AN AUTOMATED TOOLKIT FOR HYETOGRAPH-HYDROGRAPH ANALYSIS

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A Thesis Submitted to the School of Graduate Studies in Partial Fulfillment of the Requirement for the Degree Master of Science

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Abstract

Understanding the nature of streamflow response to precipitation inputs is at the core of applied hydrological applications such as flood forecasting and water resource management. Indices such as the runoff ratio, recession constant and response time of a watershed retain an important place in hydrology decades after their establishment as metrics to compare watersheds and understand the impact of human activity, geology, geomorphology, soils and climate on precipitation-runoff relations. Extracting characteristics of the hyetograph-hydrograph relationship is often done manually, resulting in subjective and inconsistent results that require considerable time. In addition, there are a large number of metrics proposed to analyze the hyetograph-hydrograph relationship and hydrograph shape that are typically subjective in application. The objective of this research is to develop an automated and flexible toolkit for rainfall-runoff analysis. Using the MATLAB language, a series of inter-related functions are created to extract rainfall-runoff events from time-series of rainfall and streamflow data and compute commonly used characteristics of the hyetograph-hydrograph relationship. Furthermore, a number of input parameters are introduced to add flexibility to the toolkit. This toolkit has been applied successfully to four watersheds in Canada and Scotland. A subsequent analysis was performed assessing the sensitivity of parameter selection on the toolkit performance, and a number of suggestions for users provided. It is anticipated that this toolkit will provide hydrologists with a rapid objective method of analyzing rainfall and runoff data where in the past manual procedures resulted in considerable subjectivity in results.

Acknowledgement

Studying at McMaster University has been one of my most enjoyable experiences. The people that I have met here provided me considerable helps in both academy and personal life. My time in Canada would have been much harder without them, and I am sure it would not have been as much fun or enjoyable.

I would like to express my special appreciation and thanks to my advisor Professor Dr. Sean K. Carey, who is also a tremendous mentor for me. He kindly provided me any supports I needed in my research, and also generously bought me beers in many afternoons. His wisdom, hardworking, high efficiency, and generosity deeply impressed me, and I have learned a lot from him. I am very pleased to have worked with him in the past two years. Thanks also go to Dr. Chris Soulsby and Dr. Doerthe Tetzlaff, for kindly offering the data in Scottish watersheds. Thanks also go to Chris DeBeer, for his previous work on Granger Creek that provided important reference for this study.

I would also like to thank my family and friends for the love and support that they give me throughout my life. Especial thanks are given to my parents, who unreservedly support me to study aboard and provided me comfort and encouragement when I was in adversity.

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List of abbreviations and symbols

β	Filter coefficient
b_t	Baseflow rate at time interval t
p_i	Precipitation in ith time interval
$Q_{sm,\, t}$	Smoothed streamflow rate at time interval t
Q_t	Streamflow rate at time interval t
q_0	Flow rate at the beginning of recession
$q_{obs,i}$	Observed flow rate of recession at ith time step
$q_{obs,max}$	Maximum observed flow rate of recession
$q_{obs,min}$	Minimum observed flow rate of recession
$q_{sim,i}$	Simulated flow rate of recession at ith time step
q_t	Stormflow rate at time interval t
$q(t)$	Flow rate t hours after the beginning of recession
T_{LC}	Centroid lag
T_{LR}	Response lag
T_{LP}	Lag-to-peak
T_{LPC}	Centroid lag-to-peak
T_b	Time base
T_c	Time of concentration
T_r	Time of rise
T_w	Duration of effective rainfall

t_{pk}	Peak of event flow
t_{q0}	Beginning of event flow
t_{qc}	Centroid of event flow
t_{qe}	End of event flow
t_{w0}	Beginning of effective rainfall
t_{wc}	Centroid of effective rainfall
t_{we}	End of effective rainfall
V_{runoff}	Volume of runoff event
V_{precip}	Volume of storm event
AT	Input parameter – advancing time
BSLP	Input parameter – beginning slope threshold
ESLP	Input parameter – ending slope threshold
INT	Input parameter – interception
RR	Input parameter – return ratio
PKTHR	Input parameter – peak discharge threshold

