Empirical Mass Balance Calibration of Analytical Hydrograph
Separation Techniques Using Electrical Conductivity

by

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A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering Department of Civil and Environmental Engineering College of Engineering University of South Florida

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DEDICATION

This thesis is dedicated to my wife Susie and daughter Ella. Susie, without your unconditional patience and support this effort would not have been possible. Ella, Daddy can’t wait to meet you, see ya in 4 months.
I would like to thank Dr. Mark Stewart, Dr. Mark Ross and Dr. Jeffrey Geurink for all their guidance as my committee members. I would also like to thank my parents, Tony and Robin, the rest of my family and all of my friends for their support throughout the course of this project. I would like to thank Don Thompson for “showing me the ropes” in the field, as well as Jeff Vomacka and John McCary for their data collection efforts. Finally, I would like to thank everyone at Water Resource Associates for granting me the support and unlimited flexibility required to complete this thesis.
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ABSTRACT

Analytical baseflow separation techniques such as those used in the automated hydrograph separation program HYSEP rely on a single input parameter that defines the period of time after which surface runoff ceases and all streamflow is considered baseflow. In HYSEP, this input parameter is solely a function of drainage basin contributing area. This method cannot be applied universally since in most regions the time of surface runoff cessation is a function of a number of different hydrologic and hydrogeologic basin characteristics, not just contributing drainage area.

This study demonstrates that streamflow conductivity can be used as a natural tracer that integrates the different hydrologic and hydrogeologic basin characteristics that influence baseflow response. Used as an indicator of baseflow as a component of total flow, streamflow conductivity allows for an empirical approach to hydrograph separation using a simple mass balance algorithm.

Although conductivity values for surface-water runoff and ground-water baseflow must be identified to apply this mass balance algorithm, field studies show that assumptions based on streamflow at low flow and high flow conditions are valid for estimating these end member conductivities. The only data required to apply the mass balance algorithm are streamflow conductivity and discharge measurements.
Using minimal data requirements, empirical hydrograph separation techniques can be applied that yield reasonable estimates of baseflow. This procedure was performed on data from 10 USGS gaging stations for which reliable, real-time conductivity data are available. Comparison of empirical hydrograph separations using streamflow conductivity data with analytical hydrograph separations demonstrates that uncalibrated, graphical estimation of baseflow can lead to substantial errors in baseflow estimates. Results from empirical separations can be used to calibrate the runoff cessation input parameter used in analytical separation for each gaging station.

In general, collection of stream conductivity data at gaging stations is relatively recent, while discharge measurements may extend many decades into the past. Results demonstrate that conductivity data available for a relatively short period of record can be used to calibrate the runoff cessation input parameter used for analytical separation. The calibrated analytical method can then be applied over a much longer period record since discharge data are the only requirement.
CHAPTER 1. INTRODUCTION

Common methods currently used for baseflow separation include those algorithms developed by Pettyjohn and Henning (1979), and made popular by the automated hydrograph separation program HYSEP (Sloto and Crouse, 1996). These algorithms are strictly analytical and include the Fixed Interval, Sliding Interval and Local Minimum Methods. Despite minor differences discussed later, each method shares the fundamental assumption that baseflow can be derived by systematically drawing connecting lines between low flow points of a streamflow hydrograph (Sloto and Crouse, 1996). Each of the three methods rely on a basin-specific parameter called “2N*”, defined as 2 times the number of days from the peak on the hydrograph of a runoff event after which surface runoff ceases and all streamflow is baseflow (Sloto and Crouse, 1996).

When using one of the three analytical, or graphical, separation methods, the 2N* parameter is based solely on the contributing area of the drainage basin as it is a function of the equation $N = A^{0.2}$ (Linsley et al. 1982). However, an equation based solely on drainage basin area cannot be applied universally since in most regions the time of surface runoff cessation is a function of more than just the contributing drainage area. In addition to basin area, surface runoff cessation can also be associated with other basin features such as the percent impervious area, average topographic slope, antecedent soil moisture conditions and the area of attenuating storage features such as wetland areas and stormwater discharge controls. Baseflow influx is also influenced by other basin features such as hydraulic conductivity of the basin soils and underlying aquifer, bed leakance through the stream and head differences between the stream and aquifer. Therefore, deriving an accurate 2N* value to estimate baseflow based solely on contributing basin area is difficult since contributing area alone does not uniquely determine the timescale of runoff cessation or magnitude of baseflow influx for a basin.
In order to accurately define a $2N^*$ value for a given drainage basin, a method must be derived that takes into account all hydrologic and hydrogeologic basin characteristics that have an effect on the timescale of runoff cessation and baseflow influx. Instead of deriving a formula containing numerous unknowns that represent these basin characteristics, the most practical approach is to identify one basin parameter that is a function of all the hydrologic and hydrogeologic characteristics that define the timescale of runoff cessation and magnitude of baseflow influx for a basin. Furthermore, measurements of that parameter should be relatively inexpensive and readily attainable. This suggests the use of naturally existing streamflow electrical conductivity data.

Streamflow conductivity is controlled by relatively low conductivity levels of surface-water inflow and relatively higher conductivity levels of ground-water inflow. As long as a valid approximation can be made for surface and ground-water inflow conductivity, streamflow conductivity can be used to measure of the approximate ratio of surface-water to ground-water within streamflow at any instant in time. Previous studies, including those from Pinder and Jones (1969), Pilgrim et al. (1979), Matsubayashi et al. (1993) and Yu and Schwartz (1999), have shown that conductivity can be used as an environmental indicator of flow component separation for a streamflow hydrograph. These studies show that streamflow conductivity values consistently vary inversely with streamflow discharge in that conductivity values drop rapidly with increasing discharge, reach a minimum during peak discharge, increase slowly with decreasing discharge, and reach a maximum once runoff ceases (Figure 1). This consistent relationship between streamflow discharge and conductivity indicates that during runoff events streams are quickly diluted by lower conductivity runoff until a minimum conductivity occurs at the peak discharge. As runoff diminishes, the higher conductivity ground-water contribution increases, thus raising streamflow conductivity values to a maximum at the time when runoff ceases.
Using inexpensive and readily available streamflow conductivity data, the baseflow contribution to a streamflow hydrograph can be empirically derived over any period of record for which conductivity values have been collected. Furthermore, by comparing baseflow values derived by this Conductivity Mass-Balance (CMB) method to baseflow derived by graphical methods, one can determine the most appropriate graphical method and calibrate that graphical method by determining the most appropriate 2N* value to be used for a specific drainage basin and gaging station. Moreover, one can use a relatively short period of conductivity record to empirically calibrate the graphical method and 2N* value of a basin, then use the calibrated method and 2N* value to analytically derive baseflow contributions over a long period of record for which conductivity data are not available. In general, collection of stream conductivity data at gaging stations is relatively recent, while discharge measurements may extend many decades into the past.

Figure 1. Streamflow discharge vs. conductivity for USGS gaging station 02303000, Hillsborough River near Zephyrhills, FL.
1.1 Previous Studies

Previous investigations on the subject of chemical mass balance hydrograph separation generally fall into two categories. The first category includes detailed investigations of the chemical characteristics of the surface-water runoff and ground-water flow end members used in the mass balance algorithms. These end member investigations typically involve the study of chemical variability in the end members with respect to flushing frequency, soil contact time and location along the flow path from the hill slope, through the near stream riparian zone and to the stream. These investigations may or may not include an actual hydrograph separation.

The second category includes investigations where simple assumptions are made to estimate the chemical characteristics of the surface and ground-water end members. These estimated values are then used in conjunction with measured streamflow data to produce chemical mass balance hydrograph separations. These hydrograph separation investigations may include analysis of either individual runoff events or continuous period of record data.

Pilgrim et al. (1979) is an end member investigation focusing primarily on the variation of conductivity with soil contact time based on the length of time both surface runoff and ground-water are in contact with basin soils. This study did not include an analysis of actual streamflow discharge and conductivity values. Analysis was instead performed on individual events generated by irrigation of test bed sites on hillslope areas up gradient from the near-stream riparian areas and receiving stream. Results from the study show that conductivity levels within the hillslope test bed rapidly increased to one half of the final stabilized value within the first hour of soil contact, then gradually increased to a stabilized value within one week. Actual hydrograph streamflow separation was not attempted as part of this study.

