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Temporal variations in baseflow for the Little River experimental watershed in South Georgia, USA☆

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ABSTRACT

Study region: The Little River Experimental Watershed (LREW) in the Southern Coastal Plain Major Land Resource Area of the U.S.A. (N31°28′54″, W83°35′03″).

Study focus: Separation of streamflow hydrographs into rapid stormflow and baseflow can vastly improve our understanding of watershed processes. The two parameter Eckhardt digital filter method for separation of high and low frequency signals was used to estimate the portion of streamflow emanating from soil water and groundwater. The method requires estimation of two fitting parameters, BFI_{max} and alpha (α). The baseflow index (BFI) is the ratio of baseflow volume to total streamflow volume. BFI_{max} was set at 0.80 and α at 0.98.

New hydrological insights for the region: Baseflow was found to produce 53% of annual streamflow. Stormflow was found to produce 47% of the annual streamflow. Baseflow was the greatest during the months from December through May (55–57%) and the least during the months from June through November (43–46%). Annual BFI was found to decrease with increasing annual precipitation, indicating that during high precipitation year's saturation excess driven stormflow increases in the LREW. Hydrograph analysis indicated an average stormflow duration of seven days, typically extended by interflow in this watershed. These observed seasonal patterns can have a significant impact on regional agriculture as well as coastal estuaries that both rely heavily upon streamflow.

1. Introduction

An understanding of streamflow processes is important for a number of purposes including water resource management, aquatic ecosystem preservation, hydropower generation, contaminant transport, and low-flow forecasting (Beck et al., 2013). Streamflow is composed of three parts: overland flow or surface runoff created by water that does not infiltrate into the soil

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and travels quickly to the stream, interflow consisting of water that infiltrates into the soil and travels laterally downslope through upper soil layers, and groundwater flow that infiltrates and travels through the aquifer. Separation of streamflow into these components is subjective since there is no method for precisely identifying each. Water that follows pathways through the subsurface reaches the stream slower, leading to delayed signatures in streamflow hydrographs. Subsurface flow can consist of both shallow interflow and deeper aquifer flow. Interflow can be driven by restrictive soil horizons that occur within many soils. Interflow moves more slowly than surface runoff but typically more rapidly than groundwater. Hydrograph separation is further complicated because interflow can reemerge downgradient as seepage at the land surface and combine with direct surface runoff. In terms of the streamflow hydrograph, it can be impossible to distinguish between the three different components. Because of this, streamflow is typically divided into two components for hydrograph separation, stormflow and baseflow. Stormflow contains true surface runoff and the quickflow portion of interflow while baseflow contains groundwater flow and the portion of interflow moving slowly through the subsoil.

Baseflow is particularly important throughout the Southern Coastal Plain (SCP) Major Land Resource Area (USDA-NRCS, 2006). A favorable climate, fertile soils, and ample rainfall make the SCP a productive agricultural region. The SCP is rich in surface and subsurface water resources that are essential for agriculture. Many of the region's surficial aquifers contribute to baseflow throughout the SCP (Miller, 1990). Transmissivity of the surficial aquifer throughout the SCP is highly variable (Miller, 1990; Santhi et al., 2008), as a result baseflow contributions to streamflow can be highly variable. Increasing demands on groundwater, changes in land-use, and changes in precipitation patterns due to climate change all are expected to impact baseflow conditions and streamflow volume. Furthermore, comprehensive planning for water resource management, development, and use can benefit from a clear understanding of seasonal baseflow patterns as well as long-term changes in baseflow behavior (Esralew and Lewis, 2010).

Separation of streamflow hydrographs into rapid stormflow and baseflow can vastly improve our understanding of streamflow and chemical transport. Because surface runoff moves rapidly into the stream while baseflow moves more slowly through the soil, separating and understanding these two processes is fundamental to understanding the hydrologic and water quality effects of many watershed processes. In many landscapes surface runoff can be intercepted by topographic depressions that can store water preventing transport to the stream and enhancing infiltration. Despite these complications, characterizing these two components of streamflow can greatly improve watershed hydrologic budgets. For validation of hydrology in model simulations, stormflow and baseflow components of streamflow hydrographs typically need to be separated. Incorrect representation of baseflow patterns can lead to erroneous model results and ultimately erroneous policy decisions (Arnold et al., 2014). For validation of hydrology in Conservation Effects Assessment Project (CEAP) model simulations, stormflow and baseflow components of streamflow hydrographs were separated for hundreds of gages across the U.S. (Santhi et al., 2008). CEAP model output was then calibrated for stormflow and baseflow, illustrating the importance of hydrograph separation.

Baseflow is typically estimated through analysis of streamflow time-series hydrographs, separating streamflow into the stormflow and baseflow. Various techniques exist for hydrograph separation. Because it is not physically possible to completely differentiate stormflow from baseflow, methods for hydrograph separation vary widely. Techniques typically fall into manual graphical, automated filtering, and tracer based methods. The most widely used graphical separation technique, referred to as the straight line method, consists of graphically extending the recession component of the hydrograph before a storm that is solely composed of baseflow, to a point of the recession after the peak of the hydrograph (Fig. 1). For this method a straight line is drawn from the start of the rising limb of the hydrograph to a selected point on the recession hydrograph, assuming that stormflow is the component above the line and baseflow is the component below the line. Selection of the

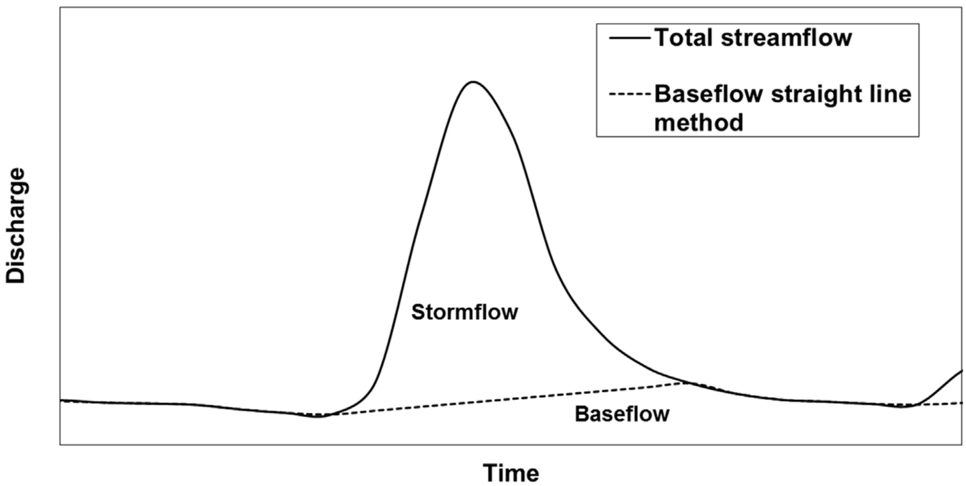

Fig. 1. An illustration of the straight line baseflow separation technique where the beginning and ending points of the dashed line represent the onset and conclusion of stormflow.

beginning point can be easily identified based upon the beginning of the hydrograph response to stormflow. Selection of the final point is often much more arbitrary (Linsley et al., 1975). The straight line method is typically isolated to a single peak hydrograph resulting from a single storm event. Complex (multiple-peak) events are difficult to interpret with respect to onset and ending time of baseflow.

