfall intensity in cm/day
' rdur means duration of the storm
' suminf means sum of infiltration for each cell during the storm event in am
Dim day(5000), da(5000), CN(100000), grow(5000), rain(5000) As Double
Dim CN_I(150), CN_II(150), CN_III(150), CNzz(400, 13100) As Double
Dim Q(400, 13100), Infter(400, 13100) As Double
Dim sday(5000), eday(5000), rinten(5000), rdur(5000) As Double
Dim asm(5000), alpha(400, 13100), suminf(400, 23100) As Double
Dim i, ii, k, kk, iP, qq As Long
Private Sub CD1_Click()
CC1.ShowOpen
yy = CC1.FileName
i = 0
Open yy For Input As #1
Do Until (EOF(1) = True)
i = i + 1
Input #1, day(i), da(i), grow(i), rain(i)
Loop
Close 1
End Sub
Private Sub CD2_Click()
ss = 1
For k0 = 1 To 5
```

```
asm(k0) = 0
Next k0
For k1 = 6 To i
asm(k1) = rain(k1 - 5) + rain(k1 - 1) + rain(k1 - 2) + rain(k1 - 3) + rain(k1 - 4)
Next k1
For k2 = 6 To i
zs = 0
zy = 0
For dd = 1 To iP
If CN(dd) < 0 Then
CNzz(k2, dd) = -9999
Q(k2, dd) = -9999
Infter(k2, dd) = -9999
GoTo 135
Else
If grow(k2) = 0 Then
Select Case asm(k2)
Case Is < 1.27:
For ii1 = 1 To ii
If CN(dd) < CN_II(ii1) Then
CNzz(k2, dd) = CN_I(ii1) - 0.2 * (CN_II(ii1) - CN(dd)) * (CN_I(ii1) - CN_I(ii1 - 1))
GoTo 100
End If
Next ii1
Case Is > 2.8:
For ii1 = 1 To ii
If CN(dd) < CN_II(ii1) Then
CNzz(k2, dd) = CN_III(ii1) - 0.2 * (CN_II(ii1) - CN(dd)) * (CN_III(ii1) - CN_III(ii1
- 1))
GoTo 100
End If
Next ii1
Case Else: CNzz(k2, dd) = CN(dd)
End Select
End If
If grow(k2) = 1 Then
Select Case asm(k2)
Case Is < 3.56:
For ii1 = 1 To ii
If CN(dd) < CN_II(ii1) Then
CNzz(k2, dd) = CN_I(ii1) - 0.2 * (CN_II(ii1) - CN(dd)) * (CN_I(ii1) - CN_I(ii1 - 1))
GoTo 100
End If
Next ii1
Case Is > 5.33:
For ii1 = 1 To ii
```

```
If CN(dd) < CN_II(ii1) Then
CNzz(k2, dd) = CN_III(ii1) - 0.2 * (CN_II(ii1) - CN(dd)) * (CN_III(ii1) - CN_III(ii1
- 1))
GoTo 100
End If
Next ii1
Case Else: CNzz(k2, dd) = CN(dd)
End Select
End If
100 If CN(dd) = 100 Then CNzz(k2, dd) = 100
End If
If rain(k2) = 0 Then
Q(k2, dd) = 0
Infter(k2, dd) = 0
Else
S = (1000 / CNzz(k2, dd)) - 10
P = rain(k2) / 2.54
Q(k2, dd) = 2.54 * (((P - 0.2 * S) ^ 2) / (P + 0.8 * S))
P = P * 2.54
If Q(k2, dd) > P Then Q(k2, dd) = P
Infter(k2, dd) = P - Q(k2, dd)
End If
135 If k2 >= sday(ss) And k2 <= eday(ss) Then
If Infter(k2, dd) = -9999 Then
suminf(ss, dd) = -9999
GoTo 256
End If
suminf(ss, dd) = Infter(k2, dd) + suminf(ss, dd)
256 If k2 = eday(ss) Then ss = ss + 1
End If
Next dd
Next k2
End Sub
Private Sub CD3_Click()
CC2.ShowSave
yy = CC2.FileName
Open yy For Output As #2
For j = 1 To qq
Print #2, sday(j);
For jjj = 1 To iP
Print #2, suminf(j, jjj);
Next jjj
Print #2, " "
Next j
Close 2
End Sub
```

```
Private Sub Command1_Click()
Unload Final
End
End Sub
Private Sub Command2_Click()
CC3.ShowOpen
yy = CC3.FileName
ii = 0
Open yy For Input As #1
Do Until (EOF(1) = True)
ii = ii + 1
Input #1, CN_II(ii), CN_I(ii), CN_III(ii)
Loop
Close 1
End Sub
Private Sub Command3_Click()
CCC.ShowOpen
yy = CCC.FileName
iP = 0
Open yy For Input As #15
Do Until (EOF(15) = True)
iP = iP + 1
Input #15, CN(iP)
Loop
Close 15
End Sub
Private Sub Command4_Click()
CCC.ShowOpen
yy = CCC.FileName
qq = 0
Open yy For Input As #19
Do Until (EOF(19) = True)
qq = qq + 1
Input #19, sday(qq), eday(qq), rinten(qq), rdur(qq)
Loop
Close 19
End Sub
```

(A.25) Computing average alpha values on event based from the weighted average discharge method

Input: day, date, growing season (yes/no), rainfall in cm, start day of storm event, end day of storm event, rainfall intensity in cm/day, duration of storm in days, curve number table for different soil moisture conditions, initial curve number value for soil moisture condition II, total infiltration during storm event

Output: average infiltration within the study area, average alpha value

---

```
'Day means day number
'Da means date
'CN means curve number
'grow means growing season yes =1 no =0
'asm means antecedent rainfall 5-days total
' rain means rainfall in cm
' CN_I, CN_II, CN_III mean Cn for dry, medium and wet conditions
' sady means start of the storm
' eday means end of the the storm
' rinten means rainfall intensity in cm/day
' rdur means duration of the storm
' suminf means sum of infiltration for each cell during the storm event in am
Dim day(5000), da(5000), CN(100000), grow(5000), rain(5000) As Double
Dim CN_I(150), CN_II(150), CN_III(150), CNzz(1000, 17950) As Double
Dim Q, P, S, Infter(1000, 17950) As Double
Dim sday(5000), eday(5000), Rinten(5000), Rdur(5000) As Double
Dim asm(5000), alpha(5000), suminf(1000, 17950), dday(5000) As Double
Dim AvgSum(5000), ggGg As Double
Dim i, ii, k, kk, iP, qq, ss, ww As Long
Private Sub CD1_Click()
CC1.ShowOpen
yy = CC1.FileName
i = 0
Open yy For Input As #1
Do Until (EOF(1) = True)
i = i + 1
Input #1, day(i), da(i), grow(i), rain(i)
Loop
Close 1
End Sub
```

```
Private Sub CD2_Click()
S = 0
Q = 0
P = 0
ss1 = 1
ww = 0
For k0 = 1 To 5
asm(k0) = 0
Next k0
For k1 = 6 To i
asm(k1) = rain(k1 - 5) + rain(k1 - 1) + rain(k1 - 2) + rain(k1 - 3) + rain(k1 - 4)
Next k1
For k2 = 1 To i
zs = 0
zy = 0
For ss = 1 To qq
If k2 >= sday(ss) And k2 <= eday(ss) And rain(k2) > 0 Then
ww = ww + 1
dday(ww) = k2
For dd = 1 To iP
If grow(k2) = 0 Then
Select Case asm(k2)
Case Is < 1.27:
For ii1 = 1 To ii
If CN(dd) < CN_II(ii1) Then
CNzz(ww, dd) = CN_I(ii1) - 0.2 * (CN_II(ii1) - CN(dd)) * (CN_I(ii1) - CN_I(ii1 -
1))
GoTo 100
End If
Next ii1
Case Is > 2.8:
For ii1 = 1 To ii
If CN(dd) < CN_II(ii1) Then
CNzz(ww, dd) = CN_III(ii1) - 0.2 * (CN_II(ii1) - CN(dd)) * (CN_III(ii1) -
CN_III(ii1 - 1))
GoTo 100
End If
Next ii1
Case Else: CNzz(ww, dd) = CN(dd)
End Select
End If
If grow(k2) = 1 Then
Select Case asm(k2)
Case Is < 3.56:
For ii1 = 1 To ii
If CN(dd) < CN_II(ii1) Then
```

```
CNzz(ww, dd) = CN_I(ii1) - 0.2 * (CN_II(ii1) - CN(dd)) * (CN_I(ii1) - CN_I(ii1 -
1))
GoTo 100
End If
Next ii1
Case Is > 5.33:
For ii1 = 1 To ii
If CN(dd) < CN_II(ii1) Then
CNzz(ww, dd) = CN_III(ii1) - 0.2 * (CN_II(ii1) - CN(dd)) * (CN_III(ii1) -
CN_III(ii1 - 1))
GoTo 100
End If
Next ii1
Case Else: CNzz(ww, dd) = CN(dd)
End Select
End If
100 If CN(dd) = 100 Then CNzz(ww, dd) = 100
S = (1000 / CNzz(ww, dd)) - 10
P = rain(k2) / 2.54
Q = 2.54 * (((P - 0.2 * S) ^ 2) / (P + 0.8 * S))
P = P * 2.54
If Q > P Then Q = P
Infter(ww, dd) = P - Q
suminf(ss, dd) = Infter(ww, dd) + suminf(ss, dd)
Next dd
End If
Next ss
Next k2
aa = 0
For z1 = 1 To qq
For z2 = 1 To iP
aa = aa + suminf(z1, z2)
Next z2
ggGg = iP
AvgSum(z1) = aa / ggGg
alpha(z1) = -0.048773 * AvgSum(z1) + 0.277548 * Rdur(z1) - 0.113226 * Rinten(z1)
If alpha(z1) < 0 Then alpha(z1) = 0
If alpha(z1) > 1 Then alpha(z1) = 1
aa = 0
Next z1
End Sub
Private Sub CD3_Click()
CC2.ShowSave
yy = CC2.FileName
Open yy For Output As #2
For j = 1 To qq
```

```
Print #2, sday(j), eday(j), Rinten(j), Rdur(j), AvgSum(j), alpha(j)
Next j
Close 2
End Sub
Private Sub Command1_Click()
Unload Final
End
End Sub
Private Sub Command2_Click()
CC3.ShowOpen
yy = CC3.FileName
ii = 0
Open yy For Input As #1
Do Until (EOF(1) = True)
ii = ii + 1
Input #1, CN_II(ii), CN_I(ii), CN_III(ii)
Loop
Close 1
End Sub
Private Sub Command3_Click()
CCC.ShowOpen
yy = CCC.FileName
iP = 0
Open yy For Input As #15
Do Until (EOF(15) = True)
iP = iP + 1
Input #15, CN(iP)
Loop
Close 15
End Sub
Private Sub Command4_Click()
CCC.ShowOpen
yy = CCC.FileName
qq = 0
Open yy For Input As #19
Do Until (EOF(19) = True)
qq = qq + 1
Input #19, sday(qq), eday(qq), Rinten(qq), Rdur(qq)
Loop
Close 19
End Sub
```

(A.26) Estimating baseflow based on computed alpha values from the modified Boughton method, the weighted average curve number method and the weighted discharge method

Input: day, date, start of storm event, end of storm event, computed alpha value from modified Boughton's method, weighted average curve number method, and weighted discharge method, total flow in m^3/s

Output: day, date, total flow in m^3/s, computed baseflow value from modified Boughton's method, weighted average curve number method, and weighted discharge method all in m^3/s.

