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A new precipitation-based method of baseflow separation and event identification for small watersheds (<50 km^2)

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SUMMARY

Baseflow separation methods are often impractical, require expensive materials and time-consuming methods, and/or are not designed for individual events in small watersheds. To provide a simple baseflow separation method for small watersheds, we describe a new precipitation-based technique known as the Sliding Average with Rain Record (SARR). The SARR uses rainfall data to justify each separation of the hydrograph. SARR has several advantages such as: it shows better consistency with the precipitation and discharge records, it is easier and more practical to implement, and it includes a method of event identification based on precipitation and quickflow response. SARR was derived from the United Kingdom Institute of Hydrology (UKIH) method with several key modifications to adapt it for small watersheds (<50 km^2). We tested SARR on watersheds in the Choptank Basin on the Delmarva Peninsula (US Mid-Atlantic region) and compared the results with the UKIH method at the annual scale and the hydrochemical method at the individual event scale. Annually, SARR calculated a baseflow index that was ~10% higher than the UKIH method due to the finer time step of SARR (1 d) compared to UKIH (5 d). At the watershed scale, hydric soils were an important driver of the annual baseflow index likely due to increased groundwater retention in hydric areas. At the event scale, SARR calculated less baseflow than the hydrochemical method, again because of the differences in time step (hourly for hydrochemical) and different definitions of baseflow. Both SARR and hydrochemical baseflow increased with event size, suggesting that baseflow contributions are more important during larger storms. To make SARR easy to implement, we have written a MatLab program to automate the calculations which requires only daily rainfall and daily flow data as inputs.

1. Introduction

Two-component flow separation is a tool that distinguishes between theoretical "baseflow" and "quickflow" components of a discharge hydrograph. Baseflow is the relatively stable flow between storms and includes contributions from groundwater and return flow. Groundwater is the dominant source of baseflow, although groundwater that has emerged onto the surface due to encountering soils with a low hydraulic conductivity may contribute to baseflow as return flow after moving downhill, typically close to the stream as a seepage face or spring (Hornberger et al., 1998).

Quickflow is empirically defined as the non-baseflow portion of the total flow hydrograph (i.e., total flow minus baseflow, Hornberger et al., 1998). Quickflow includes contributions from (1) direct precipitation onto the stream channel and nearby saturated areas, (2) overland flow, composed of both infiltration excess (also called Hortonian overland flow) and saturation excess, (3) shallow subsurface stormflow (also called interflow), and (4) groundwater flow. Synonyms for quickflow such as 'runoff' and 'stormwater' are misleading because they imply an exclusive association with overland flow or precipitation, which is not always the case, especially in forested watersheds where quickflow often has a large groundwater component (Hornberger et al., 1998). In addition, the term 'runoff' has conflicting definitions. In other fields, "runoff" is used to mean any water that drains off a watershed

Abbreviations: SARR, Sliding Average with Rain Record; WU, Weather Underground.

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(synonymous with "river discharge"), and the US Geological Survey (USGS) uses the term "runoff" for total streamflow per unit watershed area (e.g., Wieczorek, 2008).

Baseflow separation is inherently a simplification of complex hydrologic processes. The process has been regarded as more of an art than a science (Bedient and Huber, 1992) because streams do not switch back and forth between discrete baseflow and quickflow conditions. In reality, streams exist along a continuum of flow rates ranging from very low flows during drought conditions to very high flows during major storms. However, baseflow separation is a necessary part of many studies ranging from hydrologic modeling to water resources management, in part due to the large changes in stream chemistry (e.g., N, P, particulates) which occur during storms (e.g., Fisher et al., 2006; Koskelo, 2008). The goal of an ideal baseflow separation method is not to estimate baseflow or quickflow precisely (since neither can be estimated), but rather to provide a reasonable, physical basis for the separation that is relatively easy to compute and which enables the computation of total watershed export of the material of interest (e.g., particulates, N, P, metals, etc.) using continuous discharge measurements and discrete sampling of baseflow and quickflow chemistry.

Many different methods exist for separating baseflow. Although no technique is universally accepted, each has advantages and disadvantages. A detailed discussion of all the available methods is outside the scope of this paper. However, we briefly mention some common methods, including (1) the fixed-base method, representative of manual graphical approaches (Linsley et al., 1975), (2) a streamflow partitioning computer program (PART), representative of automated separation methods (Rutledge, 1993), (3) a hydrochemical tracer-based technique (Hornberger et al., 1998; Katsuyama et al., 2001; Hangen et al., 2001), (4) the smoothed minima approach and its versions (IH, 1980; Piggott et al., 2005; Aksoy et al., 2008, 2009), (5) the rating curve method (Kliner and Knezek, 1974), (6) the recursive filtering method (also known as the digital filtering method) (Lyne and Hollick, 1979; Eckhardt, 2005; Gonzales et al., 2009), and (7) the nonlinear baseflow separation approach (Wittenberg, 1999, 2003; Wittenberg and Sivapalan, 1999; Wittenberg and Aksoy, 2010; Aksoy and Wittenberg, 2011).

Existing baseflow separation methods generally suffer from one or more major drawbacks. These include: labor intensive procedures, the requirement for expensive observation wells or chemical tracer sampling, limited application for event-scale analysis in small watersheds, dependency on modeling a groundwater recession curve (which is not always feasible), poor standardization, and subjectivity. To fill this gap in methodology, we developed a new precipitation-based method of flow separation and event identification known as SARR (**S**liding **A**verage with **R**ain **R**ecord). The strength of SARR is practicality; the process demands few of the labor- or materials-intensive procedures mentioned above. Rather, the technique requires only daily flow and precipitation data; therefore, the method has a strong physical basis. SARR is designed for distinguishing individual events in small watersheds (<50 km^2).

The SARR method was developed to adapt a smoothed minima technique known as the United Kingdom Institute of Hydrology or UKIH method (IH, 1980; Gustard et al., 1992) to smaller watersheds and individual events for use in a separate study on watershed N and P export in the Mid-Atlantic region (Koskelo, 2008). The UKIH method has been modified previously and called RUKIH, AdUKIH, and FUKIH by Piggott et al. (2005), Aksoy et al. (2008), and Aksoy et al. (2009), respectively. Their modifications vary depending on the purposes of the study, but in general they focus on mathematical alterations to the algorithms, for example changing the parameter 0.9 in the UKIH method. In contrast, SARR includes both mathematical changes *and* empirical extensions to the UKIH method such as the addition of precipitation and the identification of events based on precipitation and quickflow response. Therefore, SARR is considered more comprehensive than previous modifications of the UKIH approach.

2. Materials and methods

2.1. Development of the SARR method

The SARR method was derived from the UKIH method, which is intended to separate baseflow in a long time series (e.g., daily flow values for 1 year or longer) in relatively large watersheds with hydrologic response times of 5 days or more. The goal is to obtain a baseflow index (BFI), a simple, non-dimensional ratio (0–1) of the proportion of baseflow out of the total flow, typically computed on an annual time scale. The UKIH method is summarized below (Gustard et al., 1992):

1. Divide mean daily flow into n non-overlapping blocks of 5 days each (see Fig. 1). Calculate the minimum of each block i (m_i) as $m_1, m_2, m_3, \ldots, m_n$, and record the day of the mimima d_i as d_1, $d_2, \ldots, d_n$.
2. For each m_i minimum, identify baseflow days as follows: If $(0.9 * m_i) < m_{i-1}$ AND $< m_{i+1}$, then m_i = baseflow.
3. Use linear interpolation to compute daily baseflow Q_{Bi} (m^3 d^{-1}) between each successive baseflow day d_i.
4. If, for any given day, the computed baseflow Q_{Bi} is > total flow Q_i (m^3 d^{-1}) set the computed baseflow Q_{Bi} = total flow Q_i.
5. Calculate BFI as $\Sigma Q_{Bi}/\Sigma Q_i$ for the period of interest (usually at least a year).