1. Introduction

Understanding the nature of stream response to precipitation input is at the core of applied hydrological applications such as flood forecasting, water resource management, and the assessment of the consequence of landscape change. Stream response reflects how a watershed transforms precipitation in to runoff, and it is an outcome integrating the influence of numerous watershed characteristics including geology, geomorphology, soils, vegetation, and climate (McNamara et al., 1998). A conventional method to study stream response is a comparative analysis of the timing and features of the precipitation hyetograph and corresponding runoff hydrograph (Dingman, 2002). Widely utilized indices such as baseflow index, recession constant, runoff ratio and response time can be derived from the information contained in hyetograph and hydrograph, and they provide first-order information to understand the rainfall-runoff relationship in watersheds (Holtan & Overton, 1963; Potter & Faulkner, 1987; Ferguson & Suckling, 1990; Jones & Grant, 1996; McNamara et al., 1998; Elsenbeer & Vertessy, 2000; Sujono et al., 2004; Dow, 2006). While there are likely thousands of papers reporting rainfall-runoff characteristics, examples of studies focusing exclusively on their relationship include: 1) McNamara et al., (1998) who used initial response time, centroid lag between hyetograph and hydrograph, and runoff/precipitation ratio for investigation of the hydrological mechanisms and processes in a permafrost environment. 2) Elsenbeer and Vertessy (2000) who utilized the hydrograph time characteristics of time of rise, response time, lag time and centroid lag time to investigate runoff generation at hillslope scale and watershed scale in an Amazonian rainforest catchment. 3) Sujono et al. (2004), who assessed recession parameters that have been applied to model surface runoff generation for continuous daily streamflow time-series. 4) Jones and Grant (1996) who evaluated timing of hydrograph characteristics, instantaneous peak discharge, and runoff volumes to quantify long-term changes in streamflow associated with clear-cutting and road construction in forested watersheds. 5) The effect of urbanization on watershed rainfall-runoff process was investigated using peak flows, low flows and total runoff by Ferguson and Suckling (1990). 6) Baseflow index and streamflow flashiness index were used by Dow (2006) to assess relationships between land use/cover and streamflow regimes. 6) The ratio of drainage area to time-to-peak (centroid lag) was recommended as a good predictor of flood quantiles on ungauged watersheds (Potter & Faulkner, 1987).

Analysis of hyetograph-hydrograph relationships are often done manually, relying on visual inspection and interpretation by hydrologists. As a result, considerable time is required to implement the analysis and results cannot typically be replicated among hydrologists as there are subjective decisions related to timing of parameters that are made. In contrast, automated hydrograph analysis provides consistency of results by removing subjectivity inherent in visual inspection and interpretation and considerably reduces the time required for manual analysis (White & Sloto, 1990). Baseflow separation is the most common feature of hydrograph analysis that has been automated by a number of methods based on graphic analysis techniques or digital filters (Nathan and McMahon, 1990; Sloto and Crouse, 1996; Rutledge 1998; Piggott et al., 2005). It aims to separate streamflow into two components - baseflow and stormflow. Baseflow is referred to as the portion of streamflow that is not related to a specific event, and it is mainly contributed by ground water. As well, stormflow (also called direct runoff, storm runoff and event flow) is the flow directly responding to a given rainfall, or other water-input events. These automated methods for baseflow separation have shown satisfactory consistency with manual analysis with considerable savings in terms of time (White and Sloto, 1990; Tallaksen, 1995; Arnold et al., 1994; Blume et al., 2007). Recession analysis, which describes the descending limb of a runoff hydrograph and is linked to basin storage characteristics (Brutsaert & Nieber, 1977; Tallaksen, 1995), remains a topic of considerable research when examining hydrograph characteristics (Tallaksen, 1995; Moore, 1997; Elsenberr & Vertessy, 2000; Brandes et al., 2005). Recession constant, the term used to describe the slope of streamflow decline from an event peak, have been linked to drainage and aquifer properties such as transmissivity and diffusivity (Arnold et al., 1995). In addition, there has been considerable research attempting to link various expressions to describe the shape of the recession with processes operating within the watershed (Moore, 1997; Wittenberg, 1999; Chapman, 1999; Sujono, Shikasho, & Hiramatsu, 2004). Tallaksen (1994) reviewed the most widely used equations used to describe hydrograph recession.