```
' sday means start of the runoff
' eday means end of the runoff
' alphaemp means alpha empirical
' alphacal means alpha the weighted average CN method
' alphanew means alpha the weighted discharge method
' dday means day
' ddate means date
' tf means total flow in m^3/s
' baseemp means baseflow form the weighted average CN method
' basenew means baseflow from the weighted discharge method
' baseequ means computed baseequ
Dim sday(10000), eday(10000), alphaemp(10000), alphacal(10000) As Double
Dim dday(10000), ddate(10000), tf(10000) As Double
Dim bdday(10000), bddate(10000), btf(10000) As Double
Dim baseemp(10000), baseequ(10000) As Double
Dim basenew(10000), alphanew(10000) As Double
Dim bemp(10000), bequ(10000), bnew(10000) As Double
Dim i, zz, ii, k, kk As Long
Private Sub CD1_Click()
CC1.ShowOpen
yy = CC1.FileName
i = 0
Open yy For Input As #1
Do Until (EOF(1) = True)
i = i + 1
Input #1, sday(i), eday(i), alphaemp(i), alphacal(i), alphanew(i)
Loop
```

```
Close 1
End Sub
Private Sub CD2_Click()
For s = 1 To ii
baseemp(s) = tf(s)
baseequ(s) = tf(s)
Next s
For s = 1 To ii
For d = 1 To i
If s >= sday(d) And s < eday(d) Then
baseemp(s + 1) = baseemp(s) + alphaemp(d) * (tf(s + 1) - baseemp(s))
baseequ(s + 1) = baseequ(s) + alphacal(d) * (tf(s + 1) - baseequ(s))
basenew(s + 1) = basenew(s) + alphanew(d) * (tf(s + 1) - basenew(s))
baseemp(eday(d)) = tf(eday(d))
baseequ(eday(d)) = tf(eday(d))
basenew(eday(d)) = tf(eday(d))
End If
Next d
Next s
zz = 0
For s = 1 To ii
If tf(s) <> 0 Then
zz = zz + 1
bemp(zz) = baseemp(s)
bequ(zz) = baseequ(s)
bnew(zz) = basenew(s)
bdday(zz) = dday(s)
bddate(zz) = ddate(s)
btf(zz) = tf(s)
End If
Next s
End Sub
Private Sub CD3_Click()
CC2.ShowSave
yy = CC2.FileName
Open yy For Output As #2
For j = 1 To zz
Print #2, bdday(j), bddate(j), btf(j), bemp(j), bequ(j), bnew(j)
Next j
Close 2
End Sub
Private Sub Command1_Click()
Unload Final
End
End Sub
Private Sub Command2_Click()
```

```
CC3.ShowOpen
yy = CC3.FileName
ii = 0
Open yy For Input As #1
Do Until (EOF(1) = True)
ii = ii + 1
Input #1, dday(ii), ddate(ii), tf(ii)
Loop
Close 1
End Sub
```

Appendix B

Summary of the Alpha Value Variation for the Little River Watershed

Table B.1. Summary of the Alpha value variation for watershed B for the period of 1972-1981 (Scenario I).

Year / Month	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	Average	SD
Jan	0.650	0.906	0.999	0.796	0.767	0.824	0.905	0.720	0.917	0.999	0.848	0.117
Feb	0.864	0.998	0.649	0.999	0.996	0.852	0.649	0.999	0.845	0.661	0.851	0.151
Mar	0.999	0.559	0.967	0.890	0.701	0.852	0.573	0.999	0.751	0.738	0.803	0.164
Apr	0.999	0.566	0.653	0.755	0.300	0.424	0.574	0.458	0.839	0.613	0.618	0.206
May	0.746	0.456	0.768	0.999	0.727	0.000	0.495	0.839	0.872	0.999	0.690	0.303
Jun	0.697	0.678	0.783	0.760	0.725	0.268	0.434	0.284	0.498	0.000	0.513	0.263
Jul	0.411	0.817	0.790	0.722	0.231	0.844	0.695	0.445	0.772	0.000	0.572	0.288
Aug	0.382	0.960	0.577	0.749	0.582	0.940	0.740	0.710	0.000	0.671	0.631	0.279
Sep	0.999	0.606	0.628	0.844	0.999	0.902	0.000	0.573	0.000	0.999	0.655	0.383
Oct	0.000	0.000	0.999	0.660	0.680	0.402	0.000	0.000	0.951	0.999	0.469	0.442
Nov	0.999	0.000	0.839	0.827	0.999	0.449	0.999	0.723	0.915	0.730	0.748	0.313
Dec	0.456	0.779	0.826	0.999	0.925	0.652	0.556	0.511	0.808	0.895	0.741	0.187
Avg.	0.683	0.610	0.790	0.833	0.719	0.617	0.552	0.605	0.681	0.692	Total Avg.	0.678
SD	0.319	0.332	0.146	0.116	0.255	0.302	0.304	0.291	0.339	0.355	Total SD	0.288

Table B.2. Summary of the Alpha value variation for watershed F for the period of 1972-1981 (Scenario I).

Year / Month	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	Average	SD
Jan	0.872	0.323	0.842	0.351	0.551	0.745	0.539	0.460	0.522	0.000	0.520	0.263
Feb	0.768	0.555	0.711	0.632	0.597	0.707	0.648	0.580	0.908	0.487	0.659	0.120
Mar	0.862	0.675	0.541	0.585	0.544	0.641	0.617	0.898	0.423	0.815	0.660	0.154
Apr	0.583	0.868	0.595	0.529	0.571	0.580	0.530	0.669	0.743	0.999	0.667	0.157
May	0.218	0.705	0.372	0.643	0.945	0.999	0.746	0.661	0.659	0.000	0.595	0.312
Jun	0.597	0.797	0.711	0.809	0.577	0.076	0.510	0.745	0.185	0.000	0.501	0.304
Jul	0.690	0.551	0.252	0.801	0.583	0.760	0.573	0.505	0.560	0.000	0.527	0.240
Aug	0.129	0.789	0.424	0.581	0.999	0.782	0.537	0.539	0.000	0.511	0.529	0.299
Sep	0.000	0.617	0.903	0.500	0.747	0.700	0.000	0.637	0.000	0.999	0.510	0.379
Oct	0.000	0.240	0.385	0.753	0.822	0.999	0.000	0.820	0.000	0.930	0.495	0.413
Nov	0.000	0.000	0.707	0.623	0.739	0.601	0.999	0.555	0.000	0.794	0.502	0.367
Dec	0.787	0.844	0.711	0.655	0.625	0.802	0.849	0.999	0.000	0.443	0.671	0.280
Avg.	0.459	0.580	0.596	0.622	0.692	0.699	0.546	0.672	0.333	0.498	Total Avg.	0.570
SD	0.360	0.268	0.203	0.130	0.158	0.237	0.294	0.165	0.341	0.413	Total SD	0.284

Table B.3. Summary of the Alpha value variation for watershed I for the period of 1972-1981 (Scenario I).

Month \ Year	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	Average	SD
Jan	0.626	0.427	0.999	0.605	0.716	0.639	0.439	0.707	0.442	0.000	0.560	0.261
Feb	0.392	0.608	0.494	0.883	0.639	0.656	0.728	0.810	0.620	0.370	0.620	0.166
Mar	0.799	0.625	0.498	0.821	0.642	0.699	0.579	0.708	0.599	0.575	0.654	0.102
Apr	0.773	0.539	0.557	0.657	0.597	0.554	0.326	0.517	0.750	0.389	0.566	0.141
May	0.284	0.791	0.398	0.568	0.604	0.449	0.389	0.532	0.582	0.000	0.460	0.214
Jun	0.641	0.634	0.504	0.643	0.613	0.000	0.480	0.280	0.999	0.000	0.479	0.310
Jul	0.458	0.649	0.397	0.819	0.721	0.206	0.414	0.726	0.401	0.000	0.479	0.255
Aug	0.000	0.713	0.497	0.592	0.368	0.621	0.401	0.708	0.000	0.607	0.451	0.264
Sep	0.000	0.248	0.742	0.000	0.778	0.999	0.000	0.741	0.000	0.524	0.403	0.396
Oct	0.000	0.000	0.405	0.449	0.683	0.515	0.000	0.869	0.000	0.631	0.355	0.331
Nov	0.000	0.000	0.592	0.451	0.748	0.719	0.000	0.832	0.000	0.869	0.421	0.381
Dec	0.143	0.999	0.829	0.579	0.645	0.594	0.502	0.808	0.000	0.902	0.600	0.321
Avg.	0.343	0.519	0.576	0.589	0.646	0.554	0.355	0.686	0.366	0.405	Total Avg.	0.504
SD	0.315	0.303	0.188	0.231	0.105	0.254	0.237	0.167	0.355	0.338	Total SD	0.279

Table B.4. Summary of the Alpha value variation for watershed J for the period of 1972-1981 (Scenario I).

