Journal of Hydrology 523 (2015) 636–649

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

A hydrograph separation method based on information from rainfall and runoff records

Yiwen Mei, Emmanouil N. Anagnostou *

Civil and Environmental Engineering, University of Connecticut, Storrs, CT, USA

A R T I C L E I N F O

Article history:
Received 4 October 2014
Received in revised form 24 January 2015
Accepted 31 January 2015
Available online 9 February 2015
This manuscript was handled by Konstantine P. Georgakakos, Editor-in-Chief, with the assistance of Marco Borga, Associate Editor

Keywords:
Baseflow separation
Flood event
Hydrograph
Rainfall record
Digital filte

S U M M A R Y

Hydrograph separation is considered as the first step to catchment-scale water balance analysis. A wide variety of hydrograph separation methods exists ranging from empirical to analytical and physical. This study discusses a physically-based approach that combines baseflow separation and event identification with minimal data requirement. The input datasets are basin-average rainfall and discharge time series. Outputs are baseflow time series, the timing of the runoff events, differentiated as single- or multi-peak, and the associated rainfall event time series. To assess the method's feasibility, hydrograph properties are evaluated for both long-term (annual and monthly) and event-scale time series. Results show that the long-term derived baseflow indices are positive (negative) correlated with basin area (runoff coefficient). The event scale analysis shows that the timing-related parameters (i.e. durations of rainfall and flow events and time lag between rainfall to flow events) increase with basin area in terms of magnitude and variability. Similar dependence on basin scale is shown for the water balance-related parameters determined from this analysis, namely event rainfall and baseflow volumes and baseflow index. Water balance parameters are shown to be characterized with less degree of variability for single-peak events relative to multi-peak events.

1. Introduction

The separation of baseflow from direct flow has been a recurring theme in hydrology for more than four decades (Koskelo et al., 2012; Chen et al., 2008; Gustard et al., 1992; Chow et al., 1988; Lyne and Hollick, 1979; Hall, 1968). The essence of hydrograph separation is traditionally considered to render a deconstructive rationale of streamflow as a two-component or multi-component process. The most commonly used scheme is the two-component scenario that considers streamflow consisting of direct flow (i.e. quick surface or subsurface flow) and baseflow (i.e. flow that comes from groundwater storage or other delayed source) (Tallaksen, 1995; Hall, 1968). Direct flow is in general formed by surface precipitation, overland flow (i.e. infiltration excess or saturation excess), interflow (i.e. shallow subsurface flow), and rapid groundwater flow, while baseflow is the relatively stable flow between storms and includes contributions from groundwater and return flow (Hornberger, 1998; Tallaksen, 1995).

There exists a wide variety of methods for baseflow separation, which are categorized into different types based on selected criteria, such as tracer-based method, graphical method, filtering method, digital filter and recession analysis (see Table 1 for a summary). Among the various methods, the tracer-based method yields the most realistic results (Buttle, 1994; Sklash and Farvolden, 1979); however, it is laborious and expensive; thus its application is restricted to small number of events, which prohibits statistical analysis. Graphical is the most intuitive method (Chow et al., 1988), but it is based on empirical assumptions and user's speculations. Another technique is the filtering method which is typically designated for long-term, daily time scale, data records. Example filtering methods are the smooth minima baseflow separation method of the United Kingdom Institute of Hydrology (UKIH) and its subsequence versions and the Hydrograph Separation Program by the United States Geologic Survey (HYSEP) (Aksoy et al., 2009, 2008; Sloto and Crouse, 1996; Gustard et al., 1992).

Digital filter is a commonly used baseflow separation method nowadays, and it can be sorted as one-, two- or multi-parameter filter depending on the number of parameters used (Lyne and Hollick, 1979; Jakeman and Hornberger, 1993; Chapman, 1999; Eckhardt, 2005). Common parameters for these filters are the recession coefficient and the maximum baseflow index (the long-term ratio of baseflow to total streamflow) (Eckhardt, 2005); the one-parameter filter has a predefined maximum baseflow index.

* Corresponding author. Tel.: +1 (860) 486 6806.
E-mail address: manos@engr.uconn.edu (E.N. Anagnostou).

http://dx.doi.org/10.1016/j.jhydrol.2015.01.083
0022-1694/

Table 1
Properties of the baseflow separation methods.

Method	Examples	Data resolution	Record length	Physical basis	In-situ experiment
Tracer-based	Buttle (1994) Sklash and Farvolden (1979)	Sub-daily or higher	Event	Highest	Required
Graphical	Straight line, fixed-base, variable slope method (Chow et al., 1988)	Daily or higher	Event	Lowest	No
Filtering	HYSEP; (Sloto and Crouse, 1996) UKIH (Gustard et al., 1992)	Daily	Long term	Low	No
Digital filter	Chapman-Maxwell Filter (Chapman and Maxwell, 1996) Recursive Digital Filter (Eckhardt, 2005) Jakeman and Hornberger Filter (Jakeman and Hornberger, 1993)	Hourly or higher	Long term or event	Medium to high	Optional[a]
Recession analysis	Constant-*k* method (Blume et al., 2007) Wittenberg and Aksoy Method (Wittenberg and Aksoy, 2010)	Hourly or higher	Event	High	No

[a] Degree of physical basis increase by running the in-situ experiment for baseflow index.