In developing the SARR method, five key modifications were made to the UKIH procedure. These changes were made to adapt the UKIH method to smaller watersheds and individual events for use in a separate study of elemental fluxes from watersheds (Koskelo, 2008). First, the non-overlapping blocks (step 1 above) were shortened from 5 to 2 day sliding blocks (Fig. 1) to match more closely the hydrologic response times of small watersheds (<50 km^2). This change reflects the reality that small streams return quickly to baseflow conditions following an event. While this modification may seem arbitrary, 2-day blocks more closely match the end of quickflow associated with a single rain storm in small watersheds (see Fig. 2). Discharge in watersheds of <50 km^2 following 2–3 cm of rain is typically elevated for 1–3 days, and the baseflow of the stream may increase following an event due to recharge of the local groundwater, especially in the fall and winter when evapotranspiration [ET] is relatively low. Without this modification, the UKIH method using 5-day blocks over-predicts quickflow in watersheds <50 km^2, sometimes projecting 10–15 days of continuous quickflow for small to moderate rain events (2–3 cm) or as much as 1–2 months for larger rain events (>3–4 cm).

The second modification to the UKIH method was the use of a sliding 2-day window. The UKIH method uses sequential 5-day windows in which the minimum discharge in each 5 day block is selected for linear interpolation between successive minima. In contrast, the SARR approach uses a sliding window with three, 2-day blocks, and the average baseflow value is assigned to the first of the 2 days in the middle block if it is classified as baseflow (see conceptual diagram in Fig. 1). The window then slides by 1 day, and the process is repeated for the entire time series.

The third change to the UKIH method was to compute each baseflow day as the average discharge in each 2-day block rather than the minimum. That is, instead of

$$\text{If } 0.9 * m_i < m_{i-1} \text{ AND } < m_{i+1}, \quad \text{then } m_i = \text{baseflow} \tag{1}$$

we used

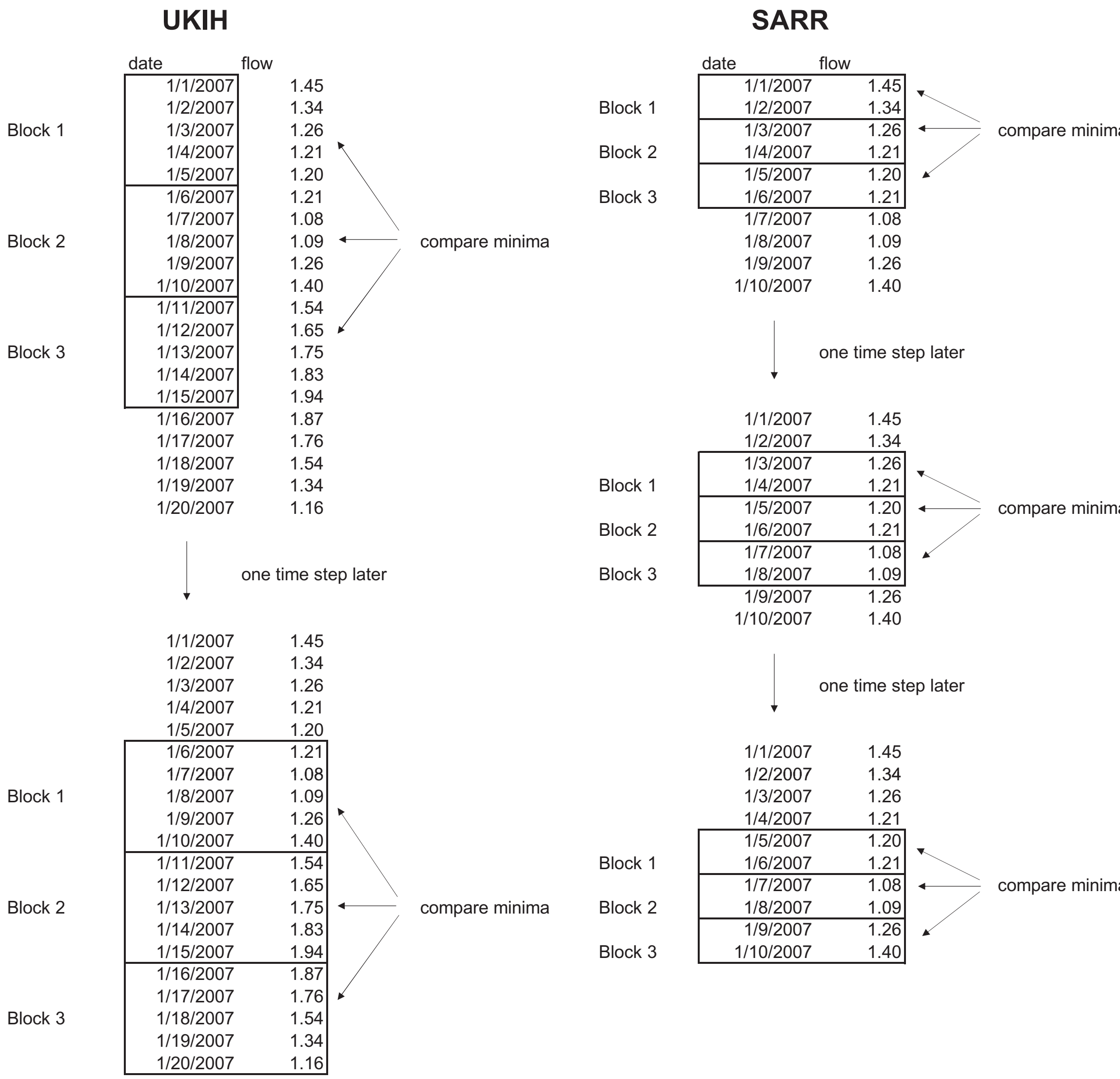

Fig. 1. Conceptual model of the selection of minimum discharge values in the non-overlapping 5 day blocks of the UKIH method (left) and in the sliding 2 day blocks of the SARR method (right). See text for details.

$$\text{If } 0.9 * m_i < m_{i-1} \text{ AND } < m_{i+1}, \text{then the } average \text{ of block } i = \text{baseflow} \quad (2)$$

The average of block *i* is assigned as baseflow to the first day of block *i*; the second day in block *i* is assigned a baseflow value in the next sliding window. Eq. (2) results in a better smoothing of the baseflow curve by averaging each 2-day block classified as baseflow. In contrast, the UKIH method uses only the minima of each 5-day block and discards the other points, which amounts to a systematic negative bias in the baseflow curve because choosing the minima as baseflow discards 80% of the measured data (i.e., 4 days out of every five). Averaging across each 2-day block in the SARR method also helps to smooth out potential aberrations in the discharge record unrelated to event flows (e.g., episodic irrigation withdrawals, diel cycles) which ultimately provides a better basis for computing baseflow conditions.

The fourth modification to the UKIH method was a slight change in the order of operations. The UKIH method performs the linear interpolation first (step 3 above) and then constrains baseflow so that it cannot exceed measured flow (step 4 above); for the SARR method, we chose to constrain baseflow first to be $\leqslant$observed flow and then interpolate. Interpolating afterward maintains a linear interpolation between empirically determined baseflow days. In contrast, the UKIH approach initially does linear interpolation, but then modifies points which exceed total flow, making the line occasionally non-linear. In most cases, this change did not make a significant difference; however, in a few events at some stations, there was a significant difference in the baseflow discharge computations.