Year / Month	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	Average	SD
Jan	0.620	0.494	0.650	0.734	0.666	0.654	0.438	0.536	0.457	0.000	0.525	0.209
Feb	0.456	0.522	0.358	0.965	0.783	0.455	0.677	0.790	0.734	0.590	0.633	0.189
Mar	0.973	0.514	0.500	0.852	0.335	0.758	0.628	0.781	0.462	0.731	0.653	0.199
Apr	0.100	0.816	0.561	0.373	0.441	0.653	0.502	0.667	0.370	0.259	0.474	0.211
May	0.743	0.662	0.182	0.817	0.691	0.000	0.474	0.634	0.695	0.000	0.490	0.313
Jun	0.585	0.340	0.440	0.461	0.509	0.000	0.388	0.328	0.999	0.000	0.405	0.287
Jul	0.199	0.551	0.699	0.753	0.259	0.000	0.749	0.635	0.349	0.000	0.419	0.297
Aug	0.000	0.459	0.449	0.667	0.410	0.376	0.587	0.346	0.000	0.133	0.343	0.229
Sep	0.000	0.000	0.755	0.000	0.383	0.722	0.000	0.560	0.000	0.344	0.276	0.317
Oct	0.000	0.999	0.214	0.321	0.423	0.691	0.000	0.807	0.000	0.247	0.370	0.357
Nov	0.000	0.000	0.999	0.620	0.480	0.567	0.000	0.792	0.000	0.922	0.438	0.407
Dec	0.746	0.483	0.879	0.674	0.681	0.666	0.355	0.610	0.000	0.741	0.583	0.251
Avg.	0.368	0.487	0.557	0.603	0.505	0.462	0.400	0.624	0.339	0.331	Total Avg.	0.467
SD	0.358	0.287	0.251	0.270	0.163	0.299	0.267	0.163	0.347	0.335	Total SD	0.289

Table B.5. Summary of the Alpha value variation for watershed K for the period of 1972-1981 (Scenario I).

Month \ Year	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	Average	SD
Jan	0.582	0.601	0.647	0.553	0.572	0.544	0.525	0.447	0.294	0.000	0.476	0.194
Feb	0.782	0.611	0.716	0.683	0.498	0.620	0.887	0.633	0.703	0.000	0.613	0.240
Mar	0.753	0.653	0.617	0.833	0.691	0.701	0.670	0.679	0.627	0.669	0.689	0.063
Apr	0.732	0.596	0.622	0.596	0.557	0.189	0.627	0.311	0.469	0.620	0.532	0.165
May	0.394	0.563	0.999	0.729	0.603	0.000	0.254	0.520	0.416	0.000	0.448	0.311
Jun	0.571	0.587	0.365	0.443	0.555	0.000	0.432	0.192	0.656	0.000	0.380	0.240
Jul	0.477	0.609	0.279	0.373	0.209	0.000	0.537	0.288	0.535	0.000	0.331	0.217
Aug	0.000	0.352	0.385	0.455	0.550	0.583	0.286	0.159	0.000	0.797	0.357	0.256
Sep	0.000	0.475	0.636	0.722	0.504	0.577	0.000	0.463	0.000	0.515	0.389	0.279
Oct	0.000	0.000	0.635	0.169	0.473	0.999	0.000	0.391	0.000	0.367	0.303	0.337
Nov	0.000	0.000	0.397	0.634	0.757	0.715	0.000	0.624	0.000	0.713	0.384	0.344
Dec	0.448	0.628	0.411	0.555	0.643	0.654	0.000	0.689	0.000	0.766	0.479	0.274
Avg.	0.395	0.473	0.559	0.562	0.551	0.465	0.351	0.450	0.308	0.371	Total Avg.	0.448
SD	0.315	0.235	0.200	0.182	0.136	0.333	0.308	0.186	0.293	0.346	Total SD	0.267

Table B.6. Summary of the Alpha value variation for watershed M for the period of 1972-1981 (Scenario I).

Month \ Year	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	Average	SD
Jan	0.533	0.781	0.911	0.774	0.883	0.701	0.414	0.639	0.562	0.000	0.620	0.268
Feb	0.471	0.626	0.738	0.451	0.603	0.452	0.720	0.747	0.750	0.735	0.629	0.129
Mar	0.747	0.790	0.308	0.527	0.615	0.746	0.702	0.707	0.404	0.744	0.629	0.164
Apr	0.999	0.777	0.682	0.421	0.473	0.789	0.314	0.730	0.581	0.512	0.628	0.205
May	0.838	0.819	0.582	0.740	0.414	0.999	0.375	0.595	0.774	0.699	0.683	0.194
Jun	0.564	0.659	0.601	0.765	0.612	0.000	0.740	0.777	0.919	0.000	0.564	0.315
Jul	0.999	0.468	0.628	0.483	0.702	0.361	0.000	0.745	0.850	0.000	0.524	0.334
Aug	0.000	0.721	0.856	0.734	0.801	0.342	0.608	0.598	0.521	0.011	0.519	0.308
Sep	0.000	0.799	0.780	0.799	0.580	0.504	0.000	0.992	0.000	0.000	0.445	0.405
Oct	0.000	0.000	0.000	0.000	0.512	0.743	0.000	0.949	0.000	0.000	0.220	0.369
Nov	0.000	0.000	0.000	0.000	0.682	0.755	0.000	0.685	0.000	0.769	0.289	0.374
Dec	0.613	0.075	0.460	0.398	0.536	0.587	0.000	0.507	0.000	0.793	0.397	0.278
Avg.	0.480	0.543	0.545	0.508	0.618	0.582	0.323	0.723	0.447	0.355	Total Avg.	0.512
SD	0.392	0.328	0.303	0.281	0.134	0.267	0.315	0.140	0.359	0.376	Total SD	0.311

Table B.7. Summary of the Alpha value variation for watershed N for the period of 1972-1981 (Scenario I).

Year / Month	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	Average	SD
Jan	0.618	0.409	0.672	0.655	0.735	0.631	0.357	0.490	0.441	0.745	0.575	0.140
Feb	0.476	0.715	0.549	0.707	0.619	0.679	0.721	0.732	0.982	0.571	0.675	0.138
Mar	0.562	0.619	0.781	0.629	0.760	0.790	0.667	0.999	0.599	0.777	0.718	0.130
Apr	0.846	0.999	0.483	0.557	0.627	0.999	0.313	0.425	0.543	0.211	0.600	0.271
May	0.722	0.705	0.609	0.819	0.792	0.000	0.706	0.736	0.661	0.000	0.575	0.309
Jun	0.625	0.537	0.495	0.532	0.779	0.000	0.601	0.787	0.821	0.000	0.518	0.296
Jul	0.383	0.558	0.666	0.347	0.794	0.000	0.534	0.654	0.420	0.000	0.436	0.268
Aug	0.833	0.828	0.904	0.748	0.356	0.527	0.272	0.000	0.000	0.355	0.482	0.339
Sep	0.000	0.538	0.864	0.532	0.846	0.620	0.000	0.689	0.000	0.607	0.470	0.343
Oct	0.424	0.000	0.574	0.615	0.601	0.709	0.000	0.851	0.000	0.343	0.412	0.316
Nov	0.519	0.290	0.673	0.704	0.592	0.894	0.387	0.612	0.000	0.849	0.552	0.269
Dec	0.396	0.752	0.880	0.586	0.658	0.765	0.580	0.555	0.664	0.846	0.668	0.147
Avg.	0.534	0.579	0.679	0.619	0.680	0.551	0.428	0.627	0.428	0.442	Total Avg.	0.557
SD	0.230	0.262	0.148	0.123	0.134	0.355	0.251	0.252	0.350	0.335	Total SD	0.265

Table B.8. Summary of the Alpha value variation for watershed O for the period of 1972-1981 (Scenario I).

Year / Month	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	Average	SD
Jan	0.566	0.380	0.728	0.490	0.799	0.798	0.684	0.526	0.535	0.492	0.600	0.144
Feb	0.373	0.610	0.653	0.674	0.849	0.541	0.706	0.932	0.413	0.730	0.648	0.175
Mar	0.601	0.555	0.711	0.667	0.722	0.576	0.637	0.772	0.526	0.695	0.646	0.081
Apr	0.999	0.999	0.410	0.610	0.619	0.729	0.508	0.536	0.577	0.565	0.655	0.199
May	0.333	0.652	0.549	0.410	0.690	0.046	0.659	0.590	0.616	0.491	0.504	0.197
Jun	0.511	0.507	0.477	0.492	0.374	0.614	0.603	0.907	0.830	0.296	0.561	0.188
Jul	0.475	0.311	0.861	0.579	0.169	0.494	0.479	0.396	0.732	0.183	0.468	0.221
Aug	0.207	0.497	0.395	0.597	0.364	0.546	0.835	0.770	0.527	0.790	0.553	0.202
Sep	0.061	0.116	0.789	0.510	0.640	0.778	0.586	0.566	0.674	0.610	0.533	0.250
Oct	0.632	0.000	0.796	0.456	0.416	0.846	0.656	0.654	0.908	0.627	0.599	0.262
Nov	0.467	0.000	0.723	0.571	0.847	0.405	0.594	0.794	0.849	0.599	0.585	0.256
Dec	0.808	0.778	0.659	0.599	0.514	0.506	0.700	0.618	0.794	0.743	0.672	0.111
Avg.	0.503	0.450	0.646	0.555	0.584	0.573	0.637	0.672	0.665	0.568	Total Avg.	0.585
SD	0.252	0.306	0.155	0.083	0.217	0.216	0.095	0.163	0.157	0.181	Total SD	0.198

Table B.9. Summary of the Alpha value variation for watershed B for the period of 1972-1981 (Scenario II).

Month \ Year	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	Average	SD
Jan	0.914	0.868	0.967	1.000	1.000	0.904	0.895	1.000	1.000	0.958	0.951	0.051
Feb	0.910	0.803	1.000	1.000	0.875	1.000	1.000	1.000	1.000	0.878	0.947	0.074
Mar	1.000	1.000	1.000	1.000	1.000	0.832	1.000	1.000	0.888	0.965	0.969	0.060
Apr	1.000	0.919	0.944	0.895	1.000	0.962	1.000	0.852	0.860	1.000	0.943	0.059
May	1.000	1.000	0.761	1.000	1.000	0.000	1.000	1.000	0.981	1.000	0.874	0.316
Jun	1.000	1.000	0.947	1.000	1.000	1.000	1.000	1.000	1.000	0.000	0.895	0.315
Jul	1.000	0.978	0.911	0.956	1.000	0.866	0.884	0.975	0.928	0.000	0.850	0.302
Aug	1.000	1.000	0.926	1.000	0.988	1.000	0.999	0.906	0.000	0.956	0.877	0.310
Sep	0.833	1.000	1.000	1.000	1.000	0.892	0.000	0.975	0.000	1.000	0.770	0.410
Oct	0.000	0.000	1.000	1.000	0.969	1.000	0.000	0.000	1.000	0.915	0.588	0.507
Nov	1.000	0.000	1.000	0.969	1.000	1.000	1.000	1.000	0.928	1.000	0.890	0.313
Dec	1.000	1.000	1.000	1.000	0.888	1.000	0.755	1.000	0.967	0.984	0.959	0.080
Avg.	0.888	0.797	0.955	0.985	0.977	0.871	0.794	0.892	0.796	0.805	Total Avg.	0.876
SD	0.285	0.378	0.069	0.032	0.045	0.281	0.379	0.285	0.375	0.378	Total SD	0.285

Table B.10. Summary of the Alpha value variation for watershed F for the period of 1972-1981 (Scenario II).

