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Base flow separation: A comparison of analytical and mass balance methods

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SUMMARY

Base flow is the ground water contribution to stream flow. Many activities, such as water resource management, calibrating hydrological and climate models, and studies of basin hydrology, require good estimates of base flow. The base flow component of stream flow is usually determined by separating a stream hydrograph into two components, base flow and runoff. Analytical methods, mathematical functions or algorithms used to calculate base flow directly from discharge, are the most widely used base flow separation methods and are often used without calibration to basin or gage-specific parameters other than basin area. In this study, six analytical methods are compared to a mass balance method, the conductivity mass-balance (CMB) method. The base flow index (BFI) values for 35 stream gages are obtained from each of the seven methods with each gage having at least two consecutive years of specific conductance data and 30 years of continuous discharge data. BFI is cumulative base flow divided by cumulative total discharge over the period of record of analysis. The BFI value is dimensionless, and always varies from 0 to 1. Areas of basins used in this study range from 27 km^2 to 68,117 km^2.

BFI was first determined for the uncalibrated analytical methods. The parameters of each analytical method were then calibrated to produce BFI values as close to the CMB derived BFI values as possible. One of the methods, the power function ($aQ^b + cQ$) method, is inherently calibrated and was not recalibrated. The uncalibrated analytical methods have an average correlation coefficient of 0.43 when compared to CMB-derived values, and an average correlation coefficient of 0.93 when calibrated with the CMB method. Once calibrated, the analytical methods can closely reproduce the base flow values of a mass balance method. Therefore, it is recommended that analytical methods be calibrated against tracer or mass balance methods.

1. Introduction

Managing water resources, determining available irrigation supply and water quality, allocating water for cooling, recreation, and navigation, calibrating hydrological and climate models, and assessing ecosystem productivity are all activities that require good estimates of base flow (Caissie et al., 1996; Yu and Schwartz, 1999; Spongberg, 2000; Stewart et al., 2007). Base flow is the ground water contribution to total stream flow (Hewlett and Hibbert, 1967). Importantly, it sustains stream flow during low rainfall periods (Hall, 1968; Steele, 1968; Nathan and McMahon, 1990; Arnold et al., 1995; Yu and Schwartz, 1999; Halford and Mayer, 2000; Risser et al., 2005; Rutledge, 2007). Several authors have shown that base flow is geochemically identified as containing higher ionic concentrations, higher total dissolved solids, and higher specific conductance than interflow or surface flow (Kunkle, 1965; Visocky, 1970; Nakamura, 1971; Pilgrim et al., 1979; Cey et al., 1998; Matsubayashi et al., 1993; Stewart et al., 2007; Pellerin et al., 2008).

Many methods have been proposed for separating the base flow component from total stream flow. The most widely used methods of separating a stream hydrograph into two components, base flow and runoff, are analytical filtering or smoothing methods. These methods assume that the base flow hydrograph is a lower amplitude, lower frequency component of the total stream flow hydrograph. Filtering or smoothing methods are similar to signal processing (Nathan and McMahon, 1990; Arnold and Allen, 1999; Huyck et al., 2005). Their advantages are ease of automation, replication of results (Arnold et al., 1995; Eckhardt, 2005; Huyck et al., 2005; Lim et al., 2005), and that the entire discharge record can be used. However, most analytical methods are uncalibrated mathematical functions or algorithms that calculate base flow directly

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from stream discharge (Arnold et al., 1995; Eckhardt, 2005; Huyck et al., 2005) and they are typically applied without reference to any hydrological basin variable other than discharge or basin area (Nathan and McMahon, 1990; Arnold and Allen, 1999; Arnold et al., 2000; Furey and Gupta, 2001; Huyck et al., 2005; Eckhardt, 2008). This study examines how well analytical methods can duplicate the base flow indices obtained from a mass balance method, and if that agreement can be improved by calibrating the analytical methods with mass balance data.

1.1. Mass-balance methods

Stable isotope tracers are commonly used to trace the different water pathways during a storm (Sklash and Farvolden, 1979) and are considered to be the best geochemical method for hydrograph separation (Klaus and McDonnell, 2013). However, isotopic analyses can be very laborious and expensive, especially for long term study (Matsubayashi et al., 1993; Stewart et al, 2007). An alternative is environmental tracer methods, also called mass-balance methods, which assume that stream flow components have identifiable isotopic or geochemical concentrations. The isotopic or geochemical concentration of stream flow at a given time allows the contribution of each component to stream flow to be determined through a simple mass balance equation. Measurement of (n) isotopic or geochemical constituents of stream flow allows up to ($n + 1$) stream flow components to be identified (Stewart et al., 2007; Kish et al., 2010). However, most mass balance base flow separations use two flow components, base flow and runoff, which requires monitoring only one isotopic or geochemical component. The advantage of the mass balance method is that site-specific variables are measured and the chemical or isotopic constituents of stream flow are related to physical processes and flow paths within a basin (Visocky, 1970; Steele, 1968; Matsubayashi et al., 1993; Stewart et al., 2007). They are a useful tool for investigating hydrological processes (Meriano et al., 2011) because they offer the possibility of gaining a better understanding of the runoff generation process (Gonzales et al., 2009), whereas analytical base flow separation methods do not. In order to separate the stream hydrograph these methods assume that stream flow components have distinct chemical constituents and each flow component chemical constituent has an identifiable concentration (Cey et al., 1998; Wagnon et al., 1998; Stewart et al., 2007). The principal disadvantage of mass balance methods is that discharge and chemical constituent measurements must be taken concurrently, making it a difficult task for large basins and long-term studies (Stewart et al., 2007) as well as being expensive.