The last modification was the integration of precipitation data during the separation process. This adds a new physical dimension to baseflow separation and, to our knowledge, is the only use of rainfall data for flow separation analyses. There are two major advantages associated with using precipitation. First, it verifies whether or not increases in discharge are attributable to actual rainfall. Irrigation water withdrawals may cause sharp changes in stage, and natural diel to weekly cycles of radiative heating and cooling often cause sinusoidal variations in stage during the summer. Either of these processes may be mistakenly identified as storms unless the rainfall record is consulted. To remove this potential misidentification of discharge events, we have added a quality control procedure which verifies that for each day on which quickflow occurs,

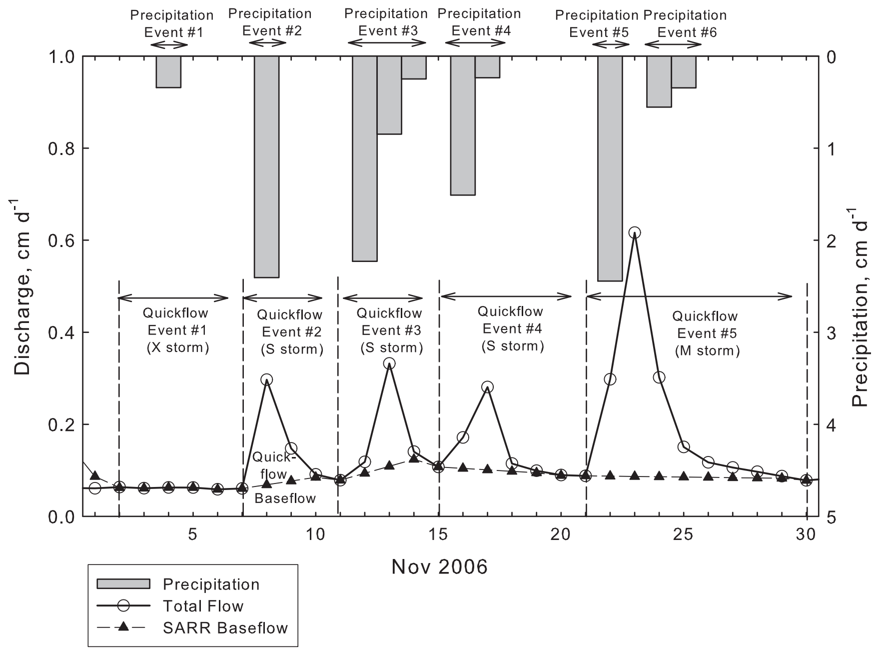

Fig. 2. The SARR method of event identification applied at the Blockston watershed. Quickflow events were defined from the last day of baseflow prior to an event to the last day of baseflow following the event (horizontal arrows in middle of graph). Precipitation events were defined as a series of one or more consecutive days of rainfall followed by at least 1 day with no rainfall (horizontal arrows along top of graph). Each quickflow event was further classified into S storms (quickflow generated by single precipitation event), M storms (quickflow generated by multiple precipitation events), and X storms (no quickflow generated by precipitation event).

some precipitation (>0) must occur on the current or previous day, unless that quickflow is part of a consecutive series of days with quickflow. If this rule is violated, baseflow is set to the measured total flow per the UKIH method (see step 4 above). This ensures that each separation of the hydrograph has accompanying rainfall to justify the separation, but it is clearly dependent on having accurate rainfall data, ideally at multiple locations within or near the watershed. The second advantage of using precipitation is that it allows one to identify individual events in terms of both rainfall inputs and quickflow outputs.

2.2. Method of event identification

Unlike existing baseflow separation methods, SARR identifies events defined by daily records of precipitation and quickflow. Although precipitation generally induces a quickflow response, in many cases it is unclear which days of precipitation contribute to a defined quickflow response. To standardize the process, we first defined events in terms of quickflow. For each quickflow event, we identified one or more precipitation events which were associated in time with the observed quickflow. Because of travel time within a watershed, a single quickflow event could be caused by several rain events separated by a day without rain. Such quickflow events often had complex shapes or multiple peaks. For simplicity, quickflow events were defined as the time period between the beginning of one quickflow cycle to the beginning of the next quickflow cycle (Fig. 2); i.e., from the last day of baseflow prior to a series of consecutive days with quickflow to the last day of baseflow prior to the next series of consecutive days of quickflow (Fig. 2). In this way, the effects of individual quickflow events on subsequent baseflow in the stream can be quantified. In a similar fashion, precipitation events were defined as a series of consecutive days with rain followed by at least 1 day with no rain (Fig. 2). In our small Choptank watersheds, precipitation events typically occurred just prior to or at the beginning of a quickflow event (Fig. 2).

After event identification, each quickflow event was classified into one of three categories (S, M, or X) based on how the observed quickflow events were related to their precipitation events:

S =	Single event =	Quickflow generated by a single precipitation event of one or more days in sucession
M =	Multiple event =	Quickflow generated by multiple precipitation events, generally close in time
X =	No event =	No quickflow generated by the precipitation event (rainfall rate < soil infiltration rate)

Examples of these classifications are shown in Fig. 2. Note that the only other possible scenario, quickflow generated but no precipitation observed, was not possible because a quality control procedure was added to the computations to remove any such cases. This eliminated spurious discharge observations that just slightly exceeded the 10% threshold for quickflow classification. Furthermore, events at the beginning and end of the discharge record (or which occurred around any gaps in the discharge data) were considered partial events if there were insufficient discharge data to delineate the entire event.

All of the modifications and additions to the UKIH method, as well as the rules for identifying events, were written into a MatLab program for automated computation. The program calculates SARR baseflow values, summarizes the precipitation and discharge data in a series of graphs, and lists all of the events identified for the period of interest.

2.3. Application of the SARR method

The SARR method was applied to flow data collected at six watersheds (five agricultural and one forested) within the

Table 1
Characteristics of the seven study watersheds including five agriculturally dominated watersheds and one forest dominated watershed (Willow Grove). The larger USGS gauge at Greensboro MD is used as a reference watershed for the six smaller ones. Soils A–D represent USDA hydrologic soil groups. 'A' soils have a relatively high infiltration rate and a low runoff potential, while 'D' soils have a relatively low infiltration rate and a high runoff potential. Hydric soils are water-saturated during most of the year and are typically associated with low-lying wetland areas. Size, land use, and soil data are from Fisher et al. (1998, 2006).

Watershed name	Size (km^2)	% Agriculture	% Forest	USDA hydrologic soil groups				% Hydric soils
				Soil A	Soil B	Soil C	Soil D	
Kittys	14	65	32	52	22	23	2	26
Cordova	27	76	18	60	22	17	1	15
Blockston	17	71	28	2	40	20	38	34
North Forge	24	67	31	33	17	30	21	51
Beaverdam	22	67	32	1	28	6	66	64
Willow Grove	15	34	58	0	1	2	97	97
USGS gauge at Greensboro	293	46	49	15	12	13	59	63

Choptank River Basin on the Delmarva Peninsula in the Mid-Atlantic Region of North America. For reference we also include data from the larger USGS gauging station at Greensboro MD (01491000). Watershed land use and soil properties are provided in Table 1, and their locations are shown in Fig. 3. The Choptank Basin lies entirely within the Mid-Atlantic coastal plain physiographic region (Omernick, 1987) and is characterized by intense agriculture (corn, wheat, soy, and chickens) and generally flat topography (<30 m asl). The basin encompasses several hydrogeomorphic settings, ranging from the well drained uplands near the estuary, with well drained, sandy soils and deeply incised stream channels, to the poorly drained headwater uplands, with shallow stream channels (Hamilton et al., 1993). From southwest to northeast, the study watersheds roughly follow an axis of increasingly poor drainage. The climate on Delmarva is a humid temperate one with an annual average precipitation of 112 cm year^{-1} (Lee et al., 2000). Although long-term records of seasonal precipitation are fairly consistent at 7–11 cm month^{-1}, large seasonal fluctuations in ET occur (Fisher et al., 2010). In summer, ET exceeds precipitation, often leading to drought conditions.