Year / Month	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	Average	SD
Jan	1.000	1.000	1.000	0.981	1.000	0.902	0.800	0.957	1.000	0.000	0.864	0.310
Feb	0.967	0.807	0.715	1.000	1.000	0.926	1.000	1.000	1.000	0.909	0.932	0.099
Mar	0.899	0.927	0.946	0.825	1.000	0.688	1.000	1.000	0.880	0.980	0.914	0.099
Apr	1.000	0.837	0.642	0.844	0.958	1.000	1.000	0.972	0.959	1.000	0.921	0.116
May	1.000	0.928	0.870	1.000	0.822	1.000	0.953	0.956	0.996	0.000	0.853	0.306
Jun	0.877	0.914	0.977	1.000	1.000	0.851	0.910	0.872	1.000	0.000	0.840	0.301
Jul	0.948	0.861	0.964	0.840	0.935	0.836	0.989	0.887	0.819	0.000	0.808	0.290
Aug	0.976	0.938	0.973	0.960	1.000	0.948	0.949	0.989	0.000	0.876	0.861	0.304
Sep	0.000	0.973	0.944	0.944	1.000	1.000	0.000	0.971	0.000	1.000	0.683	0.472
Oct	0.000	1.000	0.944	0.944	0.981	1.000	0.000	1.000	0.000	0.980	0.685	0.473
Nov	0.000	0.000	1.000	0.932	0.940	1.000	1.000	1.000	0.000	1.000	0.687	0.475
Dec	1.000	1.000	1.000	0.975	0.968	1.000	0.846	1.000	0.000	1.000	0.879	0.312
Avg.	0.722	0.849	0.915	0.937	0.967	0.929	0.787	0.967	0.555	0.645	Total Avg.	0.827
SD	0.437	0.275	0.117	0.065	0.052	0.097	0.373	0.044	0.492	0.478	Total SD	0.321

Table B.11. Summary of the Alpha value variation for watershed I for the period of 1972-1981 (Scenario II).

Year / Month	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	Average	SD
Jan	0.993	0.907	1.000	0.981	0.884	0.907	0.733	0.976	0.874	0.000	0.825	0.301
Feb	0.959	0.823	0.773	0.941	0.913	0.918	0.927	0.949	0.922	1.000	0.912	0.066
Mar	0.958	0.914	0.967	0.772	0.909	0.769	0.876	0.944	0.753	1.000	0.886	0.091
Apr	1.000	0.723	0.769	0.812	0.887	0.924	0.983	0.903	0.984	1.000	0.899	0.100
May	0.974	0.967	0.911	1.000	0.840	1.000	0.906	0.960	0.908	0.000	0.847	0.302
Jun	0.655	0.844	0.936	0.846	0.962	0.000	0.927	0.856	1.000	0.000	0.703	0.382
Jul	0.947	0.813	0.902	0.763	0.943	0.926	0.808	0.907	0.948	0.000	0.796	0.287
Aug	0.000	0.867	0.820	0.967	0.992	0.896	0.864	0.795	0.000	0.788	0.699	0.374
Sep	0.000	1.000	0.954	0.000	1.000	1.000	0.000	0.876	0.000	1.000	0.583	0.503
Oct	0.000	0.000	0.891	0.548	0.910	1.000	0.000	1.000	0.000	0.928	0.528	0.471
Nov	0.000	0.000	0.795	1.000	0.907	1.000	0.000	0.958	0.000	1.000	0.566	0.491
Dec	1.000	1.000	0.961	1.000	1.000	0.982	1.000	1.000	0.000	0.846	0.879	0.313
Avg.	0.624	0.738	0.890	0.802	0.929	0.860	0.669	0.927	0.533	0.630	Total Avg.	0.760
SD	0.470	0.354	0.081	0.287	0.051	0.279	0.409	0.062	0.474	0.470	Total SD	0.351

Table B.12. Summary of the Alpha value variation for watershed J for the period of 1972-1981 (Scenario II).

Month \ Year	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	Average	SD
Jan	0.980	0.927	1.000	0.978	0.980	0.936	0.792	0.964	0.891	0.000	0.845	0.303
Feb	0.961	0.862	0.692	0.913	1.000	0.923	0.938	0.941	1.000	0.765	0.899	0.100
Mar	0.962	0.907	0.929	0.779	0.990	0.763	0.883	1.000	0.708	0.871	0.879	0.100
Apr	1.000	0.859	0.740	0.821	0.899	0.967	0.816	0.902	0.920	1.000	0.892	0.085
May	0.828	0.951	0.947	1.000	0.837	0.000	0.811	0.952	0.921	0.000	0.725	0.387
Jun	0.636	0.927	0.899	0.901	0.845	0.000	0.910	1.000	1.000	0.000	0.712	0.389
Jul	0.873	0.779	0.945	0.895	0.901	0.000	1.000	0.973	0.894	0.000	0.726	0.387
Aug	0.000	0.895	0.892	0.784	0.804	0.909	0.895	0.747	0.000	0.619	0.654	0.356
Sep	0.000	0.000	0.811	0.000	0.950	1.000	0.000	0.820	0.000	0.832	0.441	0.469
Oct	0.000	1.000	0.958	0.777	0.912	1.000	0.000	0.964	0.000	0.422	0.603	0.450
Nov	0.000	0.000	1.000	0.965	0.842	1.000	0.000	0.958	0.000	0.928	0.569	0.492
Dec	1.000	0.725	0.948	1.000	0.953	0.866	0.734	0.967	0.000	0.880	0.807	0.301
Avg.	0.603	0.736	0.897	0.818	0.909	0.697	0.648	0.932	0.528	0.526	Total Avg.	0.729
SD	0.457	0.352	0.099	0.271	0.066	0.426	0.397	0.076	0.472	0.416	Total SD	0.359

Table B.13. Summary of the Alpha value variation for watershed K for the period of 1972-1981 (Scenario II).

Year / Month	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	Average	SD
Jan	0.963	0.902	0.934	0.924	0.861	0.809	0.748	0.853	0.878	0.000	0.787	0.284
Feb	0.896	0.907	0.770	0.867	0.921	0.944	0.950	0.776	0.922	0.000	0.795	0.287
Mar	0.921	0.935	0.972	0.719	0.914	0.762	0.933	0.972	0.615	0.887	0.863	0.122
Apr	1.000	0.926	0.798	0.821	0.882	0.989	0.909	0.971	0.896	0.724	0.891	0.089
May	0.817	0.907	1.000	1.000	0.834	0.000	0.890	0.947	0.917	0.000	0.731	0.390
Jun	0.635	0.856	0.858	0.943	0.913	0.000	0.882	0.910	0.871	0.000	0.687	0.372
Jul	0.972	0.789	0.944	0.834	0.887	0.778	0.768	0.847	0.905	0.000	0.772	0.280
Aug	0.000	0.850	0.907	0.920	1.000	1.000	1.000	0.805	0.000	0.807	0.729	0.391
Sep	0.000	0.880	0.955	0.916	0.951	1.000	0.000	0.816	0.000	1.000	0.652	0.453
Oct	0.000	0.000	0.846	0.921	0.868	0.833	0.000	0.972	0.000	0.555	0.499	0.443
Nov	0.668	0.000	0.846	0.817	0.967	0.923	0.000	1.000	0.000	1.000	0.622	0.440
Dec	0.959	0.968	0.901	0.976	0.889	0.897	0.000	0.954	0.000	0.955	0.750	0.396
Avg.	0.653	0.743	0.894	0.888	0.907	0.745	0.590	0.902	0.500	0.494	Total Avg.	0.732
SD	0.410	0.350	0.071	0.079	0.047	0.358	0.441	0.078	0.449	0.453	Total SD	0.348

Table B.14. Summary of the Alpha value variation for watershed M for the period of 1972-1981 (Scenario II).

Year / Month	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	Average	SD
Jan	0.857	0.838	1.000	0.902	0.895	0.843	0.782	0.882	0.818	0.000	0.782	0.281
Feb	0.886	0.931	0.726	1.000	1.000	0.849	0.947	0.904	0.911	0.705	0.886	0.101
Mar	1.000	0.792	1.000	0.593	0.975	0.800	0.926	0.942	0.706	0.946	0.868	0.139
Apr	1.000	0.726	0.769	0.752	0.768	0.943	0.875	0.787	0.939	0.954	0.851	0.101
May	0.858	0.927	0.864	1.000	0.692	0.833	0.933	0.932	0.951	0.863	0.885	0.085
Jun	0.527	0.828	0.809	0.894	0.898	0.000	0.884	0.949	0.858	0.000	0.665	0.369
Jul	0.848	0.680	0.832	0.744	0.760	0.391	0.000	0.882	0.836	0.254	0.623	0.302
Aug	0.000	0.896	0.866	0.945	0.788	0.787	0.704	0.912	0.691	0.456	0.704	0.286
Sep	0.000	0.889	0.891	0.828	0.892	1.000	0.000	0.834	0.000	0.000	0.533	0.461
Oct	0.000	0.000	0.833	0.000	0.956	0.856	0.000	0.934	0.000	0.434	0.401	0.446
Nov	0.000	0.000	0.000	0.000	0.899	0.944	0.000	0.871	0.000	0.917	0.363	0.469
Dec	0.486	0.810	0.944	0.958	0.868	0.755	0.000	1.000	0.000	0.836	0.666	0.379
Avg.	0.538	0.693	0.795	0.718	0.866	0.750	0.504	0.902	0.559	0.530	Total Avg.	0.686
SD	0.427	0.332	0.264	0.356	0.095	0.281	0.450	0.057	0.420	0.390	Total SD	0.349

Table B.15. Summary of the Alpha value variation for watershed N for the period of 1972-1981 (Scenario II).