Previous automated tools for hydrograph analysis have focused on only a select few aspects of the hydrograph including baseflow separation, recession analysis and total stormflow calculation (Arnold et al., 1995; Sloto and Crouse, 1996; Rutledge, 1998; Chapman, 1999; Lim et al., 2005; Piggott et al., 2005). Conversely, extracting other characteristics such as response lag, rainfall duration, time of concentration is typically done manually, and there has been very little research exploring these characteristics and methods to automate their analysis. Furthermore, none of the developed automated tools relate the results of hydrograph analysis with timing and shape features on hyetograph. Therefore, it is useful to develop a tool able to automate comparative analysis between the hyetograph and hydrograph and extract of shape and timing features between them.

Dingman (2002) summarizes a wide variety of hydrograph characteristics that describe the shape of the hydrograph and expressions that relate the timing of hyetograph and hydrograph features (Table 1 and Figure 1). The response lag and duration of rising and recession have been used to quantitatively describe the stream response of watersheds and incorporated in comparative studies of watershed (McNamara et al., 1998). Linkages between the time to peak and land cover/use change has been investigated by Huang et al., (2008) to evaluate the impact of urbanization on hydrological behavior at watershed scale. Carey and DeBeer (2008) used a number of parameters of hydrograph timing response in combination with statistical analysis to identify their relations to ground thaw in a discontinuous permafrost watershed. The computation of time characteristics and event-based analysis involve a number of procedures, including separating baseflow, extracting event flow, and identifying timing features on hyetograph and hydrograph. Sometimes, hundreds of events must be analyzed in order to obtain statistically representative results, so these procedures must be done repeatedly, requiring considerable time and labour.

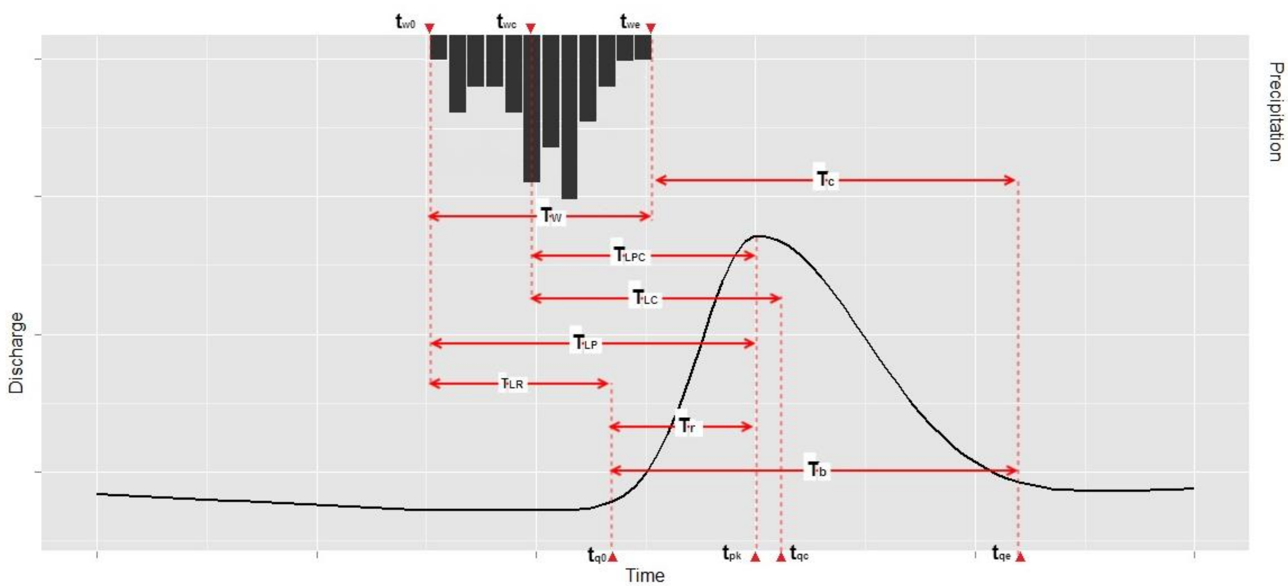


Figure 1. Definition of time characteristics for hyetograph-hydrograph relations.