The analysis of the flow data was performed over two time scales: annual and event. At the annual scale, flow data for water year (WY) 2007 were separated using the Matlab program developed for the SARR method. To compare with an established base-

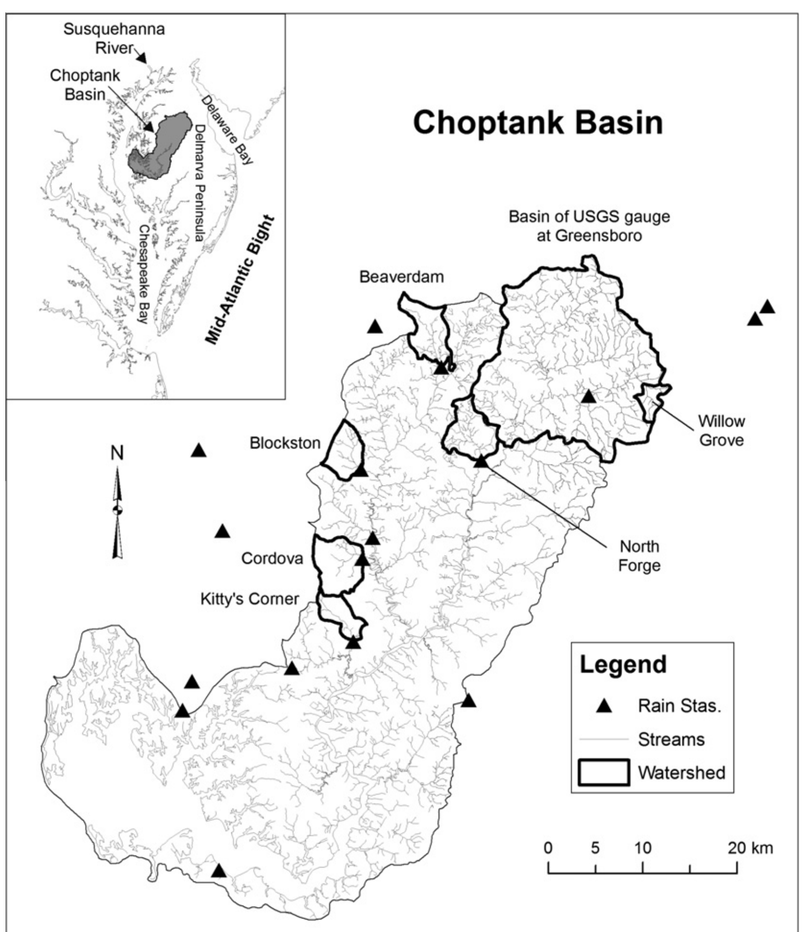

Fig. 3. Location of the Choptank River Basin (inset, upper left) on the Delmarva Peninsula, mid-atlantic region, USA. The six study watersheds and the USGS gauging station at Greensboro MD are drawn as polygons. Also shown are the 17 regional precipitation stations (triangles).

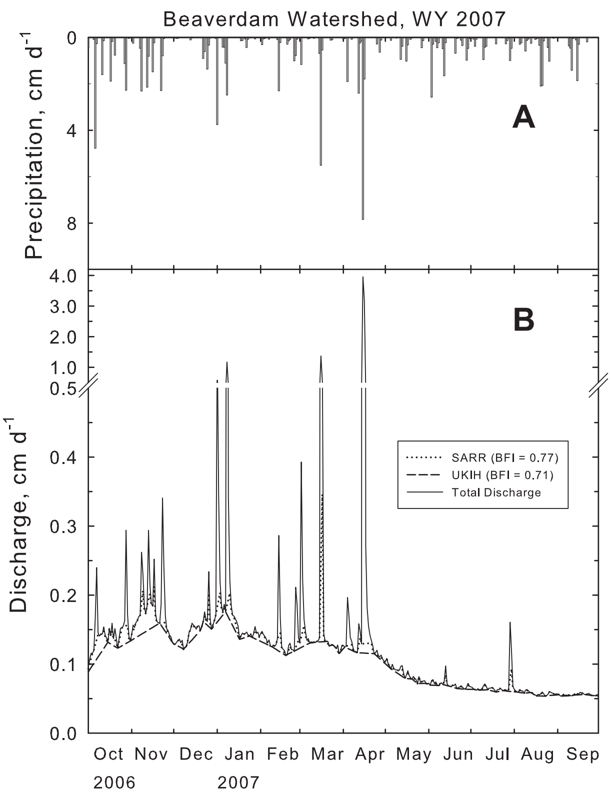

Fig. 4. Annual-scale flow separation at the Beaverdam watershed during WY 2007. Upper panel (A): precipitation; lower panel (B): total discharge and the results of the two baseflow separation methods (SARR and UKIH).

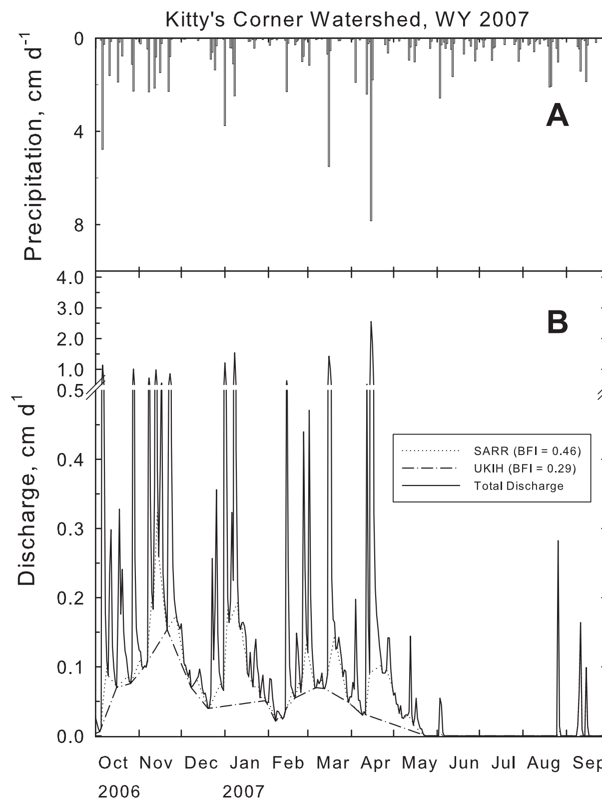

Fig. 5. Annual-scale flow separation at the Kitty's Corner watershed during WY 2007. Upper panel (A): precipitation; lower panel (B): total discharge and the results of the two baseflow separation methods (SARR and UKIH).

flow separation technique, we compared SARR results with the unmodified UKIH method. Results were tested for significant correlations with watershed characteristics including land use, United States Department of Agriculture (USDA) hydrologic soil groups (A–D), % hydric soils, and watershed size. Land use in the watersheds was based on 1990 aerial photos (Norton and Fisher, 2000). Hydrologic soil groups A–D were determined from the USDA's Soil Survey Geographic Database (SSURGO). The hydrologic soil groups are classified as follows: 'A' soils have coarse texture, high infiltration rates, and low runoff potential; at the other extreme, 'D' soils have fine texture, low infiltration rates, and high runoff potential (Soil Survey, 1993). Hydric soils are wetland soils that typically occur in low-lying areas with poor drainage such as stream valleys, and data on hydric soils are included in the SSURGO geodatabase.

We also applied the SARR method to assess individual events. We compared the SARR results to those of the hydrochemical method using specific electrical conductivity (SEC) as a tracer, but we could not apply UKIH at the event scale since it is intended for longer time scales. SEC data were available from Koskelo (2008) as hourly aliquots during 32 sampled events at four watersheds (Kitty's Corner, Blockston, North Forge, and Beaverdam; Table 1). To explore seasonal and storm size effects, the results were tested for significant correlations with mean event water temperature and event discharge (Koskelo, 2008). Water temperature data were available from data loggers (Solinst model 3001 Levelogger F15/M3) installed in the streams, and event discharge was computed from hydrographs and rating curves (Koskelo, 2008).