Graphical hydrograph separation techniques work well for isolated events. However, most streamflow records include numerous events over any given period. Graphical analysis for extended records can be impractical. Because of this, automated methods have been developed for hydrograph separation. For continuous hydrographs, automated techniques are typically used that process the entire time-series data and derive baseflow. These methods are typically referred to as digital filtering procedures that use numeric algorithms to separate the flow. In general, filtering methods do not have hydrological basis but aim to generate an objective, repeatable, and easily automated method to derive baseflow response of a catchment. Digital filtering methods remove inconsistencies inherent in graphical methods and reduce the time required for hydrograph separation. Many filtering methods exist, only a few of which will be discussed here. An excellent review of filtering methods is presented by Brodie and Hostetler (2005). One widely used baseflow separation application is the U.S. Geological Survey HYSEP program (Sloto and Crouse, 1996). HYSEP is a public domain computer program with three separation methods: fixed interval, sliding interval, and local minimum. Additional numeric techniques include the single parameter (Nathan and McMahan, 1990) and the two parameter (Eckhardt, 2005) digital filters. The two parameter digital filter has been shown to provide comparable results to the widely used HYSEP method (Lim et al., 2005). Gonzales et al. (2009) also compared several methods for estimating baseflow and reported that the Eckhardt two parameter digital filter method yielded baseflow index (BFI) estimates comparable to those obtained using tracer tests. The BFI is the ratio of baseflow volume to total flow volume, often expressed as a percentage, determined after the hydrograph separation has been completed. Tracer methods make direct measurements of the stormflow and baseflow components. However, even with tracer techniques considerable uncertainty exists with hydrograph separation (Gonzales et al., 2009; Rumsey et al., 2015).

The BFI varies depending upon geology, topography, and season. Within any given watershed, it can vary as the vadose zone within the watershed changes in water content. The analysis of Wolock (2003) for the conterminous United States indicated BFI ranges from 0.20 to 0.60 for the Georgia section of the SCP. Santhi et al. (2008) estimated baseflow for the conterminous United States using the single parameter digital filter method during low ET (non-summer) months and found index values from 0.30-0.50 for the Georgia SCP. Shrimohammadi et al. (1984) examined hydrographs using the straight line method for the Little River Experimental Watershed (LREW) in South Georgia, USA for the period from 1968 to 1981 for rainfall events exceeding 5 mm. The determination of the final point on the recession hydrograph was made based upon the anticipated stormflow runoff duration from any event, a function of watershed area. They reported BFIs ranging from 0.58 to 0.81 for watersheds ranging in scale from 2.6 to 334 km^2, with an estimate of 0.68 for primary Little River drainage. They further reported a BFI of 0.79 for a 1494 km^2 portion of the Little River (1968–1970).

As expressed, baseflow is expected to vary seasonally, a function of varying levels of evapotranspiration and aquifer storage. Streamflow during the months of December through April in watersheds throughout the SCP is typically much greater than during the months of May through November (Sheridan, 1997). Greater precipitation and smaller evapotranspiration rates during the winter and spring months create greater soil-moisture and greater aquifer recharge, increasing surface runoff responses and groundwater contributions to streamflow. Sheridan (1997) reported that 54% of the precipitation received in January through April becomes streamflow while only 12% becomes streamflow throughout the remainder of the year. Shirmohammadi et al. (1986) reported that alluvial storage surrounding regional streams in the Southeastern U.S. varies from 0 to 20% available during late winter and spring to 100% available during late summer and fall. The lack of available storage in the winter and spring subsequently leads to high peak flows and high streamflow (Shirmohammadi et al., 1986). For regions with surficial aquifers, baseflow can cease during summer and fall periods when the surficial aquifer tends to be dry. Streamflow during summer and fall may be dominated by surface runoff generated during high intensity precipitation events.

The SCP region consists mainly of low-elevation flat to rolling terrain with numerous streams, abundant rainfall, a complex coastline, and many wetlands. Streams throughout the ecoregion are relatively low gradient and sandy bottom. The region contains many areas with shallow aquifer systems that feed streamflow. The Little River Experimental Watershed (LREW) was established as a long-term study site in the SCP by the U.S. Department of Agriculture, Agricultural Research Service in 1968. The Little River is considered to be generally representative of the climate, topography, soils, geology, stream networks, and agricultural production systems within the Level III Southeastern Plains ecoregion. Additionally, the contribution of surface water to deep seepage is believed to be relatively small, simplifying defining experimental watershed water budgets. The LREW is in the headwaters of the Suwannee River Basin. An extensive body of hydrologic data exists for the LREW (Bosch et al., 2007a).

While some studies have examined baseflow in the LREW (Shrimohammadi et al., 1984; Shirmohammadi et al., 1986; Nejadhashemi et al., 2009), these studies focused on a small sub-watershed of the LREW and short periods of record. A consistent examination of baseflow on the larger LREW, an extensive analysis of the complete database, and analysis of seasonal trends in the baseflow is lacking. The objectives of this research were to: 1) Quantify annual baseflow conditions in the Georgia LREW and 2) Quantify seasonal characteristics of baseflow in the Georgia LREW.

2. Materials and methods

2.1. Site and instrumentation

The LREW, located near Tifton, Georgia, in the SCP of the U.S.A. (N31°28′54″, W83°35′03″) was selected for the study (Fig. 2). The LREW is part of the Gulf Atlantic Coastal Plain LTAR (Maddox, 2013). The hydrology and water quality of the LREW has been monitored by the Southeast Watershed Research Laboratory (SEWRL) since 1967 (Bosch et al., 2007a). The climate is humid subtropical with a long growing season. Annual precipitation averages 1200 mm yr^{-1}. Mean annual temperature is around 18.7 °C, with the coldest month of the year being January with an average temperature of 10.6 °C and the warmest being July with an average temperature of 26.8 °C.

The 334 km^2 LREW is a mixed land-use watershed that contains row crop agriculture, pasture and forage, upland forest, and riparian forest. The agricultural fields are typically less than 40 ha in size and nested among forested drainages (Bosch