Matsubayashi et al. (1993) is also an end member investigation that includes analysis of the effects of rainfall conductivity variability, soil ion availability and soil contact time on hydrograph separation by mass balance. The study includes experiments to test these effects on both the surface and ground-water flow components used in
hydrograph separation. Surface runoff experiments involved the recirculation of water through a test trough to observe changes in conductivity associated with contact time. Experiments were also repeated using various degrees of initial soil washing and source water conductivities to observe changes in conductivity associated with different soil ion availability and initial rainfall conductivity. Ground-water flow experiments were similar to those described for surface experiments, however, a vertical infiltration soil column was used instead of a runoff trough. Results of the contact time analysis showed that surface and ground-water conductivity increased rapidly within the first hour, and then leveled off to a relatively stable value within hours. Results of the soil ion availability analysis show that unwashed soil conditions produced conductivity values slightly higher than washed soil conditions. However, based on the data displayed in the study for these experiments, the maximum conductivity difference resulting from washed vs. unwashed soils was only 2 to 4 µS/cm. Specific results from rainfall conductivity variability analysis were not discussed.

Hooper et al. (1998) is an end member investigation focusing on the differences between hillslope and near-stream riparian chemical characteristics. Unlike other studies where ground-water end member chemistry is investigated to more accurately identify the magnitude of baseflow in streamflow, this study involved using streamflow chemistry in an attempt to more accurately identify the source and flow path of the ground-water entering the stream through baseflow. The study shows significant differences between hillslope ground-water chemistry and riparian ground-water chemistry. Results show that the chemical signature of the hillslope ground-water could not be discerned from streamflow chemistry, even though the hillslope is by far largest landform component of the basin. The study concludes that streamflow chemical dynamics, for the most part, reflect the chemistry of the riparian zone and provide little indication of the chemical processes occurring up gradient in the hillslope area.

Pinder and Jones (1969) is a hydrograph separation investigation of the variation in the chemical composition of streamflow discharge in three small drainage basins in Nova Scotia. The purpose of the study was to determine the baseflow component of discharge during high flow periods. Instead of performing a detailed analysis of ground-
water and surface-water chemical characteristics measured at hillslope test bed sites, Pinder and John made the assumptions that measurements at extreme low flows represent composite baseflow chemical characteristics and measurements of extreme high flows represent composite surface runoff chemical characteristics. Pinder and John used these end member assumptions to perform chemical mass balance hydrograph separations using measured streamflow chemical concentrations over a 6-week period. Results from the study show that baseflow contributed between 32 and 42% of total streamflow during peak flow periods for the three basins. These results are contrary to analytical methods performed graphically that typically indicate negligible ground-water flow at peak stream discharge. No calibration of graphical methods was performed in this study.

Of the previous studies reviewed, Yu and Schwartz (1999) come the closest to calibration of analytically derived baseflow by means of an empirical hydrograph separation method using streamflow conductivity. Baseflow separation using conductivity was applied to a 68-day period of record of streamflow discharge and conductivity data for Big Darby Creek watershed in Ohio. Overland flow conductivity measurements during runoff events were used to represent the surface-water conductivity end member, while ground-water point samples were used to estimate the ground-water conductivity end member. The resulting baseflow hydrograph derived empirically using the CMB Method was then used to verify the validity of a baseflow hydrograph derived using an analytical graphical method. Yu and Schwartz found that the two baseflow hydrographs were similar enough to consider the analytical model valid. However, no attempt was made to better calibrate the graphical model based on the empirical results.

Finally, A study by Perry (1995), argues that a 60-day 2N* value best represents the timescale for runoff cessation in Florida basins. This takes into account the minimal topographic slopes and large magnitude of attenuating storage features associated with most Florida basins, as well as the four-month summer rainy season associated with Florida weather patterns. Perry’s argument suggests that the N=A^{0.2} relationship derived by Pettyjohn and Henning, will significantly underestimate the timescale of runoff cessation in basins similar to those found in Florida, thus significantly overestimating baseflow.
CHAPTER 2. METHODOLOGY

The methodology applied in this study includes CMB hydrograph separation using continuous discharge and conductivity values obtained at ten USGS streamflow gaging stations. The results of this empirical separation are used to determine the most appropriate analytical baseflow separation method to be used for each gaging station. Results from the CMB separation are also used to calibrate the most appropriate 2N* value to be used for each gaging station.

2.1 Analytical Methods for Baseflow Separation

The three analytical algorithms developed by Pettyjohn and Henning (1979), and made popular by the automated hydrograph separation program HYSEP, include the Fixed Interval, Sliding Interval and Local Minimum Methods. These methods can be described conceptually as three different algorithms to systematically draw connecting lines between the low points on the streamflow hydrograph. The sequence of these connecting lines defines the base-flow hydrograph. (Sloto and Crouse, 1979)

Each algorithm uses the derived N value as the duration of surface runoff. The N value for each method is calculated from the following empirical relationship:

\[ N = A^{0.2} \quad (1) \]

(Linsley et al. 1982)

In this equation A represents the drainage area in square miles and N is in days. Each graphical separation method uses a time window defined by the interval 2N* as the odd integer between 3 and 11 nearest to 2N (Pettyjohn and Henning, 1979). Application of the 2N* interval in each of the three separation techniques is describe in the following excerpts from Sloto and Crouse (1996).
1. Fixed Interval Method
The fixed-interval method assigns the lowest discharge in each interval (2N*) to all days in that interval starting with the first day of the period of record. The method can be visualized as moving a bar 2N* days wide upward until the bar first intersects the hydrograph. The discharge at that point is assigned to all days in the interval. The bar is then moved 2N* days horizontally, and the process is repeated. The assigned values are then connected to define the base-flow hydrograph.

2. Sliding Interval Method
The sliding-interval method finds the lowest discharge in one half the interval minus 1 day [0.5(2N*-1) days] before and after the day being considered and assigns it to that day. The method can be visualized as moving a bar 2N* wide upward until it intersects the hydrograph. The discharge at that point is assigned to the median day in the interval. The bar then slides over to the next day, and the process is repeated. The assigned daily values are then connected to define the base-flow hydrograph.

3. Local Minimum Method
The local-minimum method checks each day to determine if it is the lowest discharge in one half the interval minus 1 day [0.5(2N*-1) days] before and after the day being considered. If it is, then it is a local minimum and is connected by straight lines to adjacent local minimums. The base-flow values for each day between local minimums are estimated by linear interpolations. The method can be visualized as connecting the lowest points on the hydrograph with straight lines.
2.2 CMB Method for Baseflow Separation

Although total discharge ($Q$) and stream conductivity ($Q_C$) are measurable values, assumptions must be made for the conductivity of the baseflow ($BF_C$) and surface runoff ($RO_C$) in order to determine the baseflow fraction ($BF_{%b}$) of total flow.

Values for $BF_C$ and $RO_C$ are assigned and assumed to be constant throughout the period of record. A value for baseflow conductivity ($BF_C$) is assigned by analyzing streamflow conductivity values during extreme low-flow periods when it is assumed that baseflow makes up 100% of the streamflow. During the transition from a wet period with frequent runoff events to a dry period dominated by baseflow, streamflow conductivity signatures show a gradual rise until a stable maximum is reached. It is assumed that the stable conductivity value during extreme low flows represents the weighted-average composite conductivity of all ground-water influx upstream from the measurement point. Therefore, this integrated low-flow conductivity value is assigned as the value for $BF_C$ and is held constant over the period of record.

A value for runoff conductivity ($RO_C$) is assigned by analyzing streamflow conductivity values at hydrograph peaks during extreme high flow periods with frequent runoff events where it is assumed that runoff makes up 100% of the streamflow. Conductivity signatures during peak flow conditions generally show a sharp and steady decrease at the start of a runoff event until a minimum conductivity value is reached that corresponds in time to the runoff peak. It is assumed that the point of minimum conductivity represents the weighted-average composite conductivity of all surface runoff from upstream of the measurement point. This integrated peak flow conductivity value is assigned as the value for $RO_C$ and held constant over the period of record.