Precipitation data were available from 11 regional stations and six manual gauges (see Fig. 3). These included National Weather Service observing sites (www.nws.noaa.gov), the Wye Research and Education Center (station MD13 in the National Atmospheric Deposition Program – http://nadp.sws.uiuc.edu), Weather Underground (WU) personal weather stations (http://www.wunderground.com),

Table 2
Summary of WY 2007 hydrologic results for the study watersheds showing a comparison of the SARR and UKIH baseflow separation methods. The water yield at the nearby USGS gauging station (01491000) near Greensboro MD (see Fig. 3) is included for comparison. Rainfall for WY2007 was 97 cm year^{-1} for all sites, somewhat below the long term average of 112 cm year^{-1} (Lee et al., 2000). Hydrologic results at North Forge are based on 328 daily observations (not 365) due to logger failure.

Watershed	Water yield (cm year^{-1})	SARR method			UKIH method			Events
		Baseflow, (cm year^{-1})	Quickflow, (cm year^{-1})	BFI	Baseflow, (cm year^{-1})	Quickflow, (cm year^{-1})	BFI	
Kittys	44	20	24	0.46	13	31	0.29	56
Cordova	44	34	10	0.77	30	14	0.69	71
Blockston	43	23	19	0.55	20	22	0.47	72
North Forge	43	27	16	0.62	21	22	0.50	47
Beaverdam	53	41	12	0.77	38	15	0.71	83
Willow Grove	49	39	10	0.80	33	17	0.67	60
USGS Gauge@Greensboro	46	–	–	–	–	–	–	–

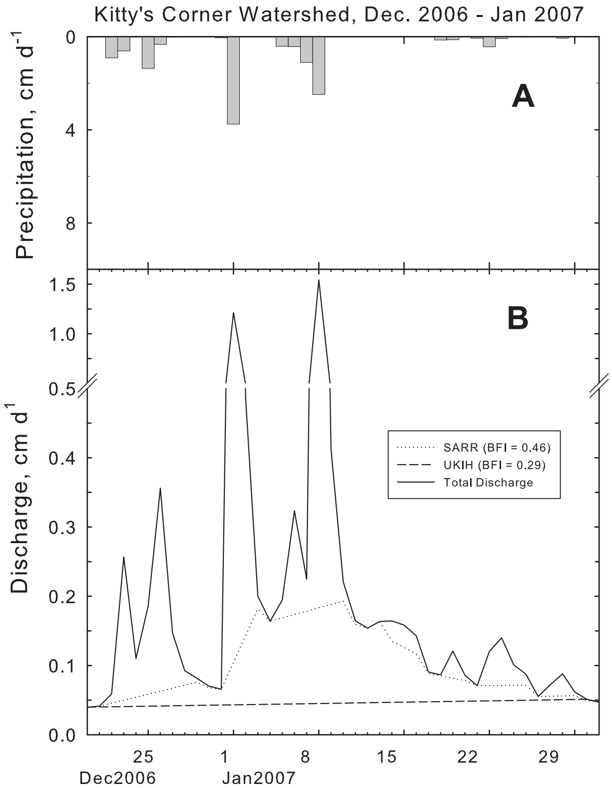

Fig. 6. Flow separation at the Kitty's Corner watershed during December 2006–January 2007 illustrating the large differences in the SARR and UKIH baseflow separation methods. Upper panel (A): precipitation; lower panel (B): total discharge and the results of the two baseflow separation methods (SARR and UKIH).

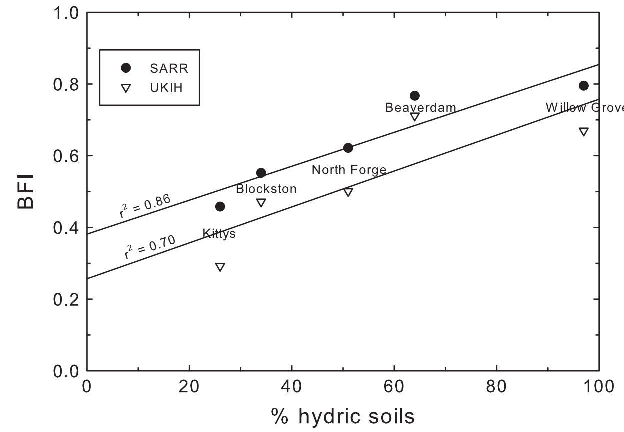

Fig. 7. Relationship of the annual baseflow index (BFI) at five agricultural watersheds with% hydric soils computed using the SARR and UKIH methods. Hydric soils retain water longer than soils with better drainage, increasing the BFI. Cordova watershed was excluded from this analysis due to the effects of a nearby beaver dam downstream.

Table 3
Number and types of events identified at each watershed during WY 2007, as developed for the SARR method of baseflow separation. Partial events (see text) were excluded, and fewer events were identified at the North Forge watershed because of missing data (only 328 daily observations). Abbreviations: S = quickflow generated by a single precipitation event, M = quickflow generated by multiple precipitation events, and X = no quickflow generated by the precipitation event (see text for details).

Watershed	S	M	X	Total
Kitty's Corner	27	13	16	56
Cordova	54	13	4	71
Blockston	54	15	3	72
North Forge	26	21	0	47
Beaverdam	64	12	7	83
Willow Grove	27	12	21	60
Sum:	252	86	51	389

and the University of Maryland Center for Environmental Sciences – Horn Point Laboratory (http://www.hpl.umces.edu). Because the WU data often showed a consistent long-term positive or negative bias compared to national collection sites, we adjusted WU data to be consistent with the national collection sites at the annual time scale (Koskelo, 2008). Despite the occasional bias, the WU data were useful to quantify the spatial variability in rainfall between watersheds, particularly in summer.

For graphical, statistical, and GIS analyses we used SigmaPlot v11 and ArcGIS v9.2. The threshold for statistical significance was set at $p < 0.05$.

3. Results

Precipitation during WY 2007 (October 2006–September 2007) was below average for this region (97 cm year^{-1}) compared to the long term mean of 112 cm year^{-1} (Lee et al., 2000). The lower than average rainfall was primarily due to the dry summer months when virtually all storms were <2 cm d^{-1} (Fig. 4A) and similar to rates of evapotranspiration (Fisher et al., 2010). During the rest of the year, rainfall was characterized by frequent small to moderate storms (<5 cm d^{-1}) and occasional large (>5 cm d^{-1}) storms, including a major storm from a low pressure system in April 2007 (8 cm d^{-1}, Fig. 4A). Because the larger storms primarily occurred in cooler months when soils were more saturated, annual water yields at the USGS gauging station at Greensboro MD (Fig. 3) were slightly above average at 46 cm year^{-1} (compared to 39 cm year^{-1} for a normal year, Fisher et al., 1998), despite the dry summer.