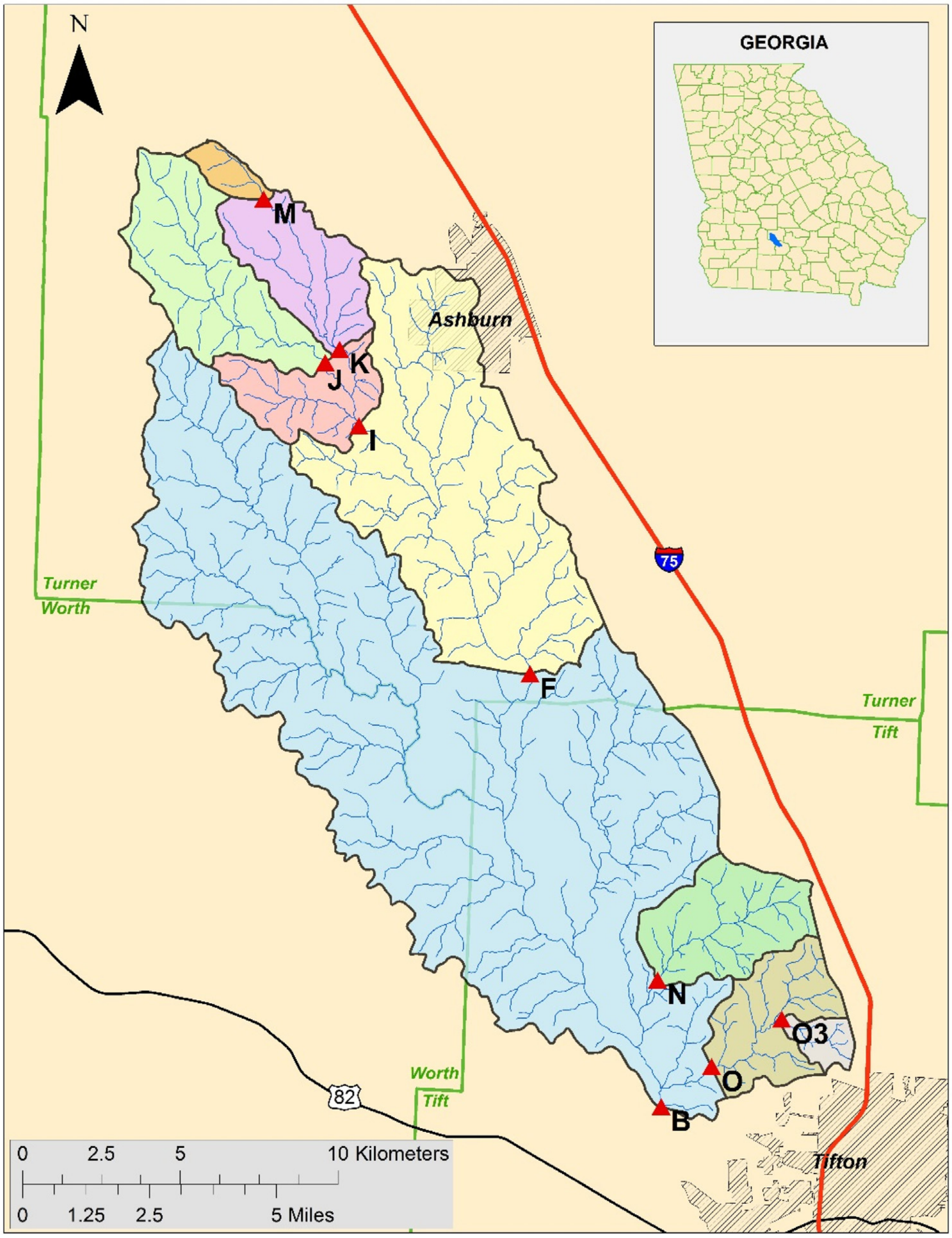

Fig. 2. Location of Little River Experimental watershed and monitoring networks. Symbols and letters denote the location of streamflow measurement stations.

et al., 2004). The surface soil textures are generally sands and sandy loams with high infiltration rates. Many of the upland soils of the LREW contain argillic horizons that include an accumulation of silicate clays that restrict vertical infiltration of water and cause shallow lateral subsurface interflow. The LREW landscape is dominated by a dense dendritic network of stream channels bordered by riparian forest wetlands (Asmussen et al., 1979) with drainage densities varying from 1.6 to 2.0 km km^{-2} (Sheridan, 1994). The drainage density is less than the drainage densities reported for Coastal Plain watersheds in South Carolina (Ssegane et al., 2013) but similar to those reported for Maryland (Carlston, 1963). Precipitation patterns during the summer show less average depth, shorter duration, higher intensity, and more frequent occurrence than events during other seasons of the year (Bosch et al., 1999).

Research within the LREW indicates that direct surface runoff can vary between 5 and 40% of annual precipitation while shallow subsurface interflow flow vary between 2 and 35% of annual precipitation (Asmussen and Ritchie, 1969; Hubbard and Sheridan, 1983; Bosch et al., 2012). Further research indicates that within the Coastal Plain landscape, saturation within the floodplain can lead to surface seepage by the shallow subsurface interflow in lower landscape positions (Bosch et al., 1996; Inamdar et al., 1999). Surface soils are underlain by the upper part of the shallow and relatively impermeable Hawthorne formation that restricts downward movement of infiltrated precipitation and leads to groundwater flow to the stream channels (Sheridan, 1997). Within the LREW, this formation can vary from 5 m below the land surface to within a meter of land surface in the floodplain (Shirmohammadi et al., 1986; Bosch et al., 1996). Baseflow within this landscape is driven by flow within the surficial aquifer above the Hawthorne formation in combination with the portion of the shallow interflow that remains below the ground surface. Within the LREW, baseflow consists of the slower contributions to the streamflow while the stormflow represents more rapid contributions (direct surface runoff and in some cases the seepage component of the shallow subsurface flow).

Historical watershed weighted precipitation and streamflow data were obtained from the SEWRL database (Bosch and Sheridan, 2007; Bosch et al., 2007b). The watershed weighted precipitation is determined using the inverse distance, or the reciprocal distance weighting technique (Smith, 1992; Dean and Snyder, 1977). The period of record examined was from 1972 to 2015. This analysis was limited to examination of data from the largest watershed, Watershed B (Fig. 2), a 334 km^2 drainage area. Daily watershed weighted precipitation and streamflow data extrapolated from the subdaily data were examined. All periods of observed streamflow were used.

2.2. Data analysis

The automated web based hydrograph analysis tool, WHAT, that utilizes numerical techniques to separate rapid direct runoff from baseflow was selected for data processing (Lim et al., 2005). WHAT allows selection of any of three methods: the local minimum method (Sloto and Crouse, 1996), the one parameter BFLOW digital filter (Lyne and Hollick, 1979; Nathan and McMahan, 1990; Arnold and Allen, 1999; Arnold et al., 2000), and the two parameter or Eckhardt digital filter (Eckhardt, 2005). The digital filter method does not consider pre-existing hydrological or climatic conditions of the watershed since its origin comes from the algorithm used in digital filters used for signal processing. Parameters of the algorithms need to be determined based on flow characteristics, seasonal variations, and storm events.

The two parameter Eckhardt digital filter method used for separation of high and low frequency signals was used here (Lim et al., 2005). Compared to other filtering methods the two parameter Eckhardt method tends to reduce high BFI estimates and increase low BFI estimates (Ekhardt, 2008). The local minimum method has been shown to consistently overestimate baseflow (Lim et al., 2005). The one parameter digital filter method has been shown to yield good results when compared to manual methods (r^2 value of 0.83 when compared to observed data, Arnold and Allen, 1999). Lim et al. (2005) found a strong correlation between the single parameter and two parameter digital filter methods (Lim et al., 2005). However, the two parameter Eckhardt digital filter method has the advantage of incorporating a reduction in streamflow and baseflow when direct runoff has ceased. The Eckhardt method requires estimation of two fitting parameters, BFI_{max} and a filter parameter (α). BFI can be calculated from the estimates of baseflow and streamflow produced by the digital filter. While α can be determined based upon analysis of individual hydrograph recession curves, selection of BFI_{max} is not measurable (Eckhardt, 2005). Error analysis performed by Eckhardt (2012) indicated that α influences the calculated baseflow more than does BFI_{max}. Based upon published recommendations for perennial streams with porous aquifers (Eckhardt, 2005), a fixed BFI_{max} value of 0.80 was selected for the LREW. As described by Ekhardt (2008), α was determined by plotting recession curves for multiple hydrographs over several years. The recession curves were obtained by plotting streamflow at day i versus streamflow at day i + 1. The parameter α is the slope of the line that forms the upper bound between the two flows (Ekhardt, 2008). Following this procedure, an α value of 0.98 was selected. These BFI_{max} and α values have been used by several other researchers for similar watersheds and have yielded good results (Lim et al., 2010; Zhang et al., 2013; Zomlot et al., 2015). Examination of the multiple hydrographs over several years and seasons for the LREW watershed using these parameters indicated a good fit to observed hydrographs and recession curves.