Table 1. Description of time instants and characteristics

Symbol	Equation	Description
t_{w0}	-	Beginning of effective rainfall
t_{wc}	-	Centroid of effective rainfall
t_{we}	-	End of effective rainfall
t_{q0}	-	Beginning of event flow
t_{pk}	-	Peak of event flow
t_{qc}	-	Centroid of event flow
t_{qe}	-	End of event flow
T_w	$t_{we} - t_{w0}$	Duration of effective rainfall
T_{LR}	$t_{q0} - t_{w0}$	Response lag
T_r	$t_{pk} - t_{q0}$	Time of rise
T_{LP}	$t_{pk} - t_{w0}$	Lag-to-peak
T_{LPC}	$t_{pk} - t_{wc}$	Centroid lag-to-peak
T_{LC}	$t_{qc} - t_{wc}$	Centroid lag
T_b	$t_{qe} - t_{q0}$	Time base
T_c	$t_{qe} - t_{we}$	Time of concentration

The objective of this thesis is to develop a toolkit in the MATLAB environment that automates the procedures of determining the temporal characteristics of hyetograph-hydrograph response. The toolkit consists of a collection of functions required for determination of time characteristics from precipitation and stream flow records including baseflow separation, hydrograph event selection and extraction, timing features recognition, and time characteristics calculation. The function for baseflow separation is developed using the previously developed digital filter by Arnold and Allen (1999), while the remaining functions are proposed as a mechanism for extracting storm hydrograph events from long-term records and calculating time characteristics. The toolkit attempts to mimic the procedure hydrologists would use when visually inspecting and interpreting the hydrograph. Despite their widespread application, the methods adopted are based on graphic analysis techniques and do not in all cases have a strong theoretical basis. The time characteristics presented in Figure 1 and Table 1, the runoff ratio and recession constant for unique rainfall-runoff event can be calculated by this toolkit. The advantage of this toolkit is that it makes hydrograph analysis objective and reproducible and saves considerable labor and time for hydrologists when analyzing a large number of runoff events. To test the efficacy of the toolkit, it is applied and evaluated at four different watersheds: one in Canada and three in Scotland.

2. Methods

This toolkit includes a series of functions to obtain event-based time characteristics, recession constant and runoff ratio from a time series of precipitation and streamflow data. Baseflow separation is the first function in this toolkit (Figure 2), which separates baseflow from a stream hydrograph. Then, runoff events are recognized and extracted from the baseflow-free hydrograph. After obtaining the individual runoff events, the recession limbs are cut out from the runoff hydrographs and then modelled by exponential equations to calculate recession constants. Concurrently, every extracted runoff event is matched with a corresponding rainfall event to create a unique rainfall-runoff event. Time characteristics and runoff ratios are then calculated for the rainfall-runoff events, and the results saved for statistical analysis.