Examples of annual discharge hydrographs for WY 2007 are shown in Figs. 4 and 5 for two watersheds with contrasting soil properties in different parts of the Choptank Basin. Beaverdam watershed lies at the N end of the Choptank Basin in the poorly drained uplands, and Kitty's Corner watershed is lower in the Choptank Basin in the well-drained uplands close to tidal waters (see Fig. 3). The flow data from these two watersheds generally showed strong seasonal differences, with higher flows from the fall through the spring and much less flow in the summer due to higher evapotranspiration and smaller storms in this year. The Beaverdam watershed, for example, had flows ranging over ~0.1–1.0 cm d^{-1} from fall through spring (Fig. 4) compared to the summer with flows of ~0.05–0.15. At the Kitty's Corner watershed (Fig. 5), discharge was also high during fall through spring (~0.05–1.0 cm d^{-1}), but essentially zero or slightly upstream (i.e., reversed) for most of the dry summer of 2007 due to a microtidal effect from the tidal fresh region of the Choptank estuary 4 km downstream. The thermal expansion of seawater and wind tides result in higher average water levels in the estuary, and high evapotranspiration and low rainfall in dry years results in lower terrestrial water levels (Fisher et al., 2010). Under dry conditions such as those in summer 2007, reversed or zero flows may occur in small coastal plain watersheds such as Kitty's Corner with well-drained soils close to tidal regions (Fig. 5).

In addition to seasonal differences at each site, there were large differences between the two watersheds in Figs. 4 and 5. Kitty's Corner has predominantly coarse-textured soils with high hydraulic conductivity which respond rapidly to rainfall events (hydrologic class A = 52%, 26% hydric, Table 1), whereas Beaverdam has predominantly fine-textured soils with low hydraulic conductivity

Table 4
Results of the hydrochemical and SARR methods of baseflow separation at the individual event scale for all 32 sampled events at the four agricultural watersheds. Shown are the % baseflow for each method, the average water temperature, and the event discharge.

Event	Sample start	Sample end	Hydrochemical % Baseflow	SARR % Baseflow	Mean event water temp. (°C)	Event discharge (cm storm^{-1})
Kitty's watershed						
1	6/27/2006	6/29/2006	37	11	23.0	2.20
2	11/7/2006	11/9/2006	84	37	13.0	1.06
3	1/5/2007	1/7/2007	71	70	11.4	0.55
4	4/11/2007	4/13/2007	79	21	9.7	0.66
5	4/14/2007	4/16/2007	46	6	8.8	4.26
6	6/3/2007	6/5/2007	86	5	19.8	0.16
7	7/29/2007	7/31/2007	113	-1	22.2	0.05
Blockston watershed						
1	6/25/2006	6/27/2006	40	7	21.7	1.18
2	9/1/2006	9/3/2006	92	59	17.7	0.17
3	9/14/2006	9/16/2006	94	57	17.4	0.14
4	11/7/2006	11/9/2006	71	40	12.8	0.43
5	1/8/2007	1/9/2007	35	11	8.4	1.93
6	3/15/2007	3/17/2007	38	9	5.6	2.37
7	4/14/2007	4/16/2007	27	4	8.7	6.09
8	6/2/2007	6/4/2007	84	69	17.7	0.20
9	7/27/2007	7/29/2007	93	50	20.5	0.15
10	8/20/2007	8/22/2007	93	74	18.1	0.13
North forge watershed						
1	11/8/2006	11/10/2006	92	58	14.0	0.43
2	1/5/2007	1/6/2007	86	96	13.8	0.18
3	2/14/2007	2/14/2007	55	19	1.4	0.36
4	3/16/2007	3/17/2007	46	14	4.7	1.65
5	4/4/2007	4/6/2007	98	73	9.3	0.28
6	4/11/2007	4/13/2007	74	51	10.3	0.54
7	4/14/2007	4/16/2007	35	9	9.4	5.35
8	6/3/2007	6/5/2007	107	64	19.0	0.14
Beaverdam watershed						
1	11/8/2006	11/10/2006	81	85	13.4	0.47
2	4/4/2007	4/6/2007	101	75	9.5	0.37
3	4/11/2007	4/13/2007	86	90	11.0	0.30
4	4/14/2007	4/16/2007	29	5	8.9	7.05
5	6/5/2007	6/7/2007	98	99	19.0	0.15
6	6/28/2007	6/30/2007	93	99	20.3	0.14
7	7/29/2007	7/31/2007	62	68	21.4	0.28

which respond slowly to rainfall events (hydrologic class D = 66%, 64% hydric, Table 1). As a consequence of its coarse-textured soils, Kitty's Corner experiences large spikes in quickflow discharge in response to rain events (1–3 cm d^{-1}, Fig. 5B) and large fluctuations in baseflow (0–0.15 cm d^{-1}, Fig. 5B) in response to seasonal variations in evapotranspiration and low rainfall in the summer of 2007. In contrast, the hydrologic responses at Beaverdam were more constrained because of surface water ponding and slow soil drainage resulting in a smaller range of baseflow (0.06–0.18 cm d^{-1}, Fig. 4B) and smaller and fewer quickflow events (except for the largest event in 2007, Fig. 4B). Surface water ponding on hydric soils is common on Delmarva (Koskelo, 2008), and ponding and slow infiltration appear to have a strong dampening effect on storm responses in the Choptank basin (Figs. 4 and 5).

3.1. Annual baseflow index values

The hydrologic responses of the watersheds for WY 2007 differed widely irrespective of the method used (either SARR or UKIH, Table 2). Water yields varied from 43–53 cm year^{-1}, compared to 46 cm year^{-1} at the nearby USGS gauging station at Greensboro (Fig. 3). The BFI values ranged from 0.46 for a quickflow-dominated watershed (Kitty's Corner, Fig. 5) to 0.77–0.80 for groundwater-dominated watersheds with poorly drained soils (Beaverdam and Willow Grove, Fig. 4). As described above, these differences are related to the positions of the watersheds within the landscape; i.e., Kitty's Corner is located in the well drained uplands close to tidal fresh waters while Beaverdam and Willow Grove are located in the poorly drained uplands at the north edge of the watershed (Fig. 3). For comparison, using the UKIH method, Jordan et al. (1997) reported BFIs ranging from 0.44–0.54 for four watersheds with similar land uses (two in the Choptank Basin and two in the nearby Chester Basin).

The SARR method generally calculated higher baseflows than the UKIH method. This was expected due to the shortening (from 5 days to 2 days) of the non-overlapping flow blocks (Fig. 1), making the calculations more responsive to changes in discharge (Figs. 4 and 5). Annually, BFIs for the SARR method were about 0.1–0.2 higher (Table 2). In both Figs. 4 and 5, the UKIH method calculated much longer durations of quickflow. For example, during a rainy period in late December 2006 through January 2007, the UKIH method identified 40 continuous days of quickflow at Kitty's Corner in response to an initial precipitation of <1 cm d^{-1} (Fig. 6), compared to SARR which identified seven unique quickflow cycles of 4–10 days responding to separate precipitation events during the same time period. The SARR results are therefore more responsive to changes within the discharge record, which shows elevated baseflow conditions for several days following a series of small to moderate events under winter conditions of low evapotranspiration.

The annual BFI values were tested for significant (p < 0.05) correlations with land use, soil properties, and watershed size. Only% hydric soils were significantly correlated with BFI computed using both the UKIH and SARR methods (Fig. 7). The systematically lower BFI of the UKIH method (~0.1 BFI unit lower or 10%) is clear in this figure, and the effects of hydric soils on the proportions of base and quickflow that are displayed in Figs. 4 and 5 are quantified in Fig. 7. Although basin size and land use variables were not significantly correlated with BFI individually, we developed significant ($p < 0.05$) multiple linear regressions with soil properties and land use for the BFI based on both the SARR and UKIH methods which explained a large fraction of the variance of BFI:

$$\mathrm{BFI(SARR)} = 0.505 + (0.00775 * \%\mathrm{hydric}) - (0.00796 * \%\ \mathrm{for}) \quad r^2 = 0.98 \tag{3}$$

$$\mathrm{BFI(UKIH)} = 0.468 + (0.0102 * \%\mathrm{hydric}) - (0.0136 * \%\ \mathrm{for}) \quad r^2 = 0.94 \tag{4}$$

where %hydric is the percentage of hydric soils in the watershed and % for is the percentage of forested land within each watershed. Percent agriculture could be substituted for % for, but with a slightly lower overall r^2. The hydric soil effect is clearly dominant (Fig. 7), but land use makes a significant contribution to the r^2 in the above equations. In general, forest land cover and hydric soils had opposing effects on the BFI probably due to higher evapotranspiration in forests and greater groundwater retention in hydric soils.