Once values have been determined for $BF_C$ and $RO_C$, the following derivation is used to calculate the baseflow fraction of the hydrograph at each time step.
Variables:

\[ Q = \text{Total Streamflow}, \]
\[ Q_C = \text{Conductivity of Streamflow}, \]
\[ BF = \text{Total Baseflow}, \]
\[ BF\% = \text{Baseflow Fraction of Total Flow}, \]
\[ BF_C = \text{Conductivity of Baseflow}, \]
\[ RO\% = \text{Runoff Fraction of Total Flow}, \]
\[ RO_C = \text{Conductivity of Runoff}, \]

Fundamental Equations:

\[
(BF\%)(BF_C) + (RO\%)(RO_C) = Q_C \quad (2)
\]
\[
(BF\%) + (RO\%) = 1 \quad (3)
\]
\[
BF = Q(BF\%) \quad (4)
\]

Derivation:

\[ RO\% = 1 - BF\% \quad \text{from (3)} \]
\[
(BF\%)(BF_C) + (1-BF\%)(RO_C) = Q_C \quad (2) \text{ into (3)}
\]
\[
BF\% = (Q_C - RO_C) / (BF_C - RO_C) \quad (5)
\]
\[
BF = Q(BF\%), \quad (4)
\]
\[
BF = Q[(Q_C - RO_C) / (BF_C - RO_C)] \quad (5) \text{ into (4)}
\]

2.3 Field Verification of Assumptions Used in the CMB Method

When using the methods described for the CMB Method it is assumed that both the baseflow conductivity and runoff conductivity can be determined based on streamflow conductivity during extreme low flows and extreme high flows, respectively. It is also assumed that these values remain constant throughout the period of record. This is contrary to previous studies including Matsubayashi et al. (1993) and Yu and Schwartz (1999) that used point measurements of ground-water and overland flow conductivity to determine baseflow and runoff conductivity values used in their analytical separation.
Pilgrim et al. (1979) also used point measurement values and concluded that variations in conductivity values caused by soil/water contact time must be accounted for. However, these studies show that soil water conductivity stabilizes soon after initial contact, while ground-water residence times in small basins are days to weeks or longer.

In order to test the assumptions that baseflow and runoff conductivity values remain constant and can be determined simply by streamflow conductivity analysis, a field study was performed at a field test site. The test site was located at Pringle Branch, located within the Fishhawk Creek drainage basin in southeast Hillsborough County, Florida. The test site at Pringle Branch has a contributing drainage basin area of approximately 4.1 square miles (Figure 2). Geographic Information System (GIS) analysis was performed using soils and land use data layers obtained from the Southwest Florida Water Management District’s GIS data library. Based on spatial analysis of the soils data layer, the contributing basin consists of primarily fine sands, whereas about 54% of the area is made up of type B/D soils. Approximately 34% of the area is made up of type C soils, 5% of type A and 6.5% of type D. Based on spatial analysis of the land use data layer, land uses within contributing basin consists of about 40% cropland and pasture, 44% forested uplands and other upland rural lands, 8% isolated wetlands and mining reservoirs and 8% riparian wetland systems along Pringle Branch. Overland flow slopes range from 3% to less than 0.5%.

The test site included a transect of 12 ground-water wells crossing perpendicular to Pringle Branch (Figure 3). The transect included six wells extending up gradient approximately 1300 feet from both the east and west banks of the small creek. During the field study the creek was fed primarily by baseflow during the dry seasons, but overtopped its banks by 30 yards on either side during the wettest months when the primary source of streamflow was surface runoff.

Conductivity of ground-water was measured in shallow wells by purging each well with a bailer until a constant conductivity value was measured using a hand-held field conductivity meter. Ground-water conductivity values were compared to observed streamflow conductivity during assumed 100% baseflow conditions. The conductivity of overland flow was measured and compared to observed streamflow conductivity during
100% runoff conditions. Conditions of assumed 100% runoff were verified based on ground-water elevation measurements adjacent to the stream that indicated that stream stage was higher than heads in the adjacent ground-water. Conductivity of ground-water was monitored in the 12 wells during a series of both extreme dry conditions and extreme saturated conditions.

Figure 2. Pringle Branch field test site basin overview.

Figure 3. Pringle Branch field test site well transect.
2.4 Calibration of Graphical Methods Using the CMB Method

Baseflow separation was completed using the CMB Method and each of the three graphical methods. The results were plotted as cumulative baseflow over time. Residual values for each time step were obtained by subtracting the cumulative analytical baseflow value for each of the three methods from the cumulative CMB baseflow. The absolute values of these residuals were summed to determine the analytical method with the smallest sum of residuals. The method showing the smallest cumulative residual was considered the most appropriate of the three graphical methods for the given streamflow gaging station. Once the most appropriate analytical method was determined, the 2N* value of that method was adjusted until the smallest sum of residuals between the CMB-derived and analytically-derived values was reached. It is assumed that the 2N* value yielding the smallest cumulative residual value is the calibrated value and represents the most appropriate 2N* value for the given basin and gaging station.

The smallest sum of residuals was used as the calibration technique in this study as it resulted in the best-fit plot over other methods when comparing calibrated analytical baseflow plots to the cumulative baseflow plots derived using the CMB Method. Other methods including the sum of residuals for the non-cumulative, time step baseflow values, and the sum of the squared residuals for cumulative and time step baseflow data were used. None of these alternative methods worked as well to calibrate the 2N* values.

2.5 Data Collection

Data utilized for this study were daily discharge and conductivity data from ten real-time USGS gaging stations in Florida, Georgia, Texas and Kentucky. These stations are listed below:

1) Station 02297100 – Joshua Ck at Nocatee, FL
2) Station 02303000 – Hillsborough River near Zephyrhills, FL
3) Station 08049500 – West Fk Trinity River near Grand Prairie, TX
4) Station 08068275 – Spring Ck near Tomball, TX
5) Station 08068400 – Panther Branch at Goslin Road, TX
6) Station 03238745 – Twelvemile Ck at Hwy 1997 near Alexander, KY
7) Station 03254480 – Cruises Ck at Hwy 17 near Piner, KY
8) Station 03254550 – Banklick Ck at Hwy 1829 near Erlanger, KY
9) Station 02204070 – South River at Klondike Road, GA
10) Station 02208150 – Alcovy River at New Hope near Graystone, GA

These stations were selected based on the quality of their conductivity data. Of the few USGS gaging stations that currently have real-time conductivity data available, many are located in tidally-influenced reaches of coastal drainage basins. The daily influx of highly saline water and tidal tailwaters results in conductivity and discharge data that are unusable for this study. The stations selected for this study have discharges that are generally unregulated and show no indication of tidal influence. Conductivity data for each station are continuous and show relatively few anomalies caused by equipment problems or irregular influxes of highly saline water.
CHAPTER 3. RESULTS

3.1 Field Verification of Assumptions Used in the CMB Method

To determine if baseflow conductivity values remain constant, conductivity of shallow ground-water was monitored in 12 wells that transect the Pringle Branch test site during both relatively dry conditions and relatively saturated conditions. (Table 1)

Table 1. Well conductivity at Pringle Branch test site.

<table>
<thead>
<tr>
<th>Well ID</th>
<th>Distance from Stream (ft)</th>
<th>Conductivity (µS/cm)</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Time 1</td>
<td>Time 2</td>
<td>Time 3</td>
<td>Average</td>
<td>Standard Deviation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>11/2/02</td>
<td>12/14/02</td>
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In Table 1, Time 1 represents conductivity measured during relatively dry conditions in November 2002. Water table elevations were one to four feet below land surface, on average. Although lower stage elevations for Pringle Branch were recorded earlier in 2002, it is assumed that at Time 1 streamflow in Pringle Branch was nearly
100% baseflow. Records show Time 1 to occur at the tail end of the receding limb of a small runoff event when stage elevation had become nearly constant.

In Table 1, Time 2 represents conductivity measured during extremely wet conditions in December 2002 after significant rainfall had raised water table elevations to 0 to 0.5 feet below land surface, on average. It is assumed that at Time 2 streamflow in Pringle Branch was nearly 100% surface-water runoff. This assumption was verified as the stream stage in Pringle Branch was approximately 0.2 ft higher than ground-water elevations measured in wells extending approximately 200 feet from the creek on each side, indicating flow from the stream into the shallow aquifer.