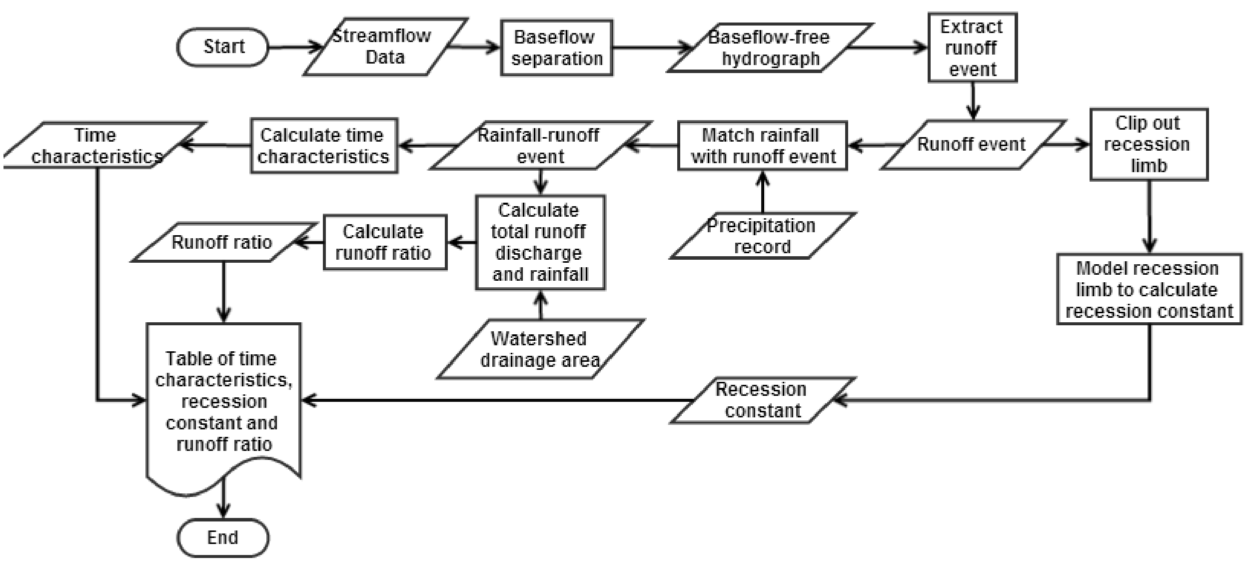


Figure 2. The working process of the toolkit

2.1. Baseflow separation

Streamflow can be divided into two components, baseflow and stormflow, according to water sources. Baseflow is defined as the portion of flow contributed by groundwater or other delayed sources, and it is not related with a specific storm event (Dingman, 2002). On the other hand, stormflow is considered the direct response to a given water-input event, such as rainfall or snowmelt. It is also referred to as quick flow, runoff flow, or event flow (Dingman, 2002; Davie, 2008). The function for baseflow separation partitions streamflow data into baseflow and storm flow. Arnold et al., (1995) reported that the recursive digital filter (Equation 1) originally used in signal analysis and processing, is a fast and objective method for baseflow separation.

$$b_t = \beta \cdot b_{t-1} + \frac{1-\beta}{2} \cdot (Q_t + Q_{t-1}) \qquad (1)$$

where b_t is the filtered baseflow at time t, Q_t is the original stream flow, and β is the filter coefficient. Although this method has limited physical basis, it is able to produce results that are acceptable with appropriate β values and is considered more objective than manual methods. Stormflow flow, q_t, can be calculated as:

$$q_t = Q_t - b_t \qquad (2)$$

Equation (1) can be applied to the stream flow data more than once and in both directions in time (forward and backward), depending on user's requirement for smoothness and the estimate of the percentage of baseflow to the total stream flow. In general, each pass will result in a smoother and flatter baseflow. By subtracting baseflow from streamflow, a hydrograph called the baseflow-free hydrograph is obtained. The baseflow-free hydrograph remains a continuous hydrograph with the same length with the original streamflow hydrograph, and subsequent functions are used to extract individual runoff events. On the baseflow-free hydrograph, the peaks are referred to as stormflow, and the steady low flow segments are considered baseflow residuals (Figure 3). In this case, baseflow separation function is not expected to completely remove baseflow component from hydrograph, but aims to make the stormflows more evident and easier to recognize on the new hydrograph.

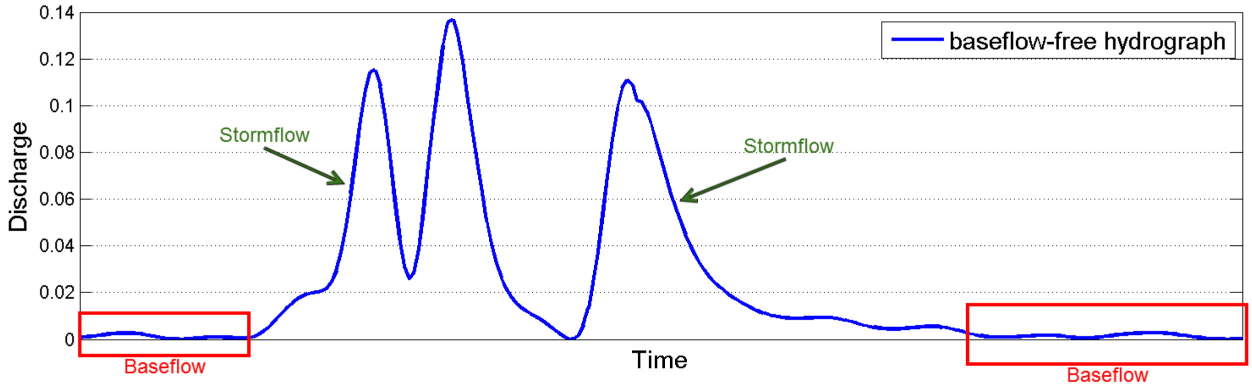


Figure 3. Example of a baseflow-free hydrograph.

2.2. Extraction of runoff event

Automated routines are utilized to extract runoff events from the baseflow-free hydrograph. Procedures are implemented to acquire runoff events, with the first step to recognize local minima and maxima (peaks) on the baseflow-free hydrograph (Figure 4). Extraction of runoff events from the baseflow-free hydrograph begins with identifying the points at which the stormflow starts and ends. The preliminary start and end point of runoff events is selected as local minimum.