There has been one previous study that compares analytical and tracer methods (Gonzales et al., 2009). They conclude that the BFI_{max} parameter of the Eckhardt filter can be calibrated with tracer methods. Also, they compare different analytical methods using the direct runoff ratio, which is the ratio of direct runoff to total discharge. Other studies (Stewart et al., 2007; Zhang et al., 2013; Miller et al., 2015), either compare or calibrate one or two analytical hydrograph separation methods to a tracer or mass balance method.

1.2. Specific conductance as a tracer

Specific conductance is a natural environmental tracer that can be inexpensively measured concurrently with stream flow measurements (Kunkle, 1965; Matsubayashi et al., 1993; Arnold et al., 1995; Caissie et al., 1996; Cey et al., 1998; Heppell and Chapman, 2006; Stewart et al., 2007; Pellerin et al., 2008). Specific conductance of stream flow is highly correlated with total dissolved solids (TDS) (Steele, 1968; Thomas, 1986; Kappel et al., 2012), so specific conductance can be used as a proxy for ionic concentration. However, the exact numerical relationship between specific conductance and TDS is gage and basin specific (Steele, 1968; Thomas, 1986). Studies spanning five decades have used specific conductance for hydrograph separation (Kunkle, 1965; Visocky, 1970; Nakamura, 1971; McNamara et al., 1997; Pilgrim et al., 1979; Matsubayashi et al., 1993; Caissie et al., 1996; Cey et al., 1998; Hayashi et al., 2004; Stewart et al., 2007; Pellerin et al., 2008; Penna et al., 2015). In this study, a two end-member mass balance method that uses specific conductance, the conductivity mass-balance (CMB; Stewart et al., 2007), is used as a proxy for all mass balance methods to compare results of uncalibrated and calibrated analytical techniques to it. The CMB represents the mass balance approach; it is set as the standard for comparison to the results of common analytical methods as well as, being used to calibrate analytic base flow separation strategies. Both, CMB and analytical techniques, can separate stream flow into two components, base flow and runoff or quick flow therefore, pairing the two allow a direct comparison.

The objective of this research is to determine the utility of the CMB method for calibrating a variety of analytical methods. However, different geochemical tracers can yield different results, thereby leading to uncertainties in the mass balance methods and the calibration of the analytical methods. Mass balance methods can be used with any conservative natural tracer. If geochemical data other than specific conductance are available, it is recommended to have more natural tracers compared for consistency in data (Laudon and Slaymaker, 1997; Klaus and McDonnell, 2013; Hayashi et al., 2004; Penna et al., 2015). Even though, specific conductance behaves as a non-conservative, as do some ions such as Ca^{+} and SO_4^{2-} (Pilgrim et al., 1979; Matsubayashi et al., 1993; Laudon and Slaymaker, 1997; Mul et al., 2008; Pellerin et al., 2008; Klaus and McDonnell, 2013), some studies have found that specific conductance can be a good surrogate for isotopes (McNamara et al., 1997; Matsubayashi et al., 1993; Pellerin et al., 2008; Klaus and McDonnell, 2013) and differences in the results of specific conductance and isotope-based hydrograph separation are usually similar (McNamara et al., 1997; Pellerin et al., 2008). Also, the measurements are inexpensive compared to natural tracers or major ions; in addition, it is commonly monitored continuously in stream water. For those reasons, specific conductance has been used in this comparison.

2. Methods

This study uses data from 35 stream gages distributed across the United States of America. Basins were selected that represent a large range of basin areas and physiographic and climatic regions. All streams used for the comparison are perennial streams, with basin areas ranging from 27 km^2 to 68,117 km^2. Each gage has at least two years of continuous specific conductance data and at least 30 years of continuous discharge data with two of those discharge years paired with specific conductance data. We excluded gages influenced by upstream discharges affected by anthropogenic sources and impoundments to minimize uncertainties, and potential errors caused by highly soluble materials such as evaporates or deicing salts. In this study, all discharge and specific conductance data are daily mean values retrieved from the United States Geological Survey's (USGS) National Water Information System (NWIS) website, http://waterdata.usgs.gov/nwis. For each set of stream gage data the period of record used is the period for which both discharge and specific conductance data are available. This period varies between gages, but is at least two years. For each gage, the same period of record for analysis was used with each base flow separation method.