In Table 1, Time 3 represents conductivity measured during extremely wet conditions in December 2002 approximately 1 week after the significant rainfall that resulted in the high water table and lower conductivity values shown at Time 2. At Time 3 Water table elevations still remained high at 0 to 0.5 ft below land surface. However, as shown in Table 1, conductivity values had returned to levels similar to those measured during dry conditions.

To determine if the conductivity of surface runoff remains relatively constant, conductivity of surface runoff was measured after three separate rainfall events at different locations at the Pringle Branch test site. The locations include two areas on each side of the creek. One area is near the topographic divide where surface runoff begins, and the other is down gradient along the same flow path, close to the creek. Data were collected after a significant rainfall event in December 2002, when the site had been previously dry, and during two other events between January and June of 2003 during a period when rainfall occurred more frequently. At each location and for each event, surface-water conductivity was found to be similar to rainfall conductivity, about 35 µS/cm near the divide at the start of runoff, increasing to about 50 µS/cm just before entering the creek on each side.

To determine if accurate baseflow and surface runoff conductivity values for the CMB Method can be determined using streamflow conductivity, conductivity in the creek was compared to ground-water and surface runoff conductivity for both assumed 100% baseflow and 100% surface runoff conditions. Ground-water conductivity at Time 1 in
Table 1 was measured during 100% baseflow conditions. As shown in Figure 4, conductivity measured 90 µS/cm approximately 1300 feet up gradient on each side of the creek. Conductivity of the ground-water increased to about 500 µS/cm approximately 200 feet from the creek, then dropped sharply near the creek where conductivity measured 194 µS/cm.

Figure 4. Cross section showing water table elevations and ground-water conductivity at Time 1 and 2.

To determine if accurate surface runoff conductivity values for the CMB Method can be determined using streamflow conductivity, conductivity in the creek was compared to conductivity of surface runoff during assumed 100% surface runoff conditions. Conductivity of surface runoff at the test site at Time 2 was 35 µS/cm 1300 feet up gradient on each side of the creek. Conductivity rose steadily to an ultimate value of 50 µS/cm directly adjacent to the creek. However, streamflow conductivity at Time 2, assumed to be 100% surface runoff, measured 83 µS/cm.
3.2 Calibration of Graphical Methods Using the CMB Method

Empirical baseflow separation was performed according to the procedures described for the CMB Method for 10 USGS gaging stations located in Florida, Georgia, Kentucky and Texas. Results for all stations are summarized in Table 3, while a more detailed analysis of Station 02297100, Joshua Creek at Nocatee, FL, is used as a representative example of the calibration process.

3.2.1 Joshua Creek Analysis

CMB baseflow separation was performed on data from Station 02297100 over the period of record from December 2001 to May 2003. Daily average discharge and conductivity were used for the analysis. The initial step in the baseflow separation using conductivity values is to determine streamflow conductivity under assumed 100% baseflow and 100% runoff conditions.

Discharge data for May, 2002, represent the end of the 2002 dry season when Joshua Creek was dominated by baseflow. Conductivity values reach a peak of about 1600 µS/cm during this period (Figure 5). This value is assumed to represent cumulative baseflow conductivity (BF$_C$) of all ground-water influx upstream of where the station is located. Discharge data for July 2002 represents the 2002 wet season when Joshua Creek was dominated by surface runoff. Conductivity reaches a minimum of about 200 µS/cm during this period. This value is assumed to represent cumulative surface runoff conductivity (RO$_C$) of all surface-water inflows upstream of the station (Figure 5).

Using BF$_C$ = 1600 µS/cm and RO$_C$ = 200 µS/cm, Equation 5 was applied to each daily conductivity value to determine the daily average percent baseflow within the creek. To complete the baseflow separation, Equation 4 was then used to quantify daily baseflow using the calculated baseflow percentage and measured streamflow discharge. Daily baseflow was then plotted along with daily conductivity and discharge data (Figure 5). Once daily baseflow values were determined, the cumulative baseflow over the period of record was calculated (Figure 6). Using the CMB Method a total of 3.5 inches of
baseflow out of the total 16.6 inches of discharge was calculated for the 15-month period of record.

Figure 5. Discharge, conductivity and CMB Method derived baseflow for USGS gaging station 02297100, Joshua Creek at Nocatee, FL.

Figure 6. Cumulative baseflow calibration for USGS gaging station 02297100, Joshua Creek at Nocatee, FL.
In order to calibrate the appropriate analytical method and associated 2N* value for the station, cumulative baseflow was derived using each of the three analytical methods (Figure 6). By using the 132 square mile contributing basin area in Equation 1, the 2N* value used for each of the analytical methods is 5 days.

Cumulative baseflow calculated using the Fixed Interval Method was determined to be 11.9 inches, while the Sliding Interval Method yielded a similar total of 11.8 inches. Cumulative baseflow calculated using the Local Minimum Method was found to yield 10.4 inches (Figure 6 and Table 2).

In order to calibrate the 2N* value using the CMB Method it was first determined which analytical method was most appropriate to use for the gaging station. By calculating the sum of the absolute value of the daily residuals between the cumulative CMB Method and each analytical method, it was determined that the Local Minimum Method resulted in the lowest sum of the residuals and the cumulative baseflow value closest to that determined by the CMB Method (Table 2).

Once it was determined that the Local Minimum Method was the most appropriate analytical method for the station, the 2N* value was calibrated to minimize the sum of the residuals between the CMB and analytical methods. Using the method described above where the residuals between the CMB Method and the analytical Local Minimum Method are minimized, it was found that an 2N* value of 31 minimizes the sum of the residuals. Using a 2N* value of 31 for the Local Minimum Method yields 3.8 inches of baseflow over the period of record for which conductivity values are available (Figure 6), only 0.3 inches (8.8%) higher than the cumulative baseflow calculated empirically by the CMB Method (Table 2). Results of baseflow separation and calibration for the additional nine USGS gaging stations are listed in Appendix B.
Table 2. Sum of residuals and cumulative baseflow for calibration of USGS gaging station 02297100, Joshua Creek near Nocatee, FL.

<table>
<thead>
<tr>
<th>Baseflow Separation Method</th>
<th>Sum of Residuals</th>
<th>Cumulative Baseflow (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed Interval</td>
<td>1587</td>
<td>11.9</td>
</tr>
<tr>
<td>Sliding Interval</td>
<td>1594</td>
<td>11.8</td>
</tr>
<tr>
<td>Local Minimum</td>
<td>1402</td>
<td>10.4</td>
</tr>
<tr>
<td>CMB Method</td>
<td>0</td>
<td>3.5</td>
</tr>
<tr>
<td>Calibrated 2N*</td>
<td>86</td>
<td>3.8</td>
</tr>
</tbody>
</table>
CHAPTER 4. DISCUSSION

4.1 Field Verification of Assumptions Used in the CMB Method

4.1.1 Assumption 1

Assumption 1: Baseflow conductivity remains constant. Conductivity measurements of shallow ground-water wells in Table 1 represent short-term conductivity fluctuations over a period of about 1 month when local ground-water conditions changed from very dry to saturated. Additional well conductivity data were gathered from December 2002 to June 2003 on a monthly basis. Despite minor fluctuations measured soon after rainfall events, ground-water conductivity during this time remained nearly constant with little deviation from those values shown for Time 1 and 3. The results suggest that cumulative baseflow conductivity remains relatively constant throughout both dry and wet seasons in this small basin.

4.1.2 Assumption 2

Assumption 2: Runoff conductivity remains constant. Although surface-runoff conductivity increased from up gradient nearer the divide to down gradient nearer the stream with increased contact time with the soil, measurements taken from one event to the next yielded consistent results. Regardless of whether or not a single runoff event occurred after a significant dry period, or frequent runoff events occurred during the wet season, surface runoff conductivity remained relatively constant. The results suggest that cumulative surface runoff conductivity remains relatively constant throughout both dry and wet seasons.
4.1.3 Assumption 3

Assumption 3: \textit{Streamflow conductivity at low flow is the most appropriate indicator of baseflow conductivity for the CMB Method.} The variability in ground-water conductivity from up gradient to down gradient raises the question of where along a transect should ground-water conductivity be measured in order to accurately determine baseflow conductivity. The answer is that an ideal location cannot be determined. This study suggests that point measurements of ground-water conductivity adjacent to the creek would not be appropriate to determine a baseflow conductivity value (BF\(_C\)) to be used in the CMB Method, as ground-water conductivity adjacent to the creek measured about 200\% greater than streamflow conductivity, even during long periods of low-flow conditions. Also, the ground-water adjacent to this in-stream measuring point contributes very little of the measured streamflow as streamflow conductivity is an integrated value influenced principally by conductivity upstream from the measuring point. Numerous ground-water well transects placed upstream within the basin would be more useful in characterizing integrated baseflow conductivity to the in-stream measuring point, however, installation and monitoring would be costly and impractical for such a data collection effort. Instead, streamflow conductivity during lowest flow conditions should be used as an indicator of cumulative baseflow conductivity as this value represents the weighted-average conductivity of all baseflow influx occurring upstream of the measurement location.