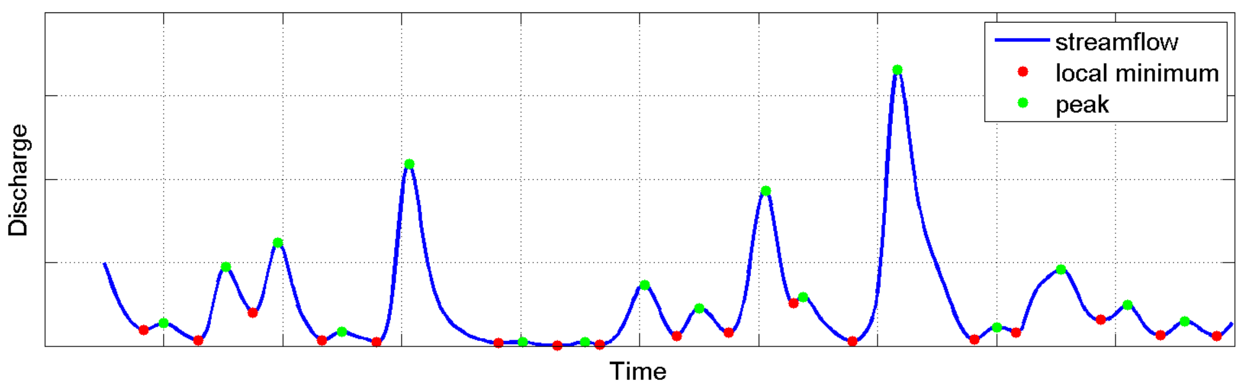


Figure 4. Example of local minimums and peaks on a synthetic hydrograph

In this method, event runoff is extracted one by one along the hydrograph time series. The identification for an event will not begin until the identification for previous one is completed. The start point of the first runoff event is selected as the local minimum prior to the first peak on the baseflow-free hydrograph. The end point of the runoff event is not necessarily the first local minimum following the peak as events occur where there are multiple peaks in a runoff event (usually caused by intermittent rainfall). The toolkit identifies the termination of a runoff event as the first local minimum following a peak flow where discharge drops back to the initial rate at (or some value near) the start point. In most cases, discharge rarely returns to pre-event flows, so a parameter termed return ratio (RR), is introduced to account for higher levels of flow following storm events. The RR defines a user-determined difference in discharge between the end and start of a stormflow event, which allows for flexibility in defining runoff events. This value can be an absolute value or a ratio of peak flow based on user preference. It is important to identify that RR controls the number of multiple-peak events. Increasing the value of RR loosens the requirement for the termination of a stormflow event, so more end points will be identified on hydrograph, resulting in the increase in the number of unique runoff events generated. Following the identification of the termination of a runoff event, a routine is implemented to determine the initiation of the subsequent runoff event. This process continues until the last local minimum on the baseflow-free hydrograph is completed.

After identifying the start and end point of an event, the hydrograph segment is extracted as a unique runoff event. However, not all extracted runoff events are suitable for analysis, and only those with a distinct peak flow are considered further. To identify an event with a suitable peak, a user-defined parameter is introduced called peak threshold (PKTHR), which defines the minimum acceptable peak flow for a runoff event. Runoff events with local maxima less than the PKTHR are excluded from subsequent analysis.

As stated, the start and end points identified based on local minima are preliminary estimates. Local minima are useful values to separate runoff events, but they do not precisely represent the location of beginning and end of a stormflow event. Tallaksen (1994) and Arnold et al. (1994) identify runoff events to start where the hydrograph exhibits a sudden rise, and the termination where the recession ceases. Considering the shape of an idealized hydrograph, the most notable feature identifying the start and end of an event are sudden changes in hydrograph slope. Consequently, the beginning and termination of an event is defined by two parameters: the beginning slope threshold (BSLP) and ending slope threshold (ESLP). Typically, the slope gradually increases at the beginning of runoff hydrograph, so the start point is positioned where the slope exceeds a user-defined value. In contrast, the slope at the end of runoff hydrograph most often exhibits a gradual decrease, and a reverse time procedure is implemented to identify a user-defined slope threshold to terminate an event. These thresholds can be used to redefine events for analysis and implement objective criteria based on flow characteristics for event analysis (Figure 5).