3.2. Event identification

Using the SARR method, 56–83 events per watershed were identified during WY 2007 at the watersheds with continuous discharge records (Table 3). The variability in the number of events per site was due to variations in soil and landuse, as well as the spatial heterogeneity of rain events. On average, quickflow generated by a single precipitation event ('S' events) was most common with 65% of the total, followed by quickflow generated by multiple precipitation events ('M' events) with 22%, and events generating no quickflow ('X' events) with 13%. The relative frequency of event types is consistent with the discharge and precipitation records which show that most of the identified storms had continuous rainfall and a single peak hydrograph while fewer storms had intermittent rainfall and multiple hydrograph peaks. Precipitation events that did not generate quickflow apparently delivered less water than the soil's infiltration capacity or fell as snow under freezing conditions. In these cases, precipitation was absorbed or held completely by the vegetation and soil without generating any quickflow. Such events were typically small, and the precipitation events often occurred in the summer under dry conditions but were also observed during other seasons (e.g., Fig. 2). These 'X' events were especially abundant at the forested watershed (Willow Grove), suggesting that vegetative interception and soil infiltration were largely responsible for the lack of quickflow response in these forested areas (Table 3).

3.3. Individual events

We sampled 32 individual storm events at hourly intervals for water chemistry at four watersheds to compare the SARR, the UKIH, and the hydrochemical methods. In these events there were significant differences between the hydrochemical and the SARR methods of baseflow separation (Table 4). Among all 32 sampled events, the % baseflow values varied depending on the storm, but typically the hydrochemical method calculated about 1–4 times more baseflow than the SARR method for the same event. For example, during event #4 at Kitty's Corner watershed (Fig. 8), the hydrochemical method calculated 79% baseflow during the event while the SARR calculated 21% baseflow, primarily due to the more coarse temporal resolution of SARR. Occasionally, the two methods gave similar results. For example, during event #7 at the Beaverdam watershed, the two methods resulted in virtually identical% baseflow values (62% versus 68%, Fig. 9). Overall, there were significantly higher ($p < 0.01$) baseflow proportions calculated by the hydrochemical method compared to SARR at Kitty's, Blockston, and North Forge; there was no significant difference at Beaverdam. Both the hydrochemical and SARR methods occasionally violated their own assumptions, resulting in unusual baseflow of either <0% or >100% for a given storm. This occurred when SEC tracer concentrations increased during quickflow, or when streamflow moved upstream due to a micro-tidal effect during an extreme summer drought.

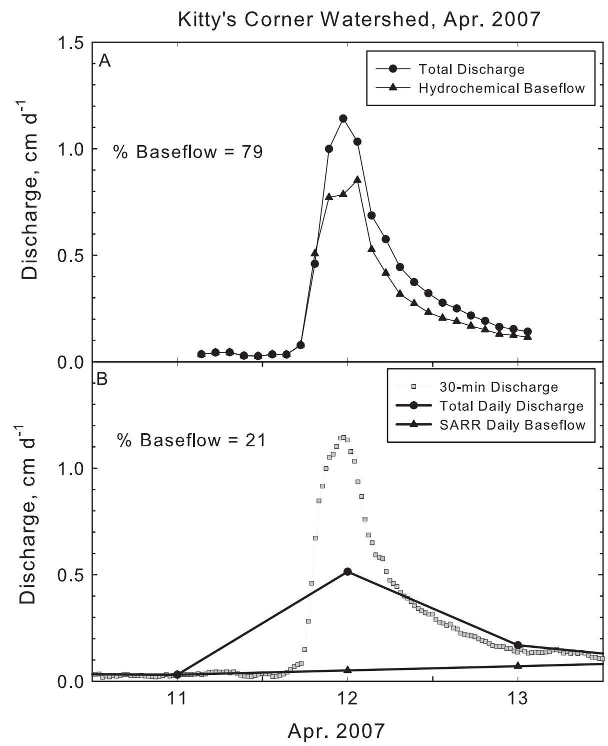

Fig. 8. Results of the hydrochemical (A) and SARR (B) methods of baseflow separation for an individual storm in April 2007 at the Kitty's Corner watershed (event #4, see Table 4). Shown in panel A are the 30 min measurements of total discharge aggregated at 2 h time steps to coincide with the composited chemistry samples (filled circles) and the baseflow computed using SEC with the hydrochemical method (filled triangles). In panel B, the original 30-min discharge data are shown (gray squares), with daily aggregated discharge (filled circles), and the SARR estimated baseflow (filled triangles). In this example, the hydrochemical method calculated almost 4× as much baseflow as the SARR method (79% versus 21%), although it is clear that a great deal of temporal resolution is lost by aggregating the discharge data to the daily time step.

The most striking difference between the hydrochemical and SARR methods was the difference in temporal resolution of the baseflow curves during events. In the hydrochemical method with two hourly samples composited every 2 h, baseflow generally tracked below total discharge with a clear rising and falling limb (Figs. 8A and 9A); however, with the daily SARR method the baseflow curve was unresolved across the event (Figs. 8B and 9B) due to the different time scales. The daily time scale used by SARR dampens discharge variations in watersheds <50 km^2 and results in a flatter baseflow curve, illustrating a limitation of SARR to daily data. If hourly flow and rainfall are available, SARR could potentially be extended to this time scale, although other processes operating at short time scales would have to be addressed (e.g., diel variations in discharge, irrigation effects, etc.). Because both the method of baseflow separation and the temporal resolution of the flow data clearly has strong effects on the computed BFI, it is important to

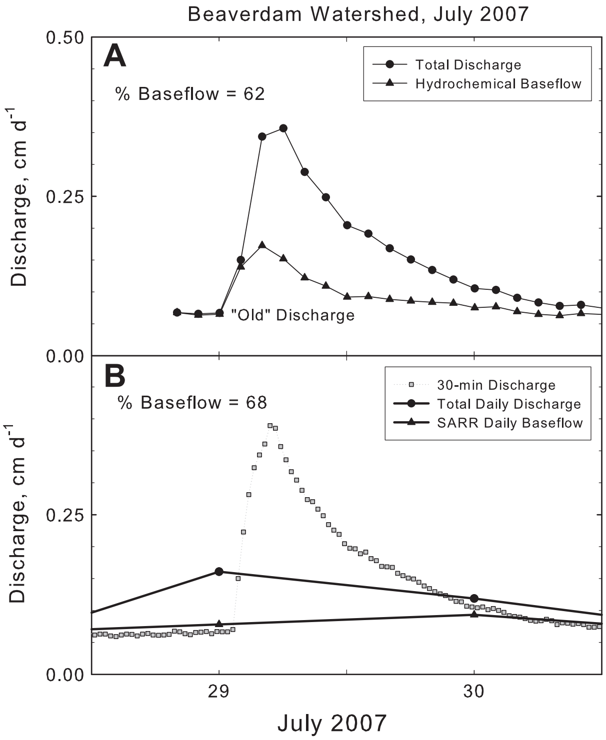

Fig. 9. Results of the hydrochemical (A) and SARR (B) methods of baseflow separation for an individual storm in July 2007 at the Beaverdam watershed (event #7, see Table 4). Shown in panel A are the measured total discharge data aggregated at 2 h time steps to coincide with the composited chemistry samples (filled circles) and the baseflow computed using the hydrochemical method (filled triangles). In panel B we show the original 30-min discharge data (gray squares) and the SARR baseflow. In this case, the hydrochemical and the SARR methods calculated similar amounts of baseflow (62% versus 68%).