4.1.4 Assumption 4

Assumption 4: \textit{Streamflow conductivity at high flow must be used as an indicator of runoff conductivity for the CMB Method.} If surface runoff adjacent to the creek matched streamflow conductivity during periods of 100\% runoff conditions, it could be assumed that point measurements of the runoff conductivities near the gaging station are sufficient to estimate surface-runoff conductivity to be used in the CMB Method. However, this is not the case in this study. In this study, surface runoff conductivity
adjacent to the stream was significantly lower than streamflow conductivity during prolonged periods of saturated, high-flow conditions. Also, as with ground-water, surface-water runoff at the point of streamflow measurement contributes very little of the measured streamflow as streamflow conductivity is an integrated value influenced by conditions upstream from the measuring point. This study suggests that point measurements of runoff conductivity adjacent to the creek at the discharge measurement point are not an accurate method to determine cumulative surface runoff conductivity (ROC) to be used in the CMB Method. Instead, streamflow conductivity during highest flow conditions should be used as an indicator of cumulative runoff conductivity, as this value represents the weighted-average conductivity of all surface runoff influx occurring upstream of the measurement location.

The field verification study performed at the Pringle Branch test site supports the assumptions that for the CMB Method of baseflow separation, baseflow and surface runoff conductivity values remain relatively constant, and should be obtained from analyzing streamflow conductivity as an indicator of baseflow and runoff conductivity during extreme low flows and extreme high flows, respectively.

4.2 Calibration of Graphical Methods Using the CMB Method

4.2.1 Joshua Creek Analysis

For the Joshua Creek analysis and calibration the three analytical methods all calculate significantly more baseflow, 275-313%, than that calibrated using the CMB Method (Table 2). Furthermore, the analytical methods show much greater sensitivity to high discharge periods where calculated cumulative baseflow values increase more rapidly using the analytical methods than values derived empirically by the CMB Method. This suggests that the 2N* value of 5 calculated for Joshua Creek, using Equation 1, intended to represent the timescale of runoff cessation, is too low. With a 2N* value of 5 the analytical methods are assuming that after approximately 2.5 days all discharge can be attributed to baseflow. However, the basin associated with Joshua Creek
is relatively flat topographically with a high concentration of wetland cover. With such low overland conveyance and high storage, discharges associated with slow surface runoff continue well after the calculated 2.5 days past the hydrograph peak of a runoff event. Without calibrating the most appropriate analytical method and $2N^*$ value over the 15-month period of record, cumulative baseflow for the Joshua Creek station could be over predicted by as much as 313% (Table 2).

4.2.2 Summary of Other USGS Gaging Stations

Results from Step 1 of the calibration of the nine other USGS gaging stations demonstrate the need for empirical calibration as there is no correlation between the analytical method that returns the lowest sum of residuals between analytical and empirical methods and basin area. Step 1 in the empirical calibration method is to select the most appropriate separation method between the Fixed Interval, Sliding Interval and Local Minimum Methods. The calibration data in Table 3 show that the most appropriate analytical method for each basin is not a function of contributing basin area. After empirical calibration using the CMB Method, the Local Minimum Method proved to be the most appropriate analytical method over the Fixed and Sliding Interval Methods for four out of the ten stations. However, the method was found to be most appropriate for the basins with both the smallest and largest contributing areas. Furthermore, stations where the Fixed and Sliding Interval methods were most appropriate also have widely varying basin areas. This suggests that empirical calibration using the CMB Method is needed to determine the most appropriate analytical method to use as there is no correlation between basin area and the most appropriate analytical method.
Table 3. Summary of USGS gaging station calibration.

<table>
<thead>
<tr>
<th>No.</th>
<th>ID</th>
<th>USGS Gaging Station</th>
<th>Basin Area</th>
<th>Uncalibrated Analytical Method</th>
<th>Calibrated using CMB Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2297100</td>
<td>Joshua Creek Near Arcadia, FL</td>
<td>132</td>
<td>10.4</td>
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<td>2</td>
<td>2303000</td>
<td>Hillsborough River at Zephyrhills, FL</td>
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<tr>
<td>3</td>
<td>8049500</td>
<td>Trinity River at Grand Prairie, TX</td>
<td>3065</td>
<td>0.5</td>
<td>Local Minimum</td>
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<td>4</td>
<td>8068275</td>
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<td>5</td>
<td>8068400</td>
<td>Panther Branch at Gosling Road, TX</td>
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<td>3.9</td>
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<td>3238745</td>
<td>Twelvemile Creek at Hwy. 1997, KY</td>
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<td>3254480</td>
<td>Cruises Creek at Hwy. 17, KY</td>
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<td>3254550</td>
<td>Banklick Creek at Hwy 1829, KY</td>
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<td>South River at Klondike Road, GA</td>
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<tr>
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<td>2208150</td>
<td>Alcovy River at New Hope Road, GA</td>
<td>31</td>
<td>19.8</td>
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The empirically calibrated $2N^*$ values match the values calculated in Equation 1 in four out of the ten stations (Figure 7). The $2N^*$ values calculated from Equation 1 are more likely to match values calibrated empirically for basins with smaller contributing areas, such as Stations 6, 7 and 8. However, this correlation does not hold true for all basins in this study as $2N^*$ values also matched for Station 4, even though the contributing basin area for Station 4 is the third largest of the ten stations. Furthermore, the calculated and calibrated $2N^*$ values for Station 5 do not match even though the contributing basin area is the smallest out of the ten Stations. Despite the fact that some stations with smaller contributing areas appear to yield analytically derived $2N^*$ values that more closely match empirically calibrated $2N^*$ values, linear regression analysis shows no trend of statistical significance (Figure 8). This suggests that empirical calibration using the CMB Method is needed to calibrate the most appropriate $2N^*$ value, as there is no statistically significant correlation between basin area and the uncalibrated $2N^*$ value derived from the relationship $2N^* = 2(A^{0.2})$. 
Figure 7. Analytically derived and calibrated $2N^*$ values vs. contributing basin area.

Figure 8. Calibrated $2N^*$ values vs. predicted $2N^*$ values derived using linear trend analysis.
CHAPTER 5. CONCLUSIONS

Current methods for determining the baseflow contribution to streamflow hydrographs include those algorithms developed by Pettyjohn and Henning (1979), and made popular by the automated hydrograph separation program HYSEP (Sloto and Crouse, 1996). These algorithms include the Fixed Interval, Sliding Interval and Local Minimum Methods. These methods are purely analytical and are based on assumptions that cannot be applied universally from basin to basin, and therefore need to be calibrated based on empirical methods. Conductivity of streamflow can be used as an inexpensive, continuous and readily available source of data to empirically calibrate analytical baseflow separation methods.

The CMB Method used to calibrate analytical baseflow separation involves a mass balance algorithm in which the baseflow portion of stream discharge can be calculated based on baseflow, runoff and streamflow conductivity values. Application of the method requires discharge and streamflow conductivity data, and estimates of the conductivity of baseflow and runoff.

A field investigation demonstrates that baseflow and runoff conductivity values cannot be accurately determined through point measurements of ground-water and surface runoff directly adjacent to the stream measurement point. Instead, in-stream conductivity must be used as an indicator. Stream conductivity during extreme low-flow conditions should be used as the baseflow conductivity ($\text{BF}_C$) in the CMB Method as it represents the weighted-average, composite conductivity of all ground-water influx upstream from the measurement point. Stream conductivity during extreme high-flow conditions should be used as the runoff conductivity ($\text{RO}_C$) in the CMB Method as it represents the weighted-average, composite conductivity of all surface-water influx upstream from the measurement point. The field investigation demonstrates that baseflow
and surface runoff conductivity values as used in the CMB Method should remain relatively constant throughout the period of record.