Year / Month	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	Average	SD
Jan	0.972	0.799	0.865	0.822	0.897	0.800	0.758	0.912	0.884	0.942	0.865	0.069
Feb	0.890	0.959	0.899	0.985	0.967	0.836	0.988	0.932	0.963	0.958	0.938	0.049
Mar	0.998	0.920	0.938	0.739	0.935	0.589	0.946	1.000	0.673	0.873	0.861	0.143
Apr	0.949	0.890	0.537	0.649	0.745	1.000	0.953	0.890	0.971	1.000	0.858	0.161
May	0.949	0.965	0.782	0.884	0.794	1.000	0.911	0.953	0.845	0.000	0.808	0.293
Jun	0.631	0.917	0.786	0.967	1.000	0.000	0.902	0.956	0.916	0.000	0.707	0.388
Jul	0.876	0.786	0.934	0.968	0.892	0.000	0.881	0.835	0.899	0.000	0.707	0.376
Aug	0.900	0.910	0.926	0.814	0.731	0.809	0.996	0.000	0.000	0.864	0.695	0.373
Sep	0.000	0.903	0.681	1.000	0.905	0.882	0.000	0.975	0.000	0.846	0.619	0.436
Oct	0.525	0.000	0.956	0.881	0.782	0.998	0.000	1.000	0.000	0.954	0.610	0.443
Nov	0.987	0.978	0.942	0.927	0.964	0.933	0.723	0.920	0.000	0.910	0.828	0.300
Dec	0.829	0.973	0.967	0.909	0.881	0.989	0.847	0.944	1.000	0.848	0.919	0.064
Avg.	0.792	0.833	0.851	0.879	0.874	0.736	0.742	0.860	0.596	0.683	Total Avg.	0.785
SD	0.289	0.270	0.132	0.107	0.091	0.364	0.356	0.275	0.448	0.415	Total SD	0.302

Table B.16. Summary of the Alpha value variation for watershed O for the period of 1972-1981 (Scenario II).

Month \ Year	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	Average	SD
Jan	0.803	0.822	0.943	0.835	0.789	0.891	0.690	0.792	0.906	0.980	0.845	0.086
Feb	0.884	0.879	0.806	0.973	0.913	0.854	0.941	0.887	0.896	0.925	0.896	0.046
Mar	1.000	0.910	0.920	0.764	0.919	0.681	0.897	0.996	0.717	0.908	0.871	0.112
Apr	1.000	0.874	0.672	0.714	0.822	0.986	0.928	0.835	0.927	0.958	0.872	0.112
May	0.904	0.939	0.851	1.000	0.889	1.000	0.820	0.980	0.853	0.908	0.915	0.064
Jun	0.631	0.826	0.742	0.914	0.877	0.804	0.953	0.971	0.907	0.929	0.855	0.106
Jul	0.739	0.818	0.895	1.000	0.906	0.892	0.906	0.991	0.911	0.962	0.902	0.078
Aug	1.000	0.989	0.888	0.893	0.000	0.932	0.947	0.923	0.950	0.821	0.834	0.298
Sep	1.000	1.000	0.991	0.946	1.000	0.970	1.000	0.977	0.972	0.862	0.972	0.043
Oct	0.676	0.000	0.888	0.885	0.697	0.940	0.958	1.000	0.873	0.909	0.783	0.294
Nov	0.953	0.000	0.914	0.971	0.930	0.855	1.000	0.952	0.916	0.929	0.842	0.298
Dec	0.945	0.885	0.943	0.949	0.927	0.940	0.800	0.945	0.966	0.827	0.913	0.057
Avg.	0.878	0.745	0.871	0.904	0.806	0.895	0.903	0.937	0.899	0.910	Total Avg.	0.875
SD	0.134	0.353	0.091	0.092	0.266	0.089	0.091	0.067	0.067	0.051	Total SD	0.164

Table B.17. Summary of the Alpha value variation for watershed B for the period of 1972-1981 (Scenario III).

Year / Month	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	Average	SD
Jan	0.921	0.825	0.972	0.923	1.000	0.909	0.910	0.976	1.000	0.958	0.939	0.053
Feb	0.912	0.810	1.000	1.000	0.871	1.000	1.000	1.000	1.000	0.884	0.948	0.072
Mar	1.000	1.000	1.000	0.918	1.000	0.839	1.000	1.000	0.892	0.968	0.962	0.058
Apr	1.000	0.822	0.939	0.905	1.000	0.965	1.000	0.856	0.865	1.000	0.935	0.069
May	1.000	1.000	0.772	1.000	0.911	0.000	1.000	1.000	0.983	0.916	0.858	0.310
Jun	1.000	0.996	0.807	1.000	1.000	1.000	1.000	1.000	1.000	0.000	0.880	0.315
Jul	1.000	0.980	0.914	0.954	1.000	0.868	0.892	0.978	0.933	0.000	0.852	0.303
Aug	1.000	1.000	0.933	1.000	0.988	0.996	1.000	0.894	0.000	0.961	0.877	0.310
Sep	0.833	1.000	1.000	1.000	1.000	0.891	0.000	0.977	0.000	1.000	0.770	0.410
Oct	0.000	0.000	1.000	1.000	0.971	1.000	0.000	0.000	1.000	0.915	0.589	0.507
Nov	1.000	0.000	0.964	0.969	1.000	1.000	1.000	1.000	0.928	1.000	0.886	0.312
Dec	1.000	1.000	1.000	1.000	0.890	0.951	0.763	1.000	0.967	0.991	0.956	0.077
Avg.	0.889	0.786	0.942	0.972	0.969	0.868	0.797	0.890	0.797	0.799	Total Avg.	0.871
SD	0.285	0.375	0.078	0.038	0.049	0.279	0.379	0.284	0.375	0.375	Total SD	0.283

Table B.18. Summary of the Alpha value variation for watershed F for the period of 1972-1981 (Scenario III).

Month \ Year	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	Average	SD
Jan	0.951	1.000	0.994	0.983	1.000	0.908	0.809	0.965	1.000	0.000	0.861	0.308
Feb	0.972	0.763	0.626	1.000	0.925	0.931	1.000	1.000	1.000	0.914	0.913	0.124
Mar	0.898	0.932	0.951	0.827	0.916	0.699	1.000	1.000	0.883	0.983	0.909	0.092
Apr	0.916	0.472	0.659	0.854	0.958	1.000	0.967	0.977	0.964	1.000	0.877	0.175
May	1.000	0.884	0.875	1.000	0.660	1.000	0.849	0.960	0.997	0.000	0.823	0.308
Jun	0.896	0.917	0.982	0.942	1.000	0.853	0.916	0.817	1.000	0.000	0.832	0.299
Jul	0.859	0.871	0.964	0.808	0.941	0.781	0.992	0.841	0.792	0.000	0.785	0.285
Aug	0.983	0.940	0.976	0.929	1.000	0.895	0.960	0.967	0.000	0.836	0.849	0.302
Sep	0.000	0.898	0.834	0.943	1.000	0.926	0.000	0.983	0.000	1.000	0.658	0.457
Oct	0.000	1.000	0.944	0.770	0.985	1.000	0.000	0.944	0.000	0.989	0.663	0.462
Nov	0.000	0.000	1.000	0.932	0.948	0.985	0.915	1.000	0.000	1.000	0.678	0.469
Dec	1.000	1.000	1.000	0.978	0.959	0.978	0.851	1.000	0.000	1.000	0.876	0.311
Avg.	0.706	0.806	0.900	0.914	0.941	0.913	0.772	0.955	0.553	0.643	Total Avg.	0.810
SD	0.428	0.292	0.131	0.079	0.093	0.095	0.366	0.062	0.492	0.478	Total SD	0.320

Table B.19. Summary of the Alpha value variation for watershed I for the period of 1972-1981 (Scenario III).

Year / Month	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	Average	SD
Jan	0.932	0.915	1.000	0.983	0.891	0.854	0.746	0.977	0.878	0.000	0.818	0.297
Feb	0.964	0.774	0.750	0.943	0.915	0.922	0.929	0.949	0.925	1.000	0.907	0.081
Mar	0.957	0.917	0.967	0.774	0.910	0.776	0.880	0.944	0.761	1.000	0.889	0.088
Apr	0.944	0.532	0.776	0.816	0.891	0.887	0.987	0.907	0.988	1.000	0.873	0.141
May	0.980	0.925	0.870	1.000	0.712	1.000	0.905	0.960	0.910	0.000	0.826	0.302
Jun	0.537	0.854	0.926	0.846	0.961	0.000	0.930	0.851	1.000	0.000	0.691	0.385
Jul	0.935	0.817	0.906	0.773	0.841	0.940	0.815	0.884	0.953	0.000	0.787	0.283
Aug	0.000	0.845	0.824	0.805	0.872	0.900	0.876	0.654	0.000	0.795	0.657	0.353
Sep	0.000	1.000	0.678	0.000	1.000	1.000	0.000	0.886	0.000	1.000	0.556	0.489
Oct	0.000	0.000	0.895	0.561	0.915	1.000	0.000	0.955	0.000	0.798	0.512	0.456
Nov	0.000	0.000	0.801	1.000	0.916	1.000	0.000	0.958	0.000	0.841	0.552	0.479
Dec	1.000	0.667	0.865	1.000	1.000	0.983	1.000	1.000	0.000	0.847	0.836	0.313
Avg.	0.604	0.687	0.855	0.792	0.902	0.855	0.672	0.911	0.535	0.607	Total Avg.	0.742
SD	0.462	0.344	0.093	0.282	0.076	0.278	0.411	0.092	0.476	0.455	Total SD	0.347

Table B.20. Summary of the Alpha value variation for watershed J for the period of 1972-1981 (Scenario III).

Year / Month	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	Average	SD
Jan	0.986	0.932	1.000	0.981	0.984	0.941	0.798	0.967	0.895	0.000	0.848	0.304
Feb	0.965	0.873	0.703	0.914	1.000	0.927	0.940	0.941	1.000	0.769	0.903	0.097
Mar	0.961	0.910	0.935	0.783	0.991	0.770	0.892	1.000	0.717	0.875	0.883	0.097
Apr	1.000	0.861	0.745	0.828	0.904	0.971	0.828	0.906	0.926	1.000	0.897	0.083
May	0.833	0.957	0.950	1.000	0.847	0.000	0.817	0.953	0.922	0.000	0.728	0.388
Jun	0.650	0.931	0.905	0.901	0.855	0.000	0.910	1.000	1.000	0.000	0.715	0.389
Jul	0.880	0.785	0.949	0.898	0.910	0.000	1.000	0.975	0.905	0.000	0.730	0.389
Aug	0.000	0.898	0.894	0.785	0.808	0.911	0.906	0.762	0.000	0.631	0.660	0.358
Sep	0.000	0.000	0.825	0.000	0.949	1.000	0.000	0.829	0.000	0.839	0.444	0.471
Oct	0.000	1.000	0.966	0.783	0.915	1.000	0.000	0.964	0.000	0.442	0.607	0.450
Nov	0.000	0.000	1.000	0.965	0.855	1.000	0.000	0.958	0.000	0.928	0.571	0.493
Dec	1.000	0.737	0.950	1.000	0.954	0.872	0.743	0.967	0.000	0.882	0.810	0.300
Avg.	0.606	0.740	0.902	0.820	0.914	0.699	0.653	0.935	0.530	0.531	Total Avg.	0.733
SD	0.458	0.353	0.096	0.271	0.063	0.427	0.399	0.071	0.473	0.417	Total SD	0.360

Table B.21. Summary of the Alpha value variation for watershed K for the period of 1972-1981 (Scenario III).