The recession coefficient (rate of change of discharge depletion during periods of little or no precipitation) can be determined reasonably well from the recession limb of the hydrograph (Nathan and McMahon, 1990), while to get a value for the maximum baseflow index would require running in-situ measurements, or acquiring it from the literature. A three-parameter filter is rarely used since it was concluded to produce baseflow hydrographs with sharp peaks compared to observations (Chapman, 1999). The most physically based method without running field experiments could be the analytical solution of recession equation. This group of methods generally starts from assuming either a linear (Blume et al., 2007; Su, 1995) or nonlinear (Wittenberg and Aksoy, 2010) relationship between storage and flow rate. To ensure a reasonable recession coefficient for a digital filter, or the analytical solution of recession, fine temporal resolution flow data is required.

Use of baseflow separation methods to study properties of hydrologic events requires determining the start and end times of these events in the streamflow record. Typically this is carried out manually by visual inspection of the time series data. However, visually inspecting the timing of events is cumbersome when it comes to long-term data records. Few studies on this topic have attempted to develop automatic event identification methods that can apply to large data records (Dhakal et al., 2012; Koskelo et al., 2012; Norbiato et al., 2009; Merz and Blöschl, 2009; Khanal, 2004).

Merz et al. (2006) introduced an automatic event identification technique by using a calibrated lump hydrologic model. The study used the technique to identify 50,000 events from 337 Austrian catchments (areas ranged from 80 to 10,000 km^2) over a 20 year period; Merz and Blöschl (2009) expanded the number of Austrian catchments to 459 (5–10,000 km^2 basin areas) and provided a more comprehensive analysis on runoff coefficient. Norbiato et al. (2009) applied this technique on 14 mountainous catchments in the eastern Italian Alps (basin areas ranged from 7 to 608 km^2) to extract 535 events over a 15-year period. In short, the Merz et al. (2006) is a reliable technique, but requires calibrating a hydrologic model, which limit it applicability in data poor regions (e.g. mountainous areas).

Khanal (2004), on the other hand, proposed a semi-automatic approach based on the unit hydrograph method, which he applied on 90 mid-slope watersheds in Texas to extract 1737 single peak events over a 27-year period. The method required manual identification and extraction of the multi-peak events as well as events with un-wanted shapes. The event database was then used in several subsequent studies. Cleveland et al. (2006) compared the differences in peak discharge and time-to-peak between the observed events and their simulated counterparts from three different unit hydrograph models; Fang et al. (2007) studied the scale dependency of the time of concentration for the selected events and found a positive relationship between time of concentration and the drainage area; Dhakal et al. (2012) investigated the responses of event-based runoff coefficients to precipitation and percentages of impervious surface for more than 1600 events from that database.

A simpler and more empirical method called SARR (Sliding Average with Rain Record) was recently developed by Koskelo et al. (2012) for daily flow data. The essence of SARR is to associate each rainfall event (i.e. a series of consecutive days with rain followed by at least one day with no rain) with a quickflow event (i.e. time period between the beginning of one quickflow cycle to the beginning of the next quickflow cycle) to form a rainfall-runoff event. In their study, Koskelo et al. (2012) found that the tracer-based method calculated about 1–4 times more baseflow than the SARR method for the same events, ascribing this to the dampening effect of using the daily temporal resolution flow data. Requirements of SARR are obviously less demanding, but the method itself is empirically based, and restricted to small basin scales (<50 km^2) and coarse temporal resolutions (daily).

In this study, we investigate an automatic hydrograph separation method that is based on long time series and hourly time scale data on basin rainfall and runoff. The new aspects of this technique are its physical basis, which requires less data to constrain the even separation algorithm. Specifically, a set of parameters (recession coefficient, maximum baseflow index, time lag between rainfall and runoff mass centers) are derived by mining the basin areal rainfall and runoff time series and used to drive the event separation algorithm. An important point to note is that the algorithm is designated for basins with clear recession period (this limitation is detailed in the conclusion part). In Section 2 below we describe the study area, rainfall and runoff data used to demonstrate the efficiency of the proposed technique. The technique's procedures used for baseflow separation and event identification are described in Sections 3.1 and 3.2, respectively. The results are discussed in Section 4, while conclusions are summarized in Section 5.

2. Study area and data

2.1. Study area

The study area is the Tar River basin in North Carolina, USA (Fig. 1 top left panel). Information about the basin can be found in Mei et al. (2013). The study area was divided into eight nested sub-basins, namely T1, T2, T3, T4, S, F1, F2 and TSF shown in Fig. 1, based on the available locations of stream gauges (each