Cumulative baseflow can first be calculated over a period of record for which streamflow conductivity data are available using each of the three analytical methods. Next, the cumulative baseflow can be calculated using the CMB Method. Analytical and empirical results can be compared to determine which of the three analytical methods is most appropriate for a basin. Once the most appropriate analytical method is selected, the $2N^*$ value can then be calibrated to match the baseflow derived empirically using the CMB Method. This calibrated $2N^*$ value can be used to derive baseflow for the entire period of record for which discharge data are available.

The results show that analytical methods can and must be calibrated by the CMB Method to ensure the accuracy of the analytical method selected, as well as the $2N^*$ value used. The CMB Method can be used to calibrate other analytical methods, in addition to those used in HYSEP. Empirical calibration should be used for accurate results as this study suggests that there is no correlation between the most appropriate analytical method and basin area for the USGS stations used. Furthermore, in this study there is no statistically significant correlation between the calibrated $2N^*$ value and basin area for the USGS stations used. Without calibration using an empirical method, there is no assurance that the analytical method selected and the calculated $2N^*$ value will yield accurate baseflow estimates.
REFERENCES


APPENDICES
Table 4. Ground-water conductivity and heads at Pringle Branch test site.

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<tr>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Depth to Water Table (ft)</td>
<td>Water Table EL. (ft-NGVD)</td>
<td>Cond. (µS/cm)</td>
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<td>65.4</td>
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<td>79.3</td>
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</table>
Appendix B. USGS Gaging Station Baseflow Separation and Calibration Data

Station 1 - USGS 02297100 Joshua Creek at Nocatee, FL
State Florida
Hydrologic Unit Code 3100101
Latitude 28°09'59"
Longitude 81°52'47"
Drainage Area (mi^2) 132
Gage Datum 3.94' NGVD
Period of Record for Study 12/20/01 to 4/12/03

CMB Method Inputs
100% B.F. (µS/cm) 1600
100% R.O. (µS/cm) 200

HYSEP Inputs
Basin Area (mi^2) 132
N 2.7
2N 5.3
2N* 5

2N* Comparison
HYSEP (Days) 5
Calibrated (Days) 31

Table 5. USGS gaging station 1 - calibration table.

<table>
<thead>
<tr>
<th>Method</th>
<th>POR Baseflow (in)</th>
<th>Sum of Residuals</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMB Method</td>
<td>3.5</td>
<td>0.00</td>
</tr>
<tr>
<td>HYSEP 1 (Fixed Interval)</td>
<td>11.9</td>
<td>1.59E+03</td>
</tr>
<tr>
<td>HYSEP 2 (Sliding Interval)</td>
<td>11.8</td>
<td>1.59E+03</td>
</tr>
</tbody>
</table>
| HYSEP 3 (Local Minimum) | 10.4             | 1.40E+03         | << Used for Calibration
| Calibrated           | 3.8               | 8.61E+01         |
Figure 9. Hydrograph separation for Station 1 – USGS gaging station 0297100, Joshua Creek at Nocatee, FL.
Appendix B. (Continued)

Figure 10. Cumulative baseflow calibration for Station 1 – USGS gaging station 0297100, Joshua Creek at Nocatee, FL.
Appendix B. (Continued)

Station 2 - USGS 02303000 Hillsborough River Near Zephyrhills, FL
State Florida
Hydrologic Unit Code 3100205
Latitude 28°08'59"
Longitude 82°13'57"
Drainage Area (mi^2) 220
Gage Datum 33.28' NGVD
Period of Record for Study 2/14/01 to 3/10/03

CMB Method Inputs
100% B.F. (mS/cm) 425
100% R.O. (mS/cm) 75

HYSEP Inputs
Basin Area (mi^2) 220
N 2.9
2N 5.9
2N* 5

2N* Comparison
HYSEP (Days) 5
Calibrated (Days) 21

Table 6. USGS gaging station 2 - calibration table.

<table>
<thead>
<tr>
<th>Method</th>
<th>POR Baseflow (in)</th>
<th>Sum of Residuals</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMB Method</td>
<td>12.6</td>
<td>0.00</td>
</tr>
<tr>
<td>HYSEP 1 (Fixed Interval)</td>
<td>22.1</td>
<td>2.16E+03</td>
</tr>
<tr>
<td>HYSEP 2 (Sliding Interval)</td>
<td>22.3</td>
<td>2.28E+03</td>
</tr>
<tr>
<td>HYSEP 3 (Local Minimum)</td>
<td>21.8</td>
<td>2.75E+03</td>
</tr>
<tr>
<td>Calibrated</td>
<td>14.5</td>
<td>2.31E+02</td>
</tr>
</tbody>
</table>

<< Used for Calibration
Figure 11. Hydrograph separation for Station 2 – USGS gaging station 002303000, Hills. River near Zephyrhills, FL.
Figure 12. Cumulative baseflow calibration for Station 2 – USGS gaging station 002303000, Hills. R. near Zephyrhills, FL.
Appendix B. (Continued)

Station 3 - USGS 08049500 W Fk Trinity River at Grand Prairie, TX
State Texas
Hydrologic Unit Code 12030102
Latitude 32°45'46"
Longitude 96°59'42"
Drainage Area (mi^2) 3065
Gage Datum 405.42' NGVD
Period of Record for Study 8/5/02 to 2/14/03

CMB Method Inputs
100% B.F. (mS/cm) 950
100% R.O. (mS/cm) 300

HYSEP Inputs
Basin Area (mi^2) 3065
N 5.0
2N 10.0
2N* 11

HYSEP Inputs
2N* Comparison
HYSEP (Days) 11
Calibrated (Days) 39

Table 7. USGS gaging station 3 - calibration table.

<table>
<thead>
<tr>
<th>Method</th>
<th>POR Baseflow (in)</th>
<th>Sum of Residuals</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMB Method</td>
<td>0.4</td>
<td>0.00</td>
</tr>
<tr>
<td>HYSEP 1 (Fixed Interval)</td>
<td>0.5</td>
<td>9.65E+00</td>
</tr>
<tr>
<td>HYSEP 2 (Sliding Interval)</td>
<td>0.5</td>
<td>4.62E+00</td>
</tr>
<tr>
<td>HYSEP 3 (Local Minimum)</td>
<td>0.5</td>
<td>4.43E+00</td>
</tr>
<tr>
<td>Calibrated</td>
<td>0.4</td>
<td>2.10E+00</td>
</tr>
</tbody>
</table>

<< Used for Calibration
Figure 13. Hydrograph separation for Station 3 – USGS gaging station 08049500, W. Fork Trinity at Grand Prairie, TX.
Figure 14. Cumulative baseflow calibration for Station 3 – USGS gaging station 08049500, W. Fk Trinity at G. Prairie, TX.
Appendix B. (Continued)

Station 4 - USGS 08068275 Spring Creek Near Tomball, TX
State Texas
Hydrologic Unit Code 12040102
Latitude 30°07'11"
Longitude 95°38'45"
Drainage Area (mi²) 186
Gage Datum 0' NGVD
Period of Record for Study 10/1/99 to 5/11/03

CMB Method Inputs
100% B.F. (mS/cm) 325
100% R.O. (mS/cm) 30

HYSEP Inputs
Basin Area (mi²) 186
N 2.8
2N 5.7
2N* 5

2N* Comparison
HYSEP (Days) 5
Calibrated (Days) 5

Table 8. USGS gaging station 4 - calibration table.