Year / Month	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	Average	SD
Jan	0.967	0.905	0.933	0.926	0.865	0.815	0.755	0.858	0.881	0.000	0.791	0.284
Feb	0.899	0.919	0.777	0.867	0.922	0.945	0.950	0.779	0.924	0.000	0.798	0.287
Mar	0.922	0.936	0.972	0.720	0.916	0.767	0.939	0.972	0.628	0.890	0.866	0.119
Apr	1.000	0.934	0.802	0.826	0.885	0.991	0.913	0.977	0.901	0.731	0.896	0.088
May	0.819	0.910	1.000	1.000	0.846	0.000	0.893	0.947	0.919	0.000	0.733	0.391
Jun	0.648	0.858	0.862	0.940	0.914	0.000	0.884	0.909	0.872	0.000	0.689	0.372
Jul	0.974	0.793	0.947	0.841	0.891	0.789	0.781	0.856	0.909	0.000	0.778	0.281
Aug	0.000	0.853	0.914	0.920	1.000	1.000	1.000	0.815	0.000	0.816	0.732	0.392
Sep	0.000	0.880	0.955	0.916	0.951	1.000	0.000	0.817	0.000	1.000	0.652	0.453
Oct	0.000	0.000	0.849	0.926	0.870	0.833	0.000	0.972	0.000	0.564	0.501	0.444
Nov	0.672	0.000	0.852	0.819	0.967	0.923	0.000	1.000	0.000	1.000	0.623	0.441
Dec	0.962	0.984	0.903	0.979	0.891	0.900	0.000	0.953	0.000	0.957	0.753	0.398
Avg.	0.655	0.748	0.897	0.890	0.910	0.747	0.593	0.905	0.503	0.497	Total Avg.	0.734
SD	0.411	0.353	0.069	0.078	0.045	0.358	0.443	0.076	0.451	0.454	Total SD	0.349

Table B.22. Summary of the Alpha value variation for watershed M for the period of 1972-1981 (Scenario III).

Year / Month	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	Average	SD
Jan	0.865	0.843	1.000	0.901	0.899	0.847	0.786	0.885	0.824	0.000	0.785	0.282
Feb	0.891	0.941	0.731	1.000	1.000	0.853	0.950	0.910	0.913	0.710	0.890	0.100
Mar	1.000	0.794	1.000	0.593	0.977	0.806	0.932	0.942	0.716	0.948	0.871	0.138
Apr	1.000	0.741	0.774	0.758	0.772	0.944	0.882	0.796	0.943	0.954	0.856	0.098
May	0.860	0.932	0.867	1.000	0.703	0.833	0.936	0.935	0.950	0.863	0.888	0.083
Jun	0.542	0.835	0.815	0.894	0.906	0.000	0.885	0.949	0.863	0.000	0.669	0.370
Jul	0.846	0.684	0.835	0.754	0.767	0.401	0.000	0.888	0.837	0.271	0.628	0.301
Aug	0.000	0.898	0.864	0.942	0.793	0.792	0.709	0.914	0.695	0.470	0.708	0.285
Sep	0.000	0.888	0.890	0.828	0.895	1.000	0.000	0.840	0.000	0.000	0.534	0.462