Data were partitioned into annual (January–December) and seasonal periods for hydrograph analysis. The seasonal selection was based upon observed climatic and hydrologic patterns and has been used in explaining the response of hydrologic, sediment, and water quality parameters to precipitation on Coastal Plain watersheds (Asmussen et al., 1975; Sheridan et al., 1982; Hubbard and Sheridan, 1983; Bosch et al., 1999). The four selected seasons were: December, January, and February termed winter; March, April, and May termed spring; June, July, and August termed summer; and September, October, and November termed fall.

Basic precipitation and flow patterns for the LREW were calculated. Long term trends were examined through linear correlation and tested for trends using the Mann-Kendall trend test for non-parametric data. Baseflow data from each year from 1972 to 2015 (n = 44) as well as each of the four seasons for each individual year were examined independently. A BFI for each year and each season was determined. Average, coefficient of variation, maximum, and minimum were determined for the annual data as well as each of the four seasons. Linear correlations and residuals were examined using the F-test.

3. Results

3.1. Precipitation and streamflow patterns

Long term watershed weighted precipitation and streamflow patterns for the LRW were examined for the period from 1972 to 2015 (Fig. 3). The average annual watershed weighted precipitation for this period was 1200 mm while the long term average annual streamflow was 320 mm, 27% of annual precipitation. Tests of the variability in the precipitation over time indicated no significant change ($\alpha = 0.05$). No trend was observed in either the streamflow or the precipitation data over the 44 year period (α=0.05). Examination of precipitation and streamflow by season indicated no significant trends in the seasonal data either ($\alpha = 0.05$).

Observed average monthly precipitation in the watershed was greatest in the months of January through March and June through August (Fig. 4). Average area weighted monthly streamflow peaked during the month of March (Fig. 4). Average monthly streamflow from June through November was small (Fig. 4).

3.2. Baseflow

Examination of the 44 years of annual flow data produced an average BFI of 0.53 (Table 1). By difference, the fraction of stormflow was 0.47. Baseflow was the greatest during the months from December through May (0.55–0.57) and the least during the months from June through November (0.43–0.46) (Table 1). There were seven years where there was not enough summer flow to obtain baseflow estimates and eleven years where there was not enough fall flow to obtain estimates. Variability of the annual data were low (CV = 7.6%) while that of the fall BFI was larger (27.7%). Summer and fall streamflow can be dramatically influenced by tropical depressions in the region, leading to greater variability in precipitation (Bosch et al., 1999) and streamflow during these periods. No long term trends in BFI were found in either the annual or seasonal data (α=0.05) (Fig. 5), indicating as with precipitation and streamflow that baseflow has remained stable over time.

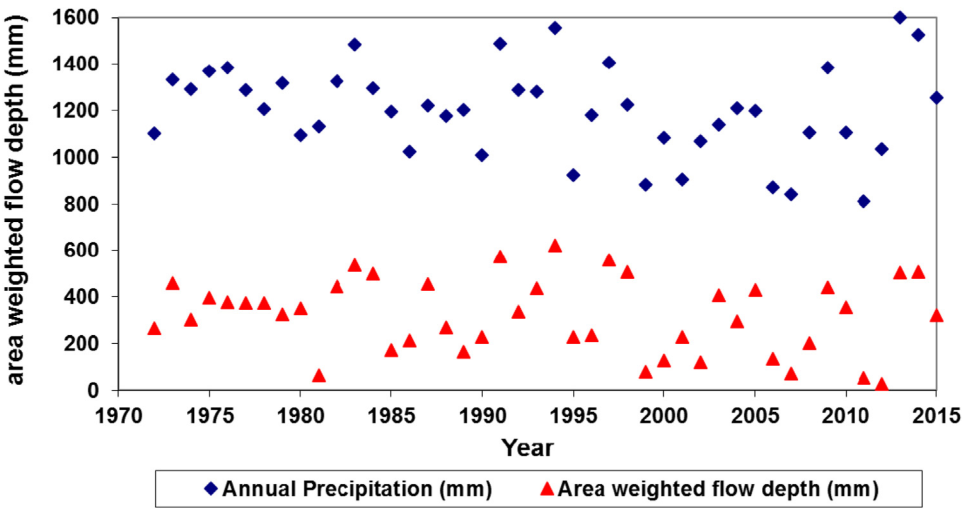

Fig. 3. Annual watershed weighted precipitation and area weighted flow depth for the LREW from 1972 to 2015.

Table 1
Results of annual and seasonal baseflow analysis for Little River Station B, 1972–2015.

Period	Winter	Spring	Summer	Fall	Annual
BFI	0.55	0.57	0.43	0.46	0.53
BFI Coefficient of Variation (%)	12.5	15.4	21.0	27.7	7.6
Maximum BFI	0.71	0.87	0.75	0.80	0.62
Minimum BFI	0.33	0.43	0.30	0.16	0.45