<table>
<thead>
<tr>
<th>Method</th>
<th>POR Baseflow (in)</th>
<th>Sum of Residuals</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMB Method</td>
<td>7.9</td>
<td>0.00</td>
</tr>
<tr>
<td>HYSEP 1 (Fixed Interval)</td>
<td>8.9</td>
<td>3.35E+02</td>
</tr>
<tr>
<td>HYSEP 2 (Sliding Interval)</td>
<td>8.0</td>
<td>2.52E+02</td>
</tr>
<tr>
<td>HYSEP 3 (Local Minimum)</td>
<td>6.7</td>
<td>3.10E+02</td>
</tr>
<tr>
<td>Calibrated</td>
<td>8.0</td>
<td>2.52E+02</td>
</tr>
</tbody>
</table>

<< Used for Calibration
Figure 15. Hydrograph separation for Station 4 – USGS gaging station 08068275, Spring Creek Near Tomball, TX.
Figure 16. Cumulative baseflow calibration for Station 4 – USGS gaging station 08068275, Spring Ck. Near Tomball, TX.
Appendix B. (Continued)

Station 5 - USGS 08068400 Panther Branch at Gosling Road, TX

State: Texas
Hydrologic Unit Code: 12040102
Latitude: 30°11'31"
Longitude: 95°29'01"
Drainage Area (mi²): 25.9
Gage Datum: 125.25' NGVD
Period of Record for Study: 1/17/01 to 3/10/03

CMB Method Inputs
100% B.F. (mS/cm): 750
100% R.O. (mS/cm): 5

HYSEP Inputs
Basin Area (mi²): 25.9
N: 1.9
2N: 3.8
2N*: 3

2N* Comparison
HYSEP (Days): 3
Calibrated (Days): 11

Table 9. USGS gaging station 5 - calibration table.

<table>
<thead>
<tr>
<th>Method</th>
<th>POR Baseflow (in)</th>
<th>Sum of Residuals</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMB Method</td>
<td>2.7</td>
<td>0.00</td>
</tr>
<tr>
<td>HYSEP 1 (Fixed Interval)</td>
<td>4.3</td>
<td>2.23E+02</td>
</tr>
<tr>
<td>HYSEP 2 (Sliding Interval)</td>
<td>6.4</td>
<td>5.74E+02</td>
</tr>
<tr>
<td>HYSEP 3 (Local Minimum)</td>
<td>3.9</td>
<td>1.80E+02</td>
</tr>
<tr>
<td>Calibrated</td>
<td>3.0</td>
<td>6.00E+01</td>
</tr>
</tbody>
</table>

<< Used for Calibration
Figure 17. Hydrograph separation for Station 5 – USGS gaging station 08068400, Panther Branch at Gosling Rd, TX.
Figure 18. Cumulative baseflow calibration for Station 5 – USGS gaging station 08068400, Panther Br. at Gosling Rd, TX.
Appendix B. (Continued)

Station 6 - USGS 03238745 Twelvemile Creek at Hwy. 1997, KY
State Kentucky
Hydrologic Unit Code 5090201
Latitude 38°57'15"
Longitude 84°20'18"
Drainage Area (mi^2) 39
Gage Datum Not Available
Period of Record for Study 1/17/01 to 3/10/03

CMB Method Inputs
100% B.F. (mS/cm) 960
100% R.O. (mS/cm) 240

HYSEP Inputs
Basin Area (mi^2) 39
N 2.1
2N 4.2
2N* 5

2N* Comparison
HYSEP (Days) 5
Calibrated (Days) 5

Table 10. USGS gaging station 6 - calibration table.

<table>
<thead>
<tr>
<th>Method</th>
<th>POR Baseflow (in)</th>
<th>Sum of Residuals</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMB Method</td>
<td>7.7</td>
<td>0.00</td>
</tr>
<tr>
<td>HYSEP 1 (Fixed Interval)</td>
<td>7.1</td>
<td>1.95E+02</td>
</tr>
<tr>
<td>HYSEP 2 (Sliding Interval)</td>
<td>7.2</td>
<td>1.77E+02</td>
</tr>
<tr>
<td>HYSEP 3 (Local Minimum)</td>
<td>6.8</td>
<td>3.50E+02</td>
</tr>
<tr>
<td>Calibrated</td>
<td>7.2</td>
<td>1.76E+02</td>
</tr>
</tbody>
</table>

<< Used for Calibration
Figure 19. Hydrograph separation for Station 6 – USGS gaging station 03238745, Twelvemile Ck. at Hwy 1997, KY.
Figure 20. Cumulative baseflow calibration for Station 6 – USGS gage 03238745, Twelvemile Ck. at Hwy 1997, KY.
Appendix B. (Continued)

Station 7 - USGS 03254480 - Cruises Creek at Hwy. 17, KY
State Kentucky
Hydrologic Unit Code 50100101
Latitude 38°50'40"
Longitude 84°31'56"
Drainage Area (mi^2) 30
Gage Datum Not Available
Period of Record for Study 6/28/02 to 4/12/03

CMB Method Inputs
100% B.F. (mS/cm) 600
100% R.O. (mS/cm) 225

HYSEP Inputs
Basin Area (mi^2) 30
N 2.0
2N 3.9
2N* 3

2N* Comparison
HYSEP (Days) 3
Calibrated (Days) 3

Table 11. USGS gaging station 7 - calibration table.

<table>
<thead>
<tr>
<th>Method</th>
<th>POR Baseflow (in)</th>
<th>Sum of Residuals</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMB Method</td>
<td>11.3</td>
<td>0.00</td>
</tr>
<tr>
<td>HYSEP 1 (Fixed Interval)</td>
<td>10.2</td>
<td>7.04E+02</td>
</tr>
<tr>
<td>HYSEP 2 (Sliding Interval)</td>
<td>10.9</td>
<td>4.27E+02</td>
</tr>
<tr>
<td>HYSEP 3 (Local Minimum)</td>
<td>10.4</td>
<td>5.95E+02</td>
</tr>
</tbody>
</table>
| Calibrated                    | 10.9             | 4.27E+02         | << Used for Calibration
Figure 21. Hydrograph separation for Station 7 – USGS gaging station 03254480, Cruises Creek at Hwy 17, KY.
Figure 22. Cumulative baseflow calibration for Station 7 – USGS gaging station 03254480, Cruises Creek at Hwy 17, KY.
Appendix B. (Continued)

Station 8 - USGS 03254550 - Banklick Creek at Hwy 1829, KY
State Kentucky
Hydrologic Unit Code 50100101
Latitude 38°58'34"
Longitude 84°32'40"
Drainage Area (mi^2) 40
Gage Datum Not Available
Period of Record for Study 12/1/00 to 3/10/03

CMB Method Inputs
100% B.F. (mS/cm) 900
100% R.O. (mS/cm) 300

HYSEP Inputs
Basin Area (mi^2) 30
N 2.0
2N 3.9
2N* 3

2N* Comparison
HYSEP (Days) 3
Calibrated (Days) 3

Table 12. USGS gaging station 8 - calibration table.

<table>
<thead>
<tr>
<th>Method</th>
<th>POR Baseflow (in)</th>
<th>Sum of Residuals</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMB Method</td>
<td>11.3</td>
<td>0.00</td>
</tr>
<tr>
<td>HYSEP 1 (Fixed Interval)</td>
<td>10.2</td>
<td>7.04E+02</td>
</tr>
<tr>
<td>HYSEP 2 (Sliding Interval)</td>
<td>10.9</td>
<td>4.27E+02</td>
</tr>
<tr>
<td>HYSEP 3 (Local Minimum)</td>
<td>10.4</td>
<td>5.95E+02</td>
</tr>
<tr>
<td>Calibrated</td>
<td>10.9</td>
<td>4.27E+02</td>
</tr>
</tbody>
</table>

<< Used for Calibration
Figure 23. Hydrograph separation for Station 8 – USGS gaging station 03254550, Banklick Creek at Hwy 1829, KY.
Figure 24. Cumulative baseflow calibration for Station 8 – USGS gaging station 03254550, Banklick Ck. at Hwy 1829, KY.
Appendix B. (Continued)

Station 9 - USGS 02204070 South River at Klondike Rd, GA
State Georgia
Hydrologic Unit Code 3070103
Latitude 33°37'47"
Longitude 84°07'43"
Drainage Area (mi²) 182
Gage Datum 660.90' NGVD
Period of Record for Study 3/12/00 to 12/2/02

CMB Method Inputs
100% B.F. (mS/cm) 425
100% R.O. (mS/cm) 50

HYSEP Inputs
Basin Area (mi²) 132
N 2.7
2N 5.3
2N* 5

2N* Comparison
HYSEP (Days) 5
Calibrated (Days) 37

Table 13. USGS gaging station 9 - calibration table.