Oct	0.000	0.000	0.833	0.000	0.954	0.857	0.000	0.934	0.000	0.464	0.404	0.446
Nov	0.000	0.000	0.000	0.000	0.905	0.946	0.000	0.873	0.000	0.923	0.365	0.471
Dec	0.516	0.836	0.944	0.958	0.870	0.763	0.000	1.000	0.000	0.837	0.672	0.379
Avg.	0.543	0.699	0.796	0.719	0.870	0.753	0.506	0.905	0.562	0.537	Total Avg.	0.689
SD	0.428	0.335	0.264	0.356	0.092	0.281	0.452	0.054	0.422	0.389	Total SD	0.350

Table B.23. Summary of the Alpha value variation for watershed N for the period of 1972-1981 (Scenario III).

Year / Month	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	Average	SD
Jan	0.976	0.807	0.874	0.828	0.902	0.805	0.767	0.918	0.888	0.943	0.871	0.067
Feb	0.895	0.969	0.904	0.989	0.967	0.842	0.990	0.934	0.962	0.962	0.941	0.048
Mar	0.998	0.923	0.943	0.743	0.937	0.600	0.958	1.000	0.680	0.875	0.866	0.141
Apr	0.953	0.891	0.558	0.662	0.760	1.000	0.961	0.897	0.977	1.000	0.866	0.154
May	0.950	0.965	0.788	0.891	0.804	1.000	0.913	0.957	0.855	0.000	0.812	0.294
Jun	0.643	0.920	0.792	0.971	1.000	0.000	0.909	0.956	0.916	0.000	0.711	0.388
Jul	0.886	0.795	0.938	0.970	0.895	0.000	0.888	0.844	0.909	0.000	0.712	0.378
Aug	0.909	0.911	0.931	0.822	0.743	0.817	0.999	0.000	0.000	0.874	0.701	0.376
Sep	0.000	0.913	0.691	1.000	0.909	0.890	0.000	0.985	0.000	0.851	0.624	0.439
Oct	0.527	0.000	0.956	0.886	0.791	1.000	0.000	1.000	0.000	0.966	0.613	0.445
Nov	0.989	0.980	0.942	0.928	0.977	0.937	0.754	0.927	0.000	0.912	0.835	0.301
Dec	0.841	0.976	0.967	0.911	0.886	0.990	0.852	0.947	1.000	0.852	0.922	0.061
Avg.	0.797	0.837	0.857	0.883	0.881	0.740	0.749	0.864	0.599	0.686	Total Avg.	0.789
SD	0.289	0.271	0.127	0.104	0.087	0.364	0.358	0.276	0.450	0.416	Total SD	0.303

Table B.24. Summary of the Alpha value variation for watershed O for the period of 1972-1981 (Scenario III).

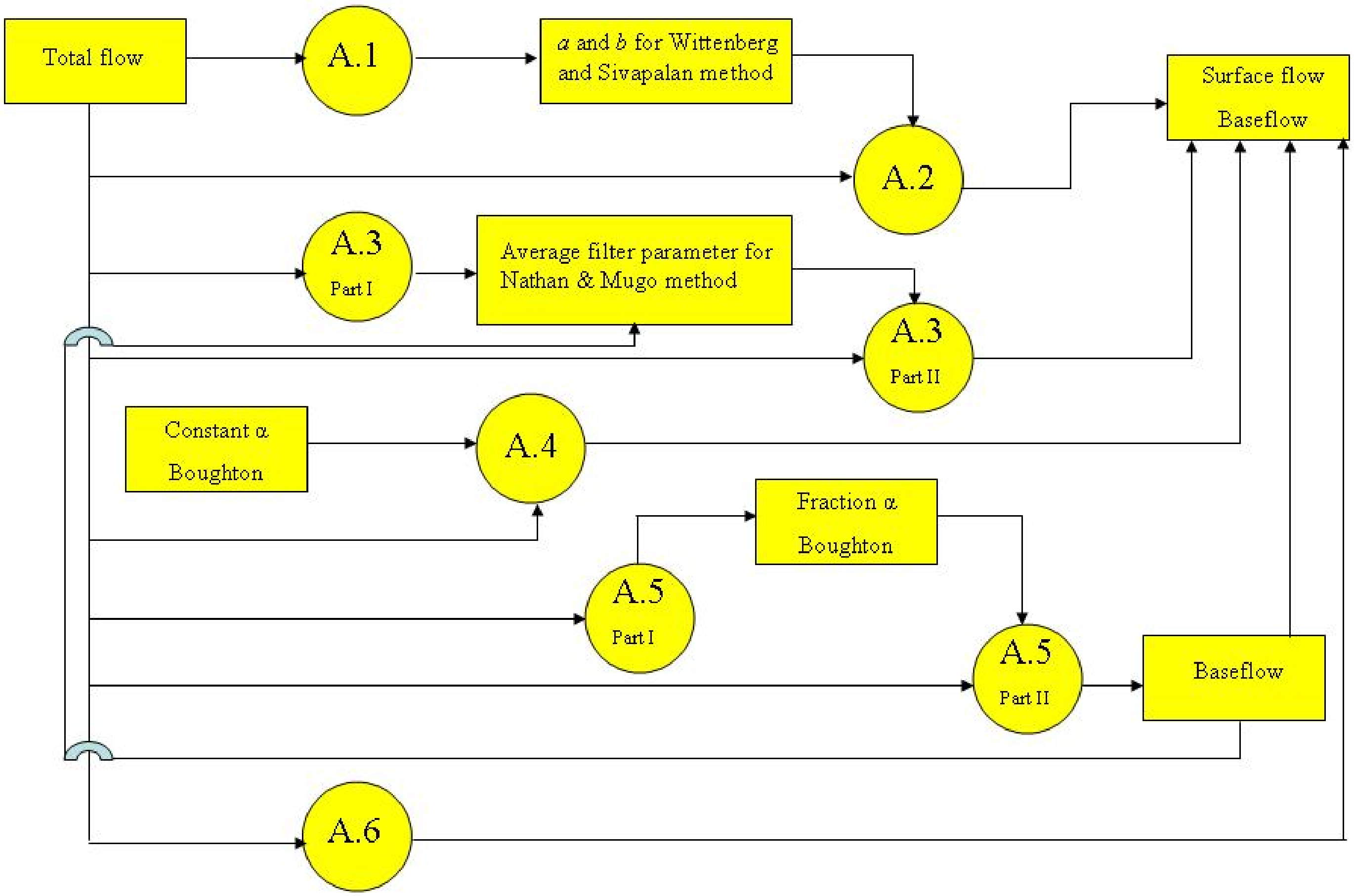
Year / Month	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	Average	SD
Jan	0.809	0.827	0.948	0.844	0.795	0.894	0.700	0.799	0.909	0.982	0.851	0.083
Feb	0.890	0.887	0.813	0.976	0.913	0.858	0.941	0.888	0.900	0.926	0.899	0.045