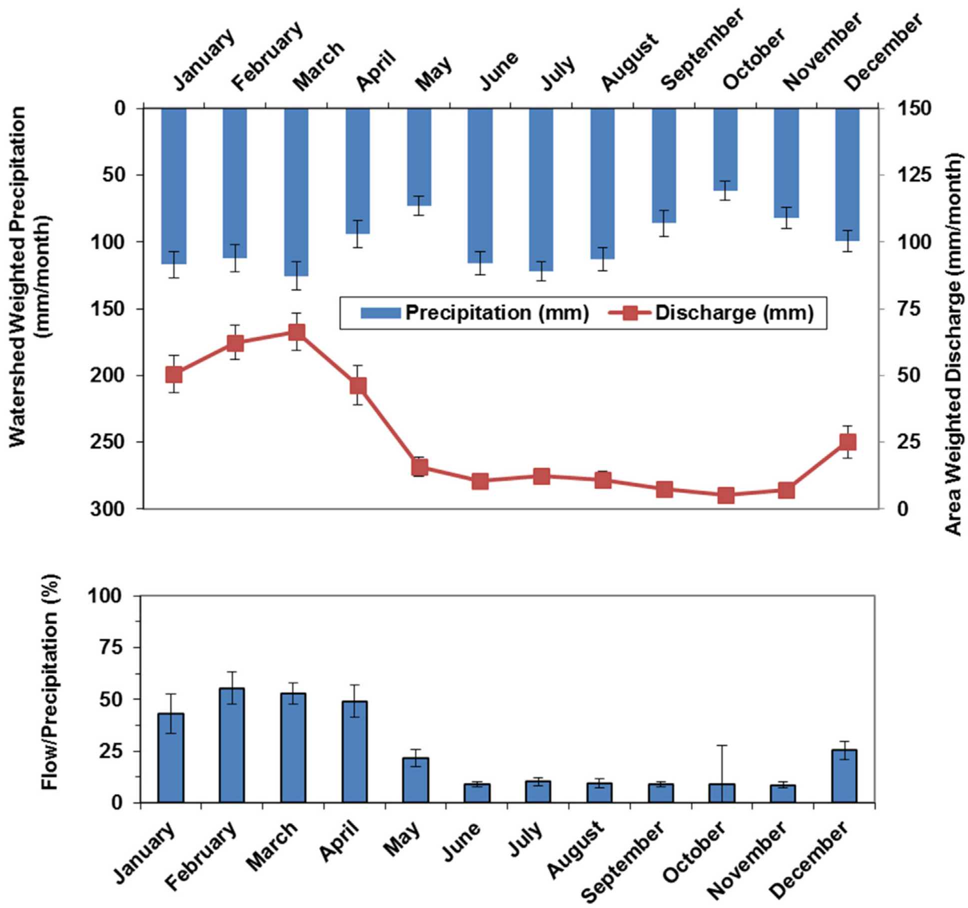

Fig. 4. Average monthly watershed weighted precipitation and area weighted discharge (top plot) and average monthly discharge to precipitation ratio (bottom plot) for the LREW from 1972 to 2015. Error bars illustrate the monthly standard error of the means.

Relationships between annual watershed weighted precipitation and annual BFI were examined (Fig. 6). Annual baseflow index was found to decrease as a function of increasing precipitation ($\alpha = 0.01$). This is attributed to the saturated soil and aquifer conditions that accompany high precipitation periods. The LREW contains shallow surficial aquifers that flow toward and saturate the floodplains (Asmussen, 1971; Bosch et al., 2003), the shallow water table conditions lead to saturation across large portions of the watershed. Bosch et al. (2006) determined that 30% of the LREW was contained in these low-lying saturated riparian buffer areas. As a consequence, high precipitation conditions saturate the floodplain and the surficial aquifer. While groundwater flow persists under these conditions, the saturated conditions lead to high saturation excess surface runoff and a higher proportion of streamflow coming from surface runoff. Examination of the seasonal data indicate the winter and spring seasons have the same trend between BFI and precipitation as the annual data but the relationships were not significant. The summer and fall seasons have no discernable trend.

Both streamflow and baseflow increase with increasing precipitation (Fig. 7). The rate of increase in streamflow with increasing precipitation exceeds the rate of increase in baseflow with increasing precipitation (Fig. 7). This is further indication that conditions of high precipitation lead to increases in saturation excess flow in this watershed, increasing the surface runoff component of streamflow at a more rapid rate than the baseflow component.

4. Discussion

Typically hydrologic simulations target a single BFI and do not make seasonal adjustments. The greatest difference observed here between the annual BFI and the seasonal BFI's was with the summer data, where a 10% difference in BFI was observed. The next greatest difference was with the fall data where a 7% difference was observed. However, in this region summer and fall flows are typically small (Fig. 4). Despite large differences in BFI in the summer and the fall, volume differences in these periods remain small. Seasonally, 37% of the annual precipitation and 70% of the annual streamflow occurs in the first four months of the calendar year. Examining the difference in baseflow area weighted flow estimates using the annual BFI versus the seasonal BFI indicates that in terms of area weighted baseflow, the greatest differences in estimated flow would be in March and April. If the annual BFI is used the March-April estimate of baseflow is 60 mm whereas

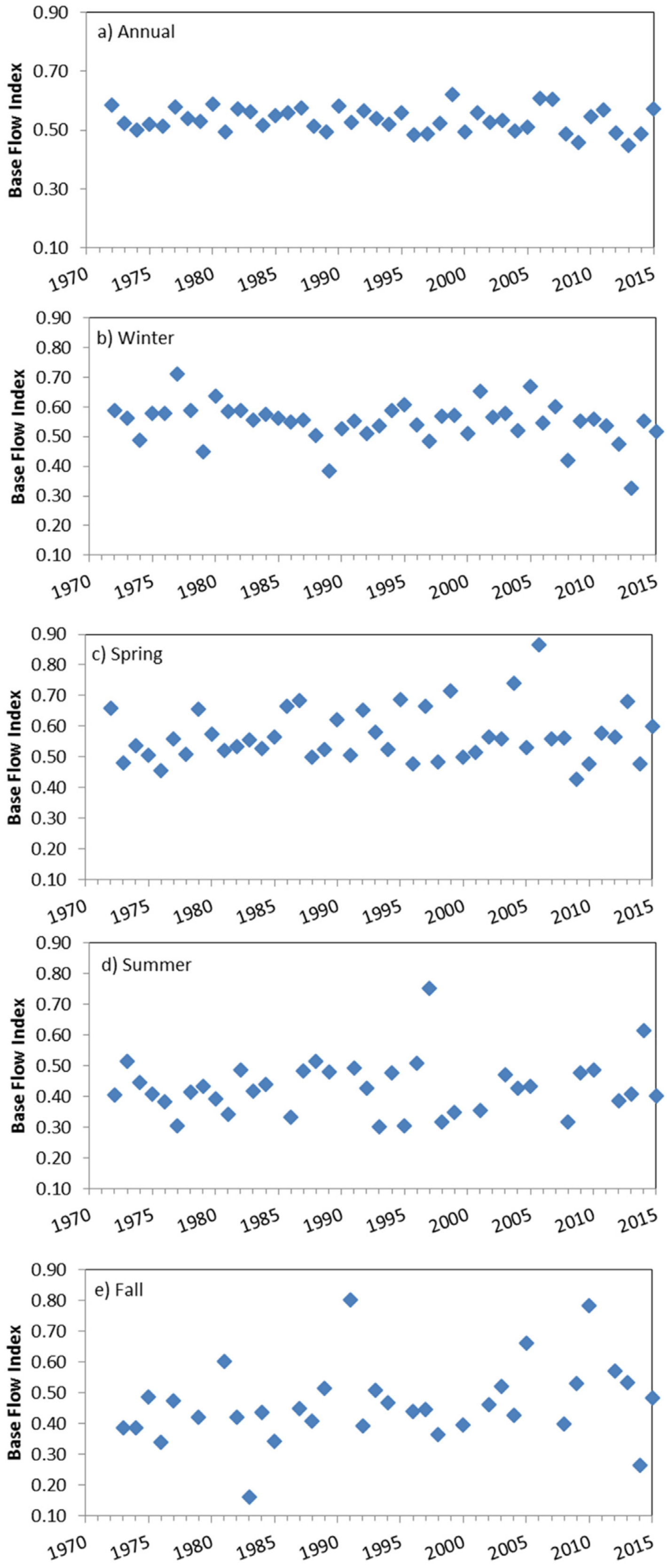

Fig. 5. Calculated baseflow indexes for the annual and the seasonal data.