<table>
<thead>
<tr>
<th>Method</th>
<th>POR Baseflow (in)</th>
<th>Sum of Residuals</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMB Method</td>
<td>18.9</td>
<td>0.00</td>
</tr>
<tr>
<td>HYSEP 1 (Fixed Interval)</td>
<td>26.3</td>
<td>3.74E+03</td>
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<tr>
<td>HYSEP 2 (Sliding Interval)</td>
<td>26.5</td>
<td>3.86E+03</td>
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<tr>
<td>HYSEP 3 (Local Minimum)</td>
<td>25.9</td>
<td>3.50E+03</td>
</tr>
<tr>
<td>Calibrated</td>
<td>19.3</td>
<td>4.72E+02</td>
</tr>
</tbody>
</table>

<< Used for Calibration
Figure 25. Hydrograph separation for Station 9 – USGS gaging station 02204070, South River at Klondike Rd, GA.
Figure 26. Cumulative baseflow calibration for Station 9 – USGS gaging station 02204070, South R. at Klondike Rd, GA.
Appendix B. (Continued)

Station 10 - USGS 02208150 Alcovy River at New Hope Rd, GA
State Georgia
Hydrologic Unit Code 3070103
Latitude 33°55'03"
Longitude 84°53'17"
Drainage Area (mi^2) 30.8
Gage Datum 850.00' NGVD
Period of Record for Study 3/7/01 to 4/12/03

<table>
<thead>
<tr>
<th>CMB Method Inputs</th>
<th>100% B.F. (mS/cm)</th>
<th>100% R.O. (mS/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>95</td>
<td>45</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>HYSEP Inputs</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Basin Area (mi^2)</td>
<td>30.8</td>
<td></td>
</tr>
<tr>
<td>N</td>
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<tr>
<td>2N</td>
<td>4.0</td>
<td></td>
</tr>
<tr>
<td>2N*</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>2N* Comparison</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>HYSEP (Days)</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Calibrated (Days)</td>
<td>9</td>
<td></td>
</tr>
</tbody>
</table>

Table 14. USGS gaging station 10 - calibration table.

<table>
<thead>
<tr>
<th>Method</th>
<th>POR Baseflow (in)</th>
<th>Sum of Residuals</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMB Method</td>
<td>18.2</td>
<td>0.00</td>
</tr>
<tr>
<td>HYSEF 1 (Fixed Interval)</td>
<td>19.8</td>
<td>5.79E+02</td>
</tr>
<tr>
<td>HYSEF 2 (Sliding Interval)</td>
<td>22.3</td>
<td>1.43E+03</td>
</tr>
<tr>
<td>HYSEF 3 (Local Minimum)</td>
<td>20.4</td>
<td>8.78E+02</td>
</tr>
<tr>
<td>Calibrated</td>
<td>17.3</td>
<td>4.40E+02</td>
</tr>
</tbody>
</table>

<< Used for Calibration
Figure 27. Hydrograph separation for Station 10 – USGS gaging station 02208150, Alcovy River at New Hope Rd, GA.
Appendix B. (Continued)

Figure 28. Cumulative baseflow calibration for Station 10 – USGS gage 02208150, Alcovy R. at New Hope Rd, GA.
Appendix C. Suggested Future Investigations

1. Anomalies in streamflow conductivity data at the start of runoff events should be investigated further. Data for gaging stations 2 and 4 show sharp peaks in streamflow conductivity at the start of the majority of runoff events. Data for gaging stations 6, 8, and 10 also show these peaks on a number of runoff events, but not a consistent majority as in 2 and 4. These peaks quickly drop off to a minimum conductivity value at or near the runoff peak. Pilgrim et al. (1979), identifies this behavior as a first flush effect where the high conductivity peak is caused by higher concentrations of solutes washed out by the initial phases of stormwater runoff. However, first flush solute loading graphs typically take the shape of runoff hydrographs, showing an increase to a peak loading followed by a gradual decrease in solute concentration to a minimum. Instead, the conductivity data in this study show a sharp increase to a peak, followed by an even sharper decrease to a minimum. The conductivity then gradually increases to a maximum. Based on a qualitative review, the magnitude and timescale of the peaks are directly in proportion to the size of the runoff event. If these data peaks represent a rapid influx of baseflow at the start of a runoff event, then they must be accounted for in baseflow separation using the CMB Method. However, if they are the result of a first flush of highly concentrated surface runoff, then the CMB Method will greatly over calculate baseflow at the start of runoff and the data may have to be filtered to remove the peaks.

2. The time lag that occurs between the minimum streamflow conductivity and the maximum discharge during some runoff events should be investigated further. Like the initial peaking anomaly, this behavior does not occur randomly throughout the data. Instead it seems that some stations are more prone to the effect. Data for gaging station 3 show this behavior the best. Conductivity data for station 3 show the usual decrease during the time to runoff peak. However,
Appendix C. (Continued)

conductivity does not reach a minimum until the 24 hours later in some cases. Based on qualitative analysis the time lag is directly proportional to the magnitude of the runoff peak. During the time lag while runoff is at a peak, conductivity has not yet reached a minimum. When using the CMB method, this results in a large portion of the total streamflow to be calculated as baseflow during the start of runoff. This effect can be seen in the sharp baseflow peaks at the start of each runoff event for station 3. With larger time lags corresponding to larger runoff events, the end result may be an overestimation of baseflow, especially for larger events.

3. The behavior of streamflow conductivity at assumed 100% runoff and 100% baseflow conduction should be investigated further. Data for some of the gaging stations do not seem to reach the definitive boundary conditions ideal for the CMB Method. The CMB Method relies heavily on a maximum stabilized conductivity value assumed to represent 100% baseflow, and a persistent minimum conductivity at runoff peaks assumed to represent 100% runoff. Data for station 1 show that a stabilized maximum conductivity value is not reached during the relatively dry period between 12/01 and 06/01. Furthermore, data for station 3 show that a persistent minimum conductivity is not reached during runoff events. Instead, the magnitude of the conductivity trough is directly proportional to the magnitude of the runoff peak. Although this relationship is expected, it is assumed that conductivity will reach a maximum boundary at the point in which runoff makes up 100% of streamflow. Unless no runoff events resulted in 100% runoff conditions, data for station 3 show that for this case conductivity will continue to decrease even after the stream reaches 100% runoff. If relatively definitive boundary conditions for 100% baseflow and 100% runoff cannot be determined, baseflow calculations may be inaccurately calculated using the CMB Method.
Appendix C. (Continued)

4. Conductivity data may be influenced by ground-water pumping, certain land use classifications, wastewater discharges, industrial discharges, construction or other activities upstream of a streamflow measurement location. Conductivity data anomalies associated with these activities, and the effect they may have on the use of the CMB Method, were not addressed in this study. The effect that these activities may have on baseflow or runoff conductivity, and ultimately streamflow conductivity, should be investigated further to determine the appropriateness of using the CMB Method in basins where they exist.

5. Long-term streamflow conductivity data at extreme high and extreme low flow conductions should be analyzed to determine a more objective and consistent algorithm for identifying conductivity values for 100% runoff and 100% baseflow. During this study boundary values used in the CMB Method were determined qualitatively by analyzing conductivity and streamflow plots for each gaging station. Meaningful statistical analysis to objectively determine these boundary values would have been difficult due to the relatively short period of record for continuous conductivity data. However, as the period of record for continuous conductivity data grows, an objective, mathematical determination of these boundary values would be required to make the CMB Method consistent if applied universally.

6. Long-term ground-water conductivity data should be collected to identify any potential long-term changes in ground-water conductivity that may occur during extreme wet or extreme dry periods. Ground-water conductivity was monitored for this study during both excessively dry and excessively wet periods and showed little fluctuation between the two. However, data was collected during
Appendix C. (Continued)

only one year. Long-term ground-water conductivity monitoring that takes into account average and extreme climatological periods would be required to either support or disqualify the fundamental assumption that baseflow conductivity remains constant in time for the CMB Method.

7. Long-term surface-water conductivity data should be collected to identify a minimum period of record required for accurate calibration of the $2N^*$ value. If $2N^*$ values were determined for a given station using different periods of record, $2N^*$ values could be plotted against period or record to show at which period of record $2N^*$ becomes constant. If a common minimum required timescale was determined it could be set as the minimum required period of record to be used for the CMB Method of calibration, thus further increasing the universal consistency of the method.