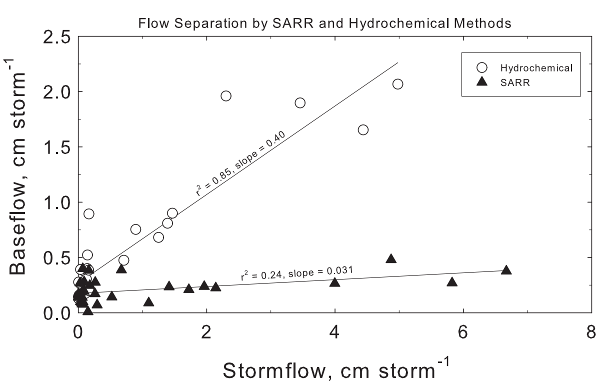

Fig. 10. Relationships between the calculated baseflow and stormflow per event for both the hydrochemical (open circles) and the SARR (triangles) methods of baseflow separation. Each point represents an individual event, and the slopes of both lines are significant ($p < 0.05$). All 32 sampled events are included except for event #7 at the Kitty's Corner watershed (see Table 4) where flow was slightly negative (i.e., moving upstream).

compare BFI values between watersheds obtained at the same time scale with the same method.

For both methods, the baseflow results were significantly correlated with stormflow summed over the event using the 30 min discharge data. Baseflow per event increased linearly with quickflow and represented 40% (hydrochemical method) or 3.1% (SARR) of the calculated quickflow (Fig. 10). Therefore, the hydrochemical method calculates that at least 30–40% of the total storm discharge (baseflow + quickflow) consisted of baseflow, even for a very large storm such as the one in April 2007. In contrast, SARR calculates only 5–10% baseflow in the total discharge of major events.

Ultimately, it is not surprising that the SARR and hydrochemical methods have different results because of the differing time steps used by each method (1 day for SARR, 2 h for hydrochemical). The value of these results is that they emphasize the importance of the time step in a flow separation technique which, depending on the goal of a baseflow separation, may or may not be appropriate for the watershed under study. Here, we found that the SARR was the easier to implement of the two methods, and provided hydrologically meaningful results appropriate to the small watersheds (<50 km^2) used in this study.

4. Discussion

We have developed and tested a new method for baseflow separation (SARR) appropriate for small watersheds (<50 km^2). The SARR flow separation has a strong physical basis, and is easy to apply with commonly available time series data (daily rainfall and discharge). It is the only method known to us that is directly linked to rainfall events. SARR is designed for individual event analysis in small watersheds at the daily time step. The strength of the SARR method lies in its practicality and ease of use; no tracer sampling, well installation, groundwater modeling, or labor-intensive computations are required. To facilitate SARR calculations, we developed a MatLab program which calculates baseflow, identifies events, and summarizes the precipitation data in a series of graphs. As inputs, the program requires only daily flow data and daily rainfall data in Excel format. The time step of the SARR method (1 day) is a critical component of the method that effectively scales the flow separation for watersheds <50 km^2. Depending on the purpose of baseflow separation and the target site, the time step is an important issue to consider. For instance, our technique is suited for small streams, while the traditional UKIH method may be more appropriate for large rivers that respond to events over relatively extended periods of time.

A major concern with using precipitation is whether or not the data adequately capture the high spatial and temporal variability of rainfall. However, by using an integrated approach which combines multiple rainfall data sources, it is possible to obtain a reasonable estimate of rainfall inputs, particularly for watersheds of <50 km^2 (Hornberger et al., 1998), within which the variability is likely to be relatively small. To complement online sources of precipitation data, we recommend installing one or more manual gauges in or near the watershed, and spatially averaging these gauged data with other sources using a weighted average technique. This can be done easily in a GIS using the inverse distance weighting tool. In addition, NEXRAD radar data (available at http://www.wunderground.com/radar/map.asp) may be useful for tracking events such as brief summer thunderstorms that can escape detection by a gauged network. However, we anticipate that radar will only be useful in a supplemental role because of its limited resolution at spatial scales <50 km^2 and because radar is generally not as reliable as gauges for obtaining rainfall depths (Kuligowski, 1997). Regardless of which data sources are used, inherent uncertainties in the rainfall data will persist. Yet we argue that the benefits for flow separation outweigh the errors, and that the uncertainties are no greater than the ambiguities of estimating discharge from watersheds.

Another consideration is how the SARR method would function during drought periods when there is no quickflow and the aquifer is slowly depleted over a period of at least some days. Our flow record had two such periods in the summer of 2006 and the summer of 2007. In these cases, the SARR baseflow method did not identify any quickflow days because the flow data did not typically meet the criteria of having a 10% decrease in local minima, i.e., the discharge from the aquifer was sufficiently slow and steady to preclude any quickflow identification. Therefore, all of the daily data were classified as baseflow, and the averaging function of the SARR method (where each 2 day period classified as baseflow is averaged) essentially performed a smoothing function to the data which was actually beneficial in that it helped remove aberrations in the flow record related to irrigation effects and diel cycles. This is considered an improvement over other separation techniques such as the UKIH method which predicts a systematic negative bias during droughts.

The SARR method provides results which are significantly different compared to established methods, largely because SARR is designed to estimate baseflow in small watersheds. Annual BFIs computed with the SARR method were generally 0.1 unit (10%) higher compared to the established UKIH method with its longer time step (Fig. 7). For individual events, SARR was compared to the hydrochemical method. The results showed that the hydrochemical method calculated 1–4× more event baseflow than SARR for the same storm because of the differences in time step (2 h for hydrochemical, 1 day for SARR) and the different definitions of baseflow (i.e., the hydrochemical method defined baseflow in terms of rapid chemical changes in the stream during storm events, while the SARR defined baseflow in terms of groundwater discharge rates prior to the storm). These differences resulted in a baseflow curve with a striking rise and fall for the hydrochemical method, versus a flatter linear baseflow curve for SARR.

Both SARR baseflow and hydrochemical baseflow increased linearly with event quickflow. The differences between the two methods were most apparent for larger storms where the hydrochemical baseflow was a major portion of total flow (Fig. 10). In support of this, many studies using the hydrochemical method have shown a dominant contribution from baseflow during event flows, typically almost 100% on the falling limb (Hornberger et al., 1998). Similarly, Gonzales et al. (2009) showed that about 90% of the total measured discharge in a lowland catchment in the Netherlands was groundwater displaced by event water infiltrating in the northern part of the watershed, and only 10% was surface runoff. In the Choptank watersheds, our data suggest that precipitation displaces groundwater in an amount which is proportional to the volume of quickflow.

In general, it is not possible to say which of the methods (SARR, hydrochemical, UKIH) is more "accurate" since baseflow is operationally defined. However, we found that SARR had significant advantages over the other methods. These include: (1) SARR had a stronger empirical basis with results that were more consistent with the precipitation and discharge records, (2) SARR was more practical and easier to implement while still giving results that were hydrologically meaningful, and (3) SARR had the added benefit of a built-in method of event identification which the other methods were lacking.

Ultimately, no flow separation method is capable of precisely estimating baseflow during storm discharges. The larger issue is how to separate baseflow in a hydrologically meaningful and practical way for applications such as computing total annual watershed export of (e.g.) N or P using periodic sampling of water chemistry. We argue that a baseflow separation method should be objective, empirically based, practical to implement, and easy to compute. Most currently available techniques require expensive and time-consuming materials and methods. Therefore, we propose that SARR can provide a useful method for small watersheds with long records of discharge and precipitation, especially in cases where tracer data are not available. We expect that SARR can be implemented in any small watershed <50 km^2 in size, and we can provide a Matlab program which automatically computes the baseflow results and identifies events. The program is freely available from the authors upon request.

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