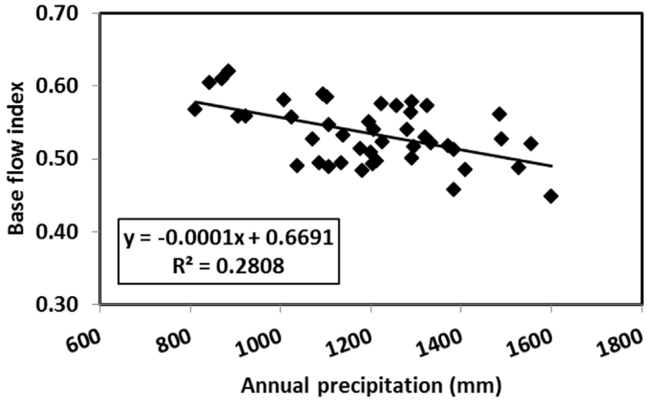

Fig. 6. Baseflow index and annual precipitation, trend line indicates a decreasing trend in baseflow as a function of increasing annual precipitation (significant at $\alpha = 0.01$).

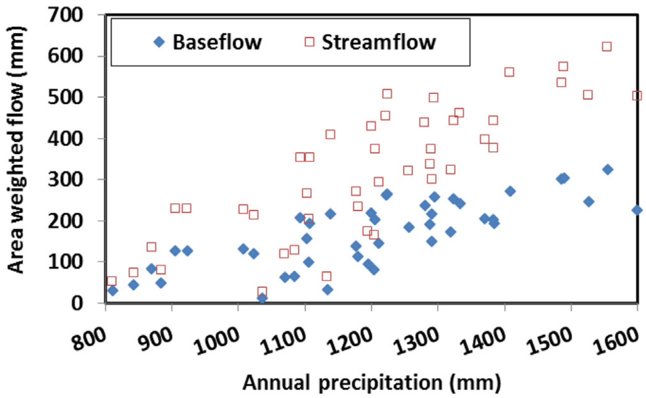

Fig. 7. Streamflow and baseflow area weighted flow (mm) as a function of annual rainfall for the LREW from 1972 to 2015.

it is 64 mm if the seasonal BFI is used. Even during the seasons of high baseflow, the differences obtained using the seasonal data do not warrant separating out the data for seasonal analysis.

Eckhardt (2012) used the two parameter digital filter to examine 65 North American catchments and reported values ranging from 0.67 for perennial streams with porous aquifers to 0.42 for ephemeral streams with porous aquifers. The LREW would be classified as a perennial stream with a porous aquifer. Santhi et al. (2008) estimated baseflow for the conterminous United States using the single parameter digital filter method during low evapotranspiration (fall and winter) months and reported BFI ranges of 0.40-0.50 for the LREW region. Our results indicate these estimates may be biased low due to the exclusion of the summer period. Shrimohammadi et al. (1984) reported BFIs ranging from 0.58 to 0.81 for Little River watersheds ranging in scale from 2.6 to 334 km^2 for the period from 1968 to 1981, with an estimate of 0.68 for the watershed reported here. They further reported a BFI of 0.79 for a 1494 km^2 portion of the Little River (1968–1970). Novak et al. (2003) studied four Coastal Plain subwatersheds from 314 to 1036 ha and found BFI to range from 0.58 to 0.73, also utilizing the single parameter digital filter method of Arnold and Allen (1999). These watersheds are similar in characteristics to the LREW watersheds. Priest (2004) characterized BFI for the 3600 km^2 neighboring Alapaha River watershed using the USGS HYSEP method (Sloto and Crouse, 1996). BFI for the Alapaha River which is similar in characteristics to the LREW was reported as 0.56 for the period from 1971 to 2001 (Priest, 2004). These reported values from the literature are generally greater than the annual average BFI of 0.53 found here. In some cases, this can be attributed to studying different climatic seasons and the application of different methods (Santhi et al., 2008; Shrimohammadi et al., 1984; Novak et al., 2003; Priest, 2004). As reported by Ekhardt (2008), the two parameter digital filter can reduce high BFI estimates. For the LREW, the method may include greater portions of the interflow into stormflow and less into baseflow.

Esralew and Lewis (2010) examined seasonal trends in BFI for several watersheds throughout the state of Oklahoma. BFI calculated from annual data were consistently less than those observed for the winter-spring periods while they were consistently greater than those for the summer-fall periods, consistent with the results we found for the LREW. It is anticipated that on an annual basis, periods of drought would have a larger fraction of streamflow generated by baseflow. The relationship illustrated by Fig. 6 indicates that years with smaller annual precipitation have higher BFIs. Drought periods were observed from 1999 to 2002 (average annual rainfall of 970 mm), 2006–2007 (avg. = 865 mm), and 2011–2012

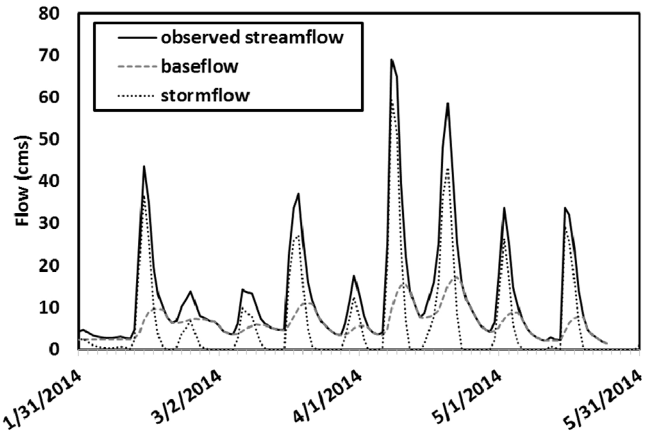

Fig. 8. Observed streamflow and calculated baseflow and stormflow from the WHAT annual analysis for the LREW from January 31, 2014 to May 31, 2014.

(avg. = 879 mm). Combined, the average BFI for these periods was 0.56, only slightly larger than the long term average of 0.53.

The analysis provided here provides a less subjective more repeatable estimate of BFI utilizing data specific for this watershed. However, as discussed in the methods, selection of the BFI_{max} and α parameters can be quite subjective and subject to uncertainty. As seen here, considerable year to year variability in baseflow can be expected (Fig. 5). Other studies have quantified the variability in BFI from 0.10 to 0.30 (Rumsey et al., 2015). Here annual BFI was found to vary from 0.45 to 0.62 with a CV of 7.6%. In this analysis we elected to select BFI_{max} equal to 0.80 based upon the recommendations provide by Eckhardt (2005). Fitting using multiple recession curves yielded an α value of 0.98. Eckhardt (2012) indicated for each percent error in α one could expect −0.77% error in BFI. Similarly, a 0.26% error in BFI could be expected for each percent error in BFI_{max}. For this study we believe the error in the estimate of BFI due to the estimate of α to be within 2%.

The 0.53 estimate of BFI obtained from the annual data provides an annual average estimate of baseflow of 169 mm (CV = 48%) for a long term average annual precipitation of 1200 mm (CV = 16%) and an average annual streamflow of 320 mm (CV = 49%). Conversely average annual stormflow is anticipated to be 151 mm. These estimates of baseflow and stormflow will provide reasonable target values for hydrologic simulation of the LREW with stormflow containing both surface runoff and the rapid component of interflow. Estimates for this watershed indicate a time to peak of 3 days for this watershed (Sheridan, 1994). Examination of stormflow and baseflow hydrographs using the annual BFI estimates derived here indicate stormflow has an average duration of seven days (Fig. 8). Prior observations indicate it is reasonable to expect that rapid interflow could contribute to stormflow over a period of seven days following a rainfall event (Asmussen and Ritchie, 1969; Hubbard and Sheridan, 1983; Bosch et al., 2012). In contrast, Shrimohammadi et al. (1984) had assumed a storm runoff duration of four days for this Little River watershed. Assuming a shorter storm runoff duration than was observed here would have led to proportioning a greater portion of streamflow to baseflow as previously reported.