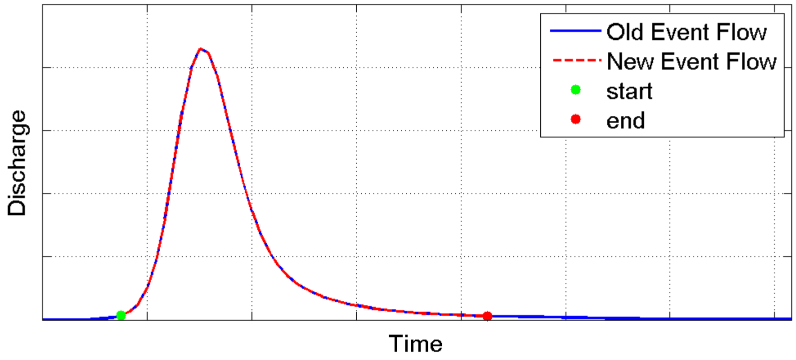


Figure 5. Relocation of start and end point using the BSLP (start) and ESLP (end) functions.

In some cases, difficulty occurs in finding local minimums and peaks due to high-frequency 'noise' in the hydrograph. To remove this high-frequency variability, a smoothing filter is employed:

$Q_{sm,t} = (Q_{t-1} + 2 \cdot Q_t + Q_{t+1})/4$ (3)

where $Q_{sm,t}$ is the smoothed streamflow rate, and Q_t is original stream flow rate at time *t*. The filter can be passed over hydrograph more than once if deemed necessary by the user to remove high-frequency noise. However, the application of the filter must be used cautiously as each application dampens the hydrograph shape. In this case, the default setting for the number of passes is 10. A comparison between smoothed hydrograph and original hydrograph is shown in Figure 6.

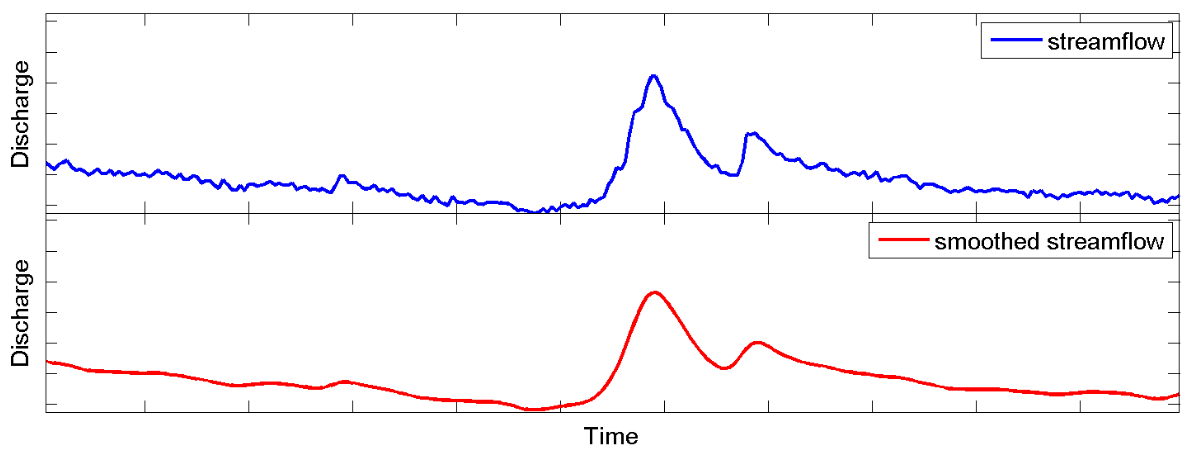


Figure 6. Comparison of smoothed hydrograph (lower) against original hydrograph (upper).

2.3. Recession parameters

The recession parameter in the toolkit is modeled by an exponential equation (Equation 4). For multiple-peak event, the parameter is identified for the recession limb following the last peak.

$q(t) = q_0 \cdot e^{-t/t^*}$ (4)

where $q(t)$ is the flow rate t hours after the beginning of recession, q_0 is the flow rate at the beginning of the recession, and t^* is the recession constant (hr). It is important to note that there are many mathematical forms that have been used to model the recession equation (see Tallaksen (1994) for review), yet here we use the most widely applied exponential equation. The toolkit includes provision for other model fits for the recession limb. As part of the evaluation of the fit of Equation 4, the Root Mean Square Error (RMSE) (Equation 5) is provided to describe the performance of model. As the value of RMSE depends on the magnitude of runoff event (greater events more likely produce higher RMSE), the Normalized Root Mean Square Error (NRMSE) (Equation 6) is reported as a measure of the goodness of fit.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(q_{obs,i} - q_{sim,i})^2}{n}} \qquad (5)$$

$$NRMSE = RMSE \,/\, (q_{obs,max} - q_{obs,min}) \qquad (6)$$

where $q_{obs,i}$ is the observed flow rate and $q_{sim,i}$ is the simulated flow rate at i^{th} time step, n denotes the total number of time steps, $q_{obs.max}$ and $q_{obs,min}$ represents the maximum and minimum value of observation respectively. In this toolkit, NRMSE is provided.