Mar	1.000	0.912	0.924	0.767	0.922	0.691	0.906	0.997	0.724	0.908	0.875	0.109
Apr	1.000	0.874	0.688	0.725	0.830	0.991	0.933	0.837	0.932	0.958	0.877	0.107
May	0.907	0.941	0.857	1.000	0.896	1.000	0.825	0.982	0.863	0.911	0.918	0.062
Jun	0.647	0.834	0.750	0.915	0.884	0.808	0.957	0.971	0.912	0.931	0.861	0.102
Jul	0.752	0.828	0.898	1.000	0.906	0.897	0.916	0.994	0.917	0.962	0.907	0.074
Aug	1.000	0.991	0.896	0.901	0.000	0.934	0.948	0.926	0.950	0.824	0.837	0.298
Sep	1.000	1.000	0.993	0.949	1.000	0.974	1.000	0.979	0.972	0.866	0.973	0.041
Oct	0.676	0.000	0.888	0.888	0.706	0.940	0.958	1.000	0.878	0.912	0.785	0.295
Nov	0.956	0.000	0.915	0.971	0.931	0.862	1.000	0.954	0.916	0.932	0.844	0.299
Dec	0.951	0.887	0.943	0.955	0.930	0.940	0.800	0.949	0.966	0.833	0.915	0.057
Avg.	0.882	0.748	0.876	0.908	0.809	0.899	0.907	0.940	0.903	0.912	Total Avg.	0.878
SD	0.130	0.354	0.087	0.089	0.266	0.087	0.089	0.066	0.065	0.049	Total SD	0.163

Appendix C

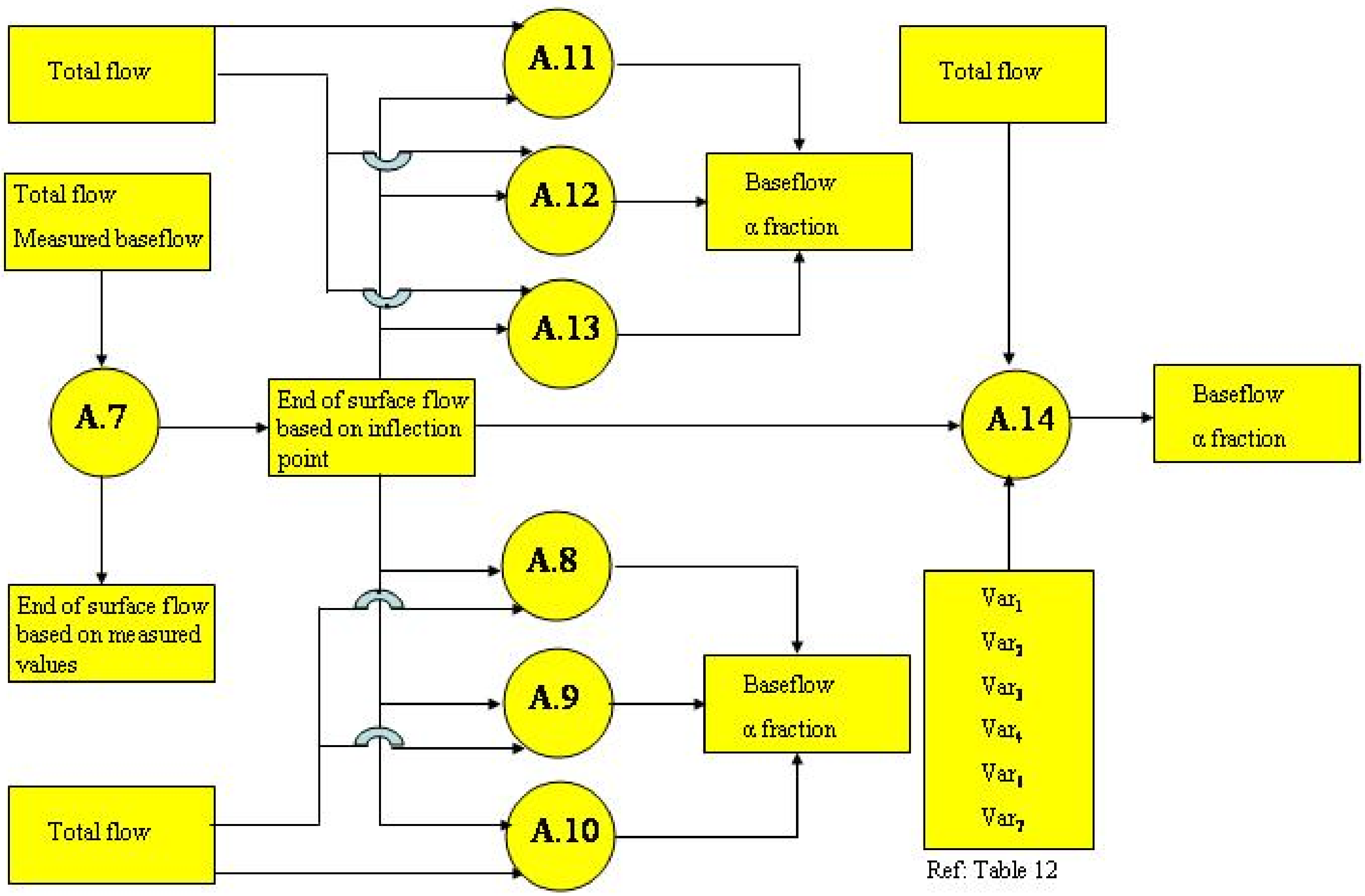
Flow charts of developed programs listed in Appendix A

In the following section, couple of flow charts were provided to show the relationship between developed programs to achieve the objectives under modeling phase of this study (chapter 4). In the following flow charts, a circle represents a program ID based on Appendix A. Rectangular represents input and output from a program.

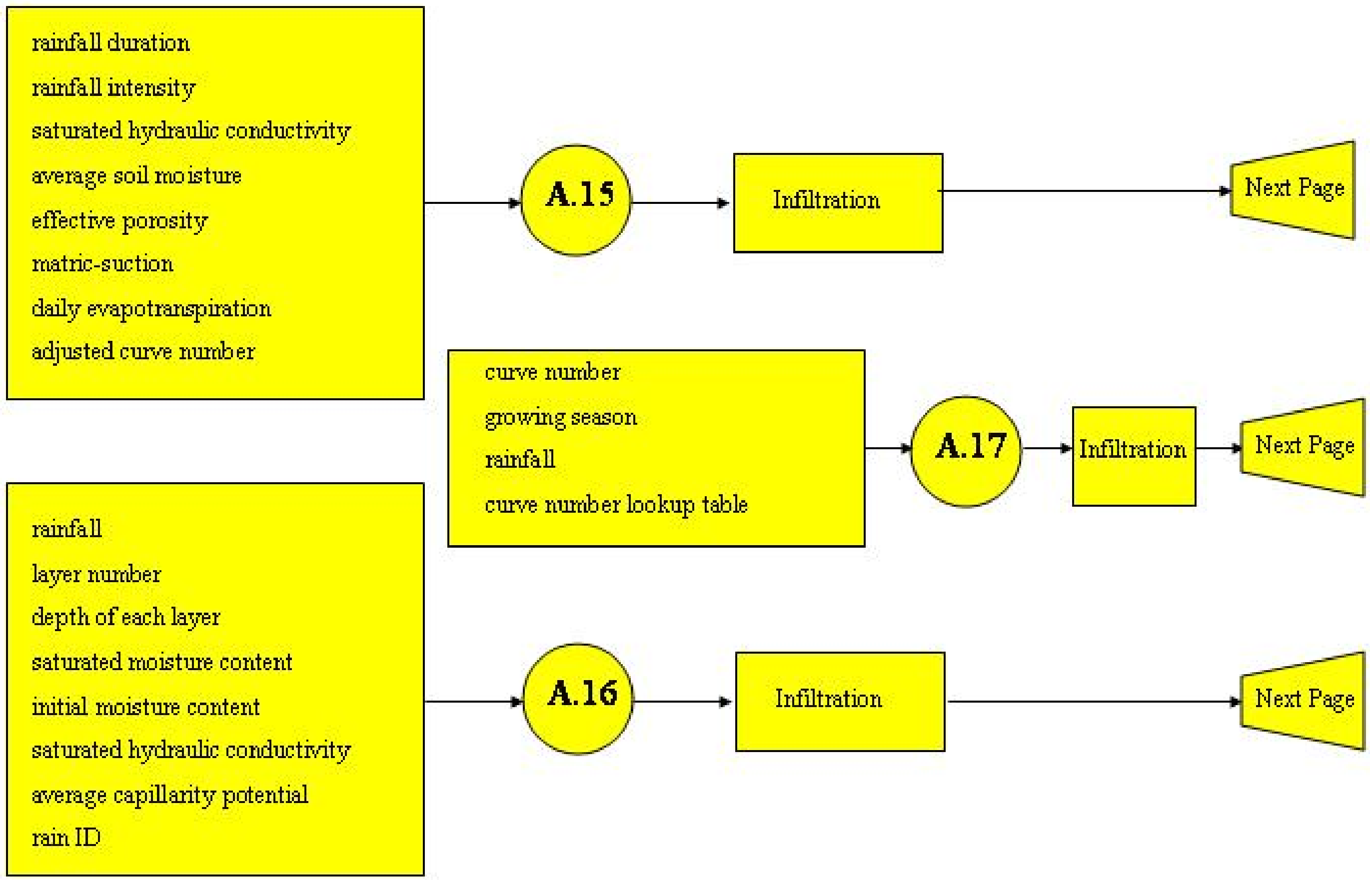
C.1 Model Determination and Evaluation



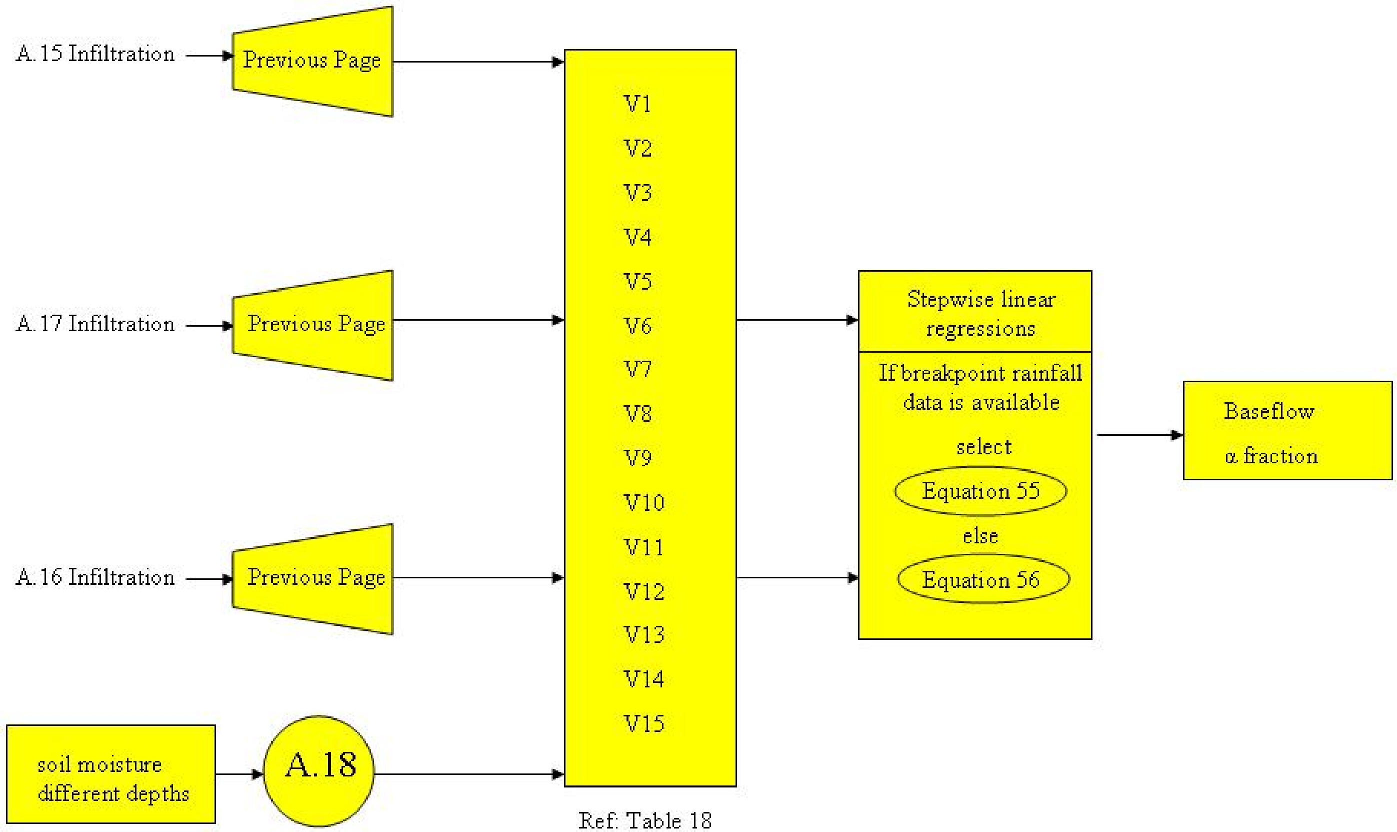
C.2 Hydrograph Separation by Incorporating Climatological Factors



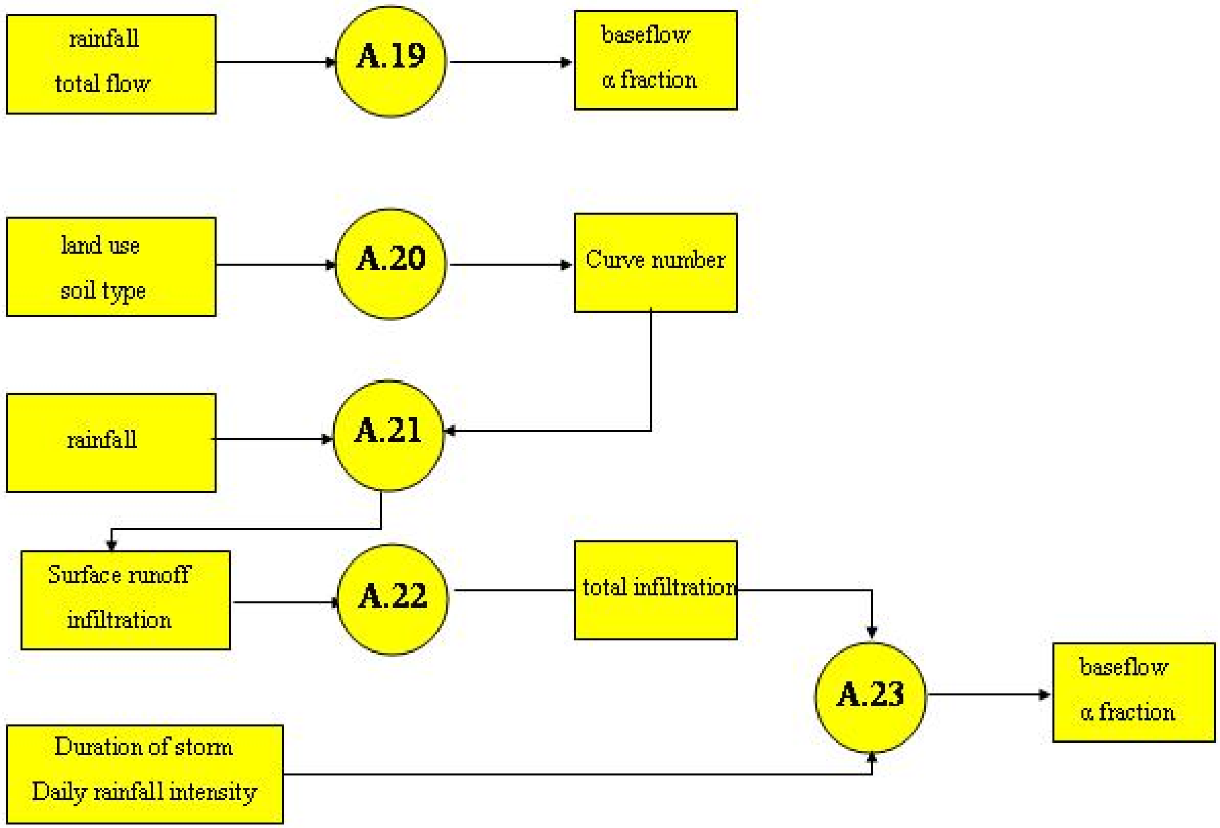
C.3 Improvement in Hydrograph Separation Estimation by Incorporating Physical and Hydrologic Characteristics of Watersheds



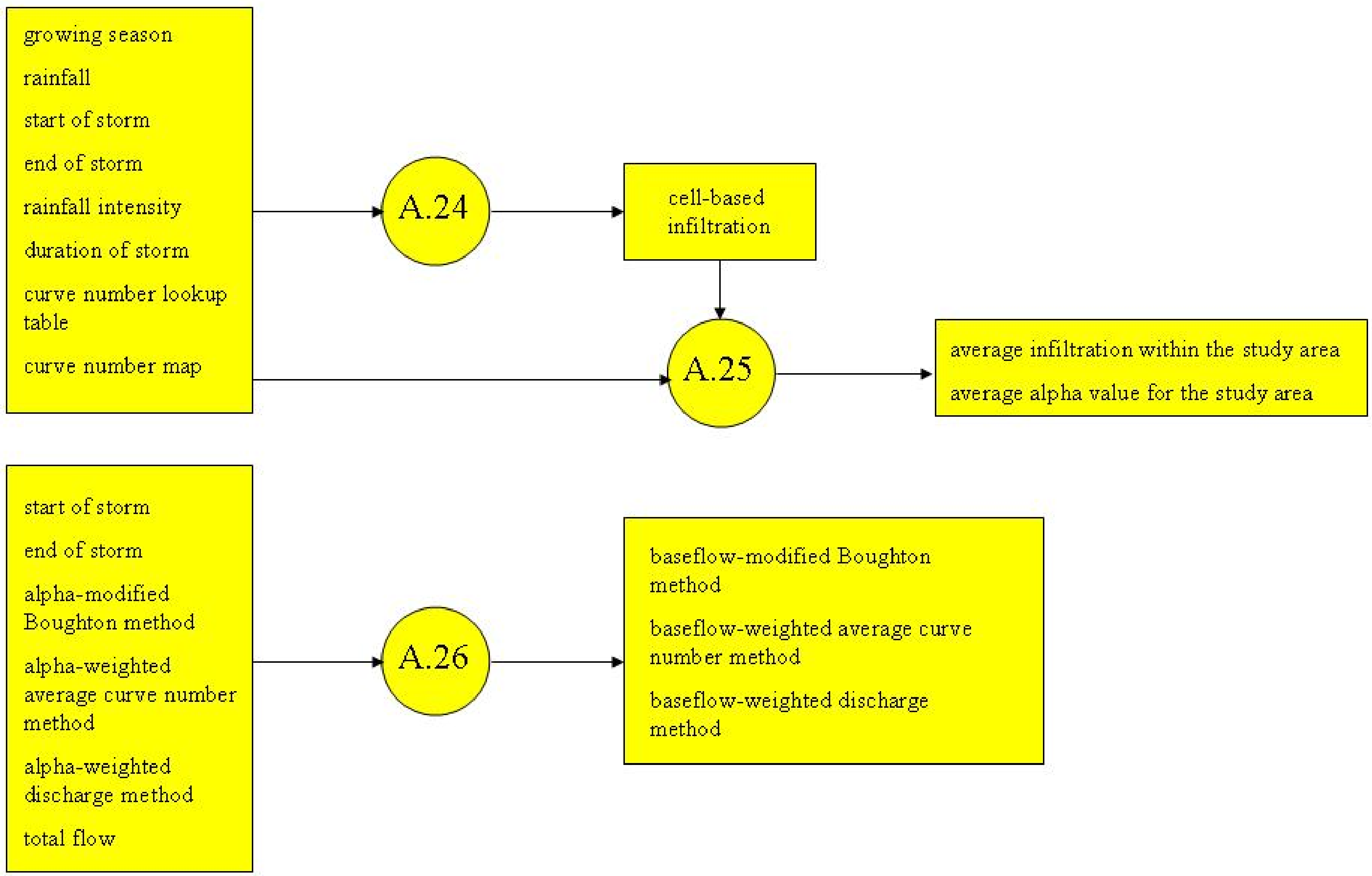
C.3 Improvement in Hydrograph Separation Estimation by Incorporating Physical and Hydrologic Characteristics of Watersheds (continued)



C.4 Model Simulation



C.4 Model Simulation (continued)



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