5. Conclusions

Annually, baseflow was found to produce 53% of annual streamflow with a CV of 7.6%. Baseflow was the greatest during the months from December through May (55–57%) and the least during the months from June through November (43–46%). Annual BFI was found to decrease with increasing annual precipitation. Conversely, baseflow is greater during years of low precipitation, indicating the estimation of baseflow for low precipitation drought years may be more critical. During high precipitation years streamflow is dominated by saturation excess driven surface runoff leading to higher proportional stormflow. The relationship between BFI and annual rainfall observed here is expected to be different for watersheds not dominated by surficial aquifer processes. No long term trends were found in either the precipitation, flow, or BFI data, indicating no statistically significant hydrologic long term changes within the LREW.

These new assessments of BFI should prove useful for hydrologic simulation of the LREW. Prior targets used for the watershed of 0.68 would lead to overestimation of the baseflow component. The 0.53 BFI estimate presented here indicates that prior estimates may have incorporated a larger component of interflow into baseflow estimates. An average stormflow duration of seven days was determined here, including both surface runoff and the faster portion of interflow. Because interflow has the potential to have significantly different chemical characteristics than either direct surface runoff or groundwater flow, future research that better characterizes the separation of interflow from direct surface runoff and groundwater flow is warranted. One possible method may be to utilize tracer methods to separate these processes.

As indicated by previous research, streamflow volume in this watershed is the greatest from January through April. During this period groundwater contributions to streamflow are the greatest. Conversely, streamflow during the months from September through November can be unreliable due to diminishing baseflow, high evapotranspiration, and largely unsaturated conditions. Streamflow during the summer and winter months contains a higher proportion of surface runoff. Surface runoff has the potential to be of reduced water quality compared to groundwater. These seasonal patterns can have a significant impact on regional agriculture as well as coastal estuaries that both rely heavily upon streamflow. The observations provided here should improve hydrologic representation of regional watersheds as well as water quality loadings.

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References

Arnold, J.G., Allen, P.M., 1999. Validation of automated methods for estimating baseflow and groundwater recharge from stream flow records. J. Am. Water Resour. Assoc. 35 (2), 411–424.

Arnold, J.G., Muttiah, R.S., Srinivasan, R., Allen, P.M., 2000. Regional estimation of baseflow and groundwater recharge in the Upper Mississippi River Basin. J. Hydrol. 227 (2000), 21–40.

Arnold, J.G., Harmel, R.D., Johnson, M.V.V., Bingner, R., Strickland, T.C., Walbridge, M., Santhi, C., Di Luzio, M., Wang, X., 2014. Impact of the ARS assessment studies on the CEAP cropland national assessment. J. Soil Water Conserv. 69 (5), 137A–144A.

Asmussen, L.E., Ritchie, J.C., 1969. Interflow or shallow phreatic flow in the Coastal Plain of Georgia. J. Hydrol. 9 (1969), 182–193.

Asmussen, L.E., Sheridan, J.M., Allison, H.D., 1975. Water Quality Inventory of the Southern Coastal Plain and Atlantic Coast Flatwoods of Georgia. U.S. Department of Agriculture. Agricultural Res. Service. Southern Region ARS-S-49, New Orleans, LA (USDA).

Asmussen, L.E., Sheridan, J.M., Booram, C.B.J., 1979. Nutrient movement in streamflow from agricultural watersheds in the Georgia Coastal Plain. Trans. Am. Soc. Agricu. Eng. 22 (4), 809–815 (821).

Asmussen, L.E., 1971. Hydrologic Effects of Quaternary Sediments Above the Marine Terraces in the Georgia Coastal Plain. Southeastern Geology, Vol. 12. Duke University, Durham, NC, pp. 189–201 (no. 3).

Beck, H.E., van Dijk, A.I.J.M., Miralles, D.G., de Jeu, R.A.M., Bruijnzeel, L.A., McVicar, T.R., Schellekens, J., 2013. Global patterns in base flow index and recession based on streamflow observations from 3394 catchments. Water Resour. Res. 49, 1–21 (2013WR013918).

Bosch, D.D., Sheridan, J.M., 2007. Stream discharge database, Little River experimental watershed, Georgia, United States. Water Resour. Res. 43 (9), W09473, http://dx.doi.org/10.1029/2006WR005833.

Bosch, D.D., Sheridan, J.M., Lowrance, R.R., 1996. Hydraulic gradients and flow rates of a shallow coastal plain aquifer in a forested riparian buffer. Trans. Am. Soc. Agric. Eng. 39 (3), 865–871.

Bosch, D.D., Sheridan, J.M., Davis, F.M., 1999. Rainfall characteristics and spatial correlation for the Georgia Coastal Plain. Trans. Am. Soc. Agric. Eng. 42 (6), 1637–1644.

Bosch, D.D., Lowrance, R.R., Sheridan, J.M., Williams, R.G., 2003. Groundwater storage effect on streamflow for a Southeastern Coastal Plain Watershed. Ground Water 41 (7), 903–912.

Bosch, D.D., Sheridan, J.M., Batten, H.L., Arnold, J.G., 2004. Evaluation of the SWAT model on a coastal plain agricultural watershed. Trans. Am. Soc. Agric. Eng. 47 (5), 1493–1506.

Bosch, D.D., Sheridan, J.M., Sullivan, D.G., 2006. Hydrologic impact of land-use changes in Coastal Plain Watersheds. Trans. Am. Soc. Agric. Biol. Eng. 49 (2), 423–432.

Bosch, D.D., Sheridan, J.M., Lowrance, R.R., Hubbard, R.K., Strickland, T.C., Feyereisen, G.W., Sullivan, D.G., 2007a. Little River experimental watershed database. Water Resour. Res. 43 (9), W09470, http://dx.doi.org/10.1029/2006WR005844.

Bosch, D.D., Sheridan, J.M., Marshall, L.K., 2007b. Precipitation, soil moisture, and climate database, Little River experimental watershed, Georgia, United States. Water Resour. Res. 43 (9), W09472, http://dx.doi.org/10.1029/2006WR005834.

Bosch, D.D., Truman, C.C., Potter, T.L., West, L.T., Strickland, T.C., Hubbard, R.K., 2012. Tillage and slope position impact on field-scale hydrologic processes in the South Atlantic Coastal Plain. Agric. Water Manage. 111 (2012), 40–52.

Brodie, R.S., Hostetler, S., 2005. A review of techniques for analyzing base flow from stream hydrographs. In: Proceedings of the NZHS-IAH-NZSSS 2005 Conference, November 28-December 2, 2005, Auckland, New Zealand.

Carlston, C.W., 1963. Drainage Density and Streamflow: Physiographic and Hydraulic Studies of Rivers. Geologic Survey Professional Paper 422-C. United States Department of the Interior. Geologic Survey, Washington, D.C., USA.

Dean, J.D., Snyder, W.M., 1977. Temporally and aerially distributed rainfall. J. Irrig. Drain. Eng. 103, 221–229.