2.4. Coupling runoff events with rainfall

After identifying a runoff event, a search algorithm is employed to identify the causal rainfall event in a window spanning n hours before the start of runoff event to the time of the last peak, where n is a user-defined parameter called advancing time (AT). For example, if AT is set as 12 hours, all precipitation records located in the window 12 hours before the start of runoff to the time of last peak will be identified. The rainfall event starts at the first non-zero precipitation record in the searching window and ends at the last non-zero record.

Not all rainfall water contributes to runoff as interception by vegetation reduces the effective precipitation that catchment receives. In regions with dense vegetation, interception can delay and significantly reduce the response of a hydrograph to rainfall. Considering this, the toolkit has a parameter to extract an absolute volume of rainfall, called interception (INT). Interception is the portion of rainfall retained by vegetation covers. After this abstraction, the remaining rainfall (called effective rainfall, the portion of rainfall virtually contributing stormflow) is matched with the runoff event to form a complete rainfall-runoff event. Subsequently, the time characteristics and runoff ratio are calculated for each of the newly generated rainfall-runoff event.

Table 2. Input parameters in this toolkit

Abbreviation (or symbol)	Full Name	Related Process	Function
β	Filter coefficient	Baseflow separation	Control the proportion of baseflow in streamflow
PKTHR	Peak flow threshold	Runoff event extraction	Select runoff event for analysis based on peak flow discharge
RR	Return ratio	Runoff event extraction	Determine the location of end point of runoff event on hydrograph
BSLP	Begin slope threshold	Runoff event extraction	Determine the slope at the start of runoff event
ESLP	End slope threshold	Runoff event extraction	Determine the slope at the end of runoff event
AT	Advancing time	Coupling rainfall and runoff event	Define the rainfall-event searching window
INT	Interception	Coupling rainfall and runoff event	Define the amount of interception at the beginning of rainfall

2.5. Time characteristics calculation

Before calculating time characteristics, time instants (see Table 1) are identified on the event hydrograph and hyetograph. t_{w0}, t_{we}, t_{q0}, and t_{qe} are discussed in the previous sections. For multiple-peak runoff event, t_{pk} is the time of the highest peak. t_{wc} and t_{qc} is calculated using Equation 7 and 8.

$$t_{qc} = \sum_i^n q_i \cdot t_i / \sum_i^n q_i \quad (7)$$

$$t_{wc} = \sum_i^n p_i \cdot t_i / \sum_i^n p_i \quad (8)$$

where q_i is the flow discharge at i = 1, 2, 3, …, n moment, p_i is the rainfall measured for i = 1, 2, 3, …, n time interval, and t_i is the ith moment or time interval. After identifying time instants, time characteristics are calculated according to the equations listed Table 1.

2.6. Runoff ratio calculation

Runoff ratio refers to the ratio of total runoff discharge to total precipitation of an event (Equation 9). By default, the unit for precipitation record is millimeter (mm) and the unit for stream discharge record is cubic meter per second (m^3/s). Before calculation of runoff ratio, precipitation and runoff are standardized to a common unit, requiring the watershed area (m^2). The total precipitation is obtained by summing up the products of precipitation records and watershed area (Equation 10), and the total runoff is acquired by summing up the products of streamflow rate and time interval (Equation 11).

$$runoff\ ratio = V_{runoff} / V_{precip} \quad (9)$$

$$V_{precip} = \sum p_i * A \quad (10)$$

$$V_{runoff} = \sum q_i * t \quad (11)$$

where V_{runoff} and V_{precip} are the total volume of runoff and rainfall water respectively, q is stormflow discharge, t denotes the time interval in seconds, p is precipitation record, and A represents watershed area.

2.7. Statistical test for output characteristics

Output characteristics were plotted using an empirical Cumulative Distribution Function (CDF) to view their distribution. Furthermore, a Kolmogorov-Smirnov (K-S) test was employed to examine the significance of difference in output characteristic between watersheds. The K