Eckhardt, K., 2005. How to construct recursive digital filters for baseflow separation. Hydrol. Processes 19 (2), 507–515.

Eckhardt, K., 2012. Technical note: analytical sensitivity analysis of a two parameter recursive digital baseflow separation filter. Hydrol. Earth Syst. Sci. 16 (2012), 451–455, http://dx.doi.org/10.5194/hess-16-451-2012.

Ekhardt, K., 2008. A comparison of baseflow indices, which were calculated with seven different baseflow separation methods. J. Hydrol. 352 (2008), 168–173, http://dx.doi.org/10.1016/j.jhydrol.2008.01.005.

Esralew, R.A., J.M., Lewis, 2010. Trends in base flow, total flow, and base-flow index of selected streams in and near Oklahoma through 2008. U.S. Geological Survey Scientific Investigations Report 2010–5104. 143 pp.

Gonzales, A.L., Nonner, J., Heijkers, J., Uhlenbrook, S., 2009. Comparison of different base flow separation methods in a lowland catchment. Hydrol. Earth Syst. Sci. 13, 2055–2068.

Hubbard, R.K., Sheridan, J.M., 1983. Water and nitrate-nitrogen losses from a small, upland, coastal plain watershed. J. Environ. Qual. 12 (2), 291–295.

Inamdar, S.P., Sheridan, J.M., Williams, R.G., Bosch, D.D., Lowrance, R.R., Altier, L.S., Thomas, D.L., 1999. Riparian Ecosystem Management Model (REMM): I. Testing of the hydrologic component for a coastal plain riparian system. Trans. Am. Soc. Agric. Biol. Eng. 42 (6), 1679–1689.

Lim, K.J., Engel, B.A., Tang, Z., Choi, J., Kim, K.-S., Muthukrishnan, S., Tripathy, D., 2005. Automated web GIS based hydrograph analysis tool, WHAT. J. Am. Water Resour. Assoc. 41 (6), 1407–1416.

Lim, K.J., Park, Y.S., Kim, J., Shin, Y.-C., Kim, N.W., Kim, S.J., Jeon, J.-H., Engel, B.A., 2010. Development of genetic algorithm-based optimization module in WHAT system for hydrograph analysis and model application. Comput. Geosci. 36 (2010), 936–944, http://dx.doi.org/10.1016/j.cageo.2010.01.004.

Linsley, R.K., Kohler, M.A., Paulhus, J.L.H., 1975. Hydrology for Engineers, 2nd ed. McGraw-Hill, New York, New York, USA.

Lyne, V.D., Hollick, M., 1979. Stochastic time-variable rainfall-runoff modeling. In: Hydrology and Water Resource Symposium. Institution of Engineers Australia, Perth, Australia, pp. 89–92.

Maddox, N., 2013. LTAR: Critical Research for Sustainable Intensification of Our Agroecosystems. Crop Science Society of America News, pp. 4–9 (June, 2013).

Miller, J.A., 1990. Ground Water Atlas of the United States: Alabama, Florida, Georgia, and South Carolina. U.S. Geological Survey (HA 730-G. 300 pp.).

Nathan, R.J., McMahan, T.A., 1990. Evaluation of automated techniques for baseflow and recession analysis. Water Resour. Res. 26 (7), 1465–1473.

Nejadhashemi, P., Shirmohammadi, A., Sheridan, J.M., Montas, H.J., Mankin, K.R., 2009. Case study: evaluation of streamflow partitioning methods. J. Irrig. Drain. Eng. 135 (6), 791–801, 10.1061(ASCE)IR.1943-4774.0000093.

Novak, J.M., Stone, K.C., Watts, D.W., Johnson, M.H., 2003. Dissolved phosphorus transport during storm and base flow conditions from an agriculturally intensive Southeastern Coastal Plain Watershed. Trans. Am. Soc. Agric. Eng. 46 (5), 1355–1363.
Priest, S., 2004. Evaluation of ground-water contribution to streamflow in coastal Georgia and parts of Florida and South Carolina. U.S. Geological Survey Scientific Investigations Report 2004–5265. 46 pp.
Rumsey, C.A., Miller, M.P., Susong, D.D., Tillman, F.D., Anning, D.W., 2015. Regional scale estimates of baseflow and factors influencing baseflow in the Upper Colorado River Basin. J. Hydrol. Reg. Stud. 4 (2015), 91–107, http://dx.doi.org/10.1016/j.ejrh.2015.04.008.
Santhi, C., Allen, P.M., Muttiah, R.S., Arnold, J.G., Tuppad, P., 2008. Regional estimation of base flow for the conterminous United States by hydrologic landscape regions. J. Hydrol. 351 (2008), 139–153.
Sheridan, J.M., Booram Jr., C.V., Asmussen, L.E., 1982. Sediment-deliver ratios for a small Coastal Plain agricultural watershed. Trans. Am. Soc. Agric. Eng. 25 (3), 610–615 (622).
Sheridan, J.M., 1994. Hydrograph time parameters for flatland watersheds. Trans. Am. Soc. Agric. Eng. 37 (1), 103–113.
Sheridan, J.M., 1997. Rainfall-streamflow relations for coastal plain watersheds. Appl. Eng. Agric. 13 (3), 333–344.
Shirmohammadi, A., Sheridan, J.M., Asmussen, L.E., 1986. Hydrology of alluvial stream channels in Southern coastal plain watersheds. Trans. Am. Soc. Agric. Eng. 29 (1), 135–142.
Shirmohammadi, A., Knisel, W.G., Sheridan, J.M., 1984. An approximate method for partitioning daily streamflow data. J. Hydrol. 74 (1984), 335–354.
Sloto, R.A., Crouse, M.Y., 1996. HYSEP: a computer program for stream flow hydrograph separation and analysis. In: Water-Resources Investigations Report 96–4040. U.S. Geological Survey, Reston, Virginia (46 pp).
Smith, J.A., 1992. Precipitation. In: Maidment, D.R. (Ed.), Handbook of Hydrology. McGraw-Hill, New York, p. 3 (1–3.47).
Ssegane, H., Amatya, D.M., Tollner, E.W., Dai, Z., Nettles, J.E., 2013. Estimation of daily streamflow of Southeastern Coastal Plain Watersheds by combining estimated magnitude and sequence. J. Am. Water Resour. Assoc. 48 (5), 1150–1166.
USDA-NRCS, 2006. Land Resource Regions and Major Land Resource Areas of the United States, the Caribbean, and the Pacific Basin. U.S. Department of Agriculture Handbook 296.
Wolock, D.M., 2003. Base-flow index grid for the conterminous United States. In: Open-File Report 03-263. U.S. Geological Survey, http://water.usgs.gov/GIS/metadata/usgswrd/XML/bfi48grd.xml. (Accessed 23 August 2016).
Zhang, Y., Ahiablame, L., Engel, B., Liu, J., 2013. Regression modeling of baseflow and baseflow index for Michigan USA. Water 5 (2013Z), 1797–1815, http://dx.doi.org/10.3390/w5041797.
Zomlot, Z., Verbeiren, B., Huysmans, M., Batelaan, O., 2015. Spatial distribution of groundwater recharge and base flow: assessment of controlling factors. J. Hydrol. Reg. Stud. 4 (2015), 349–368, http://dx.doi.org/10.1016/j.ejrh.2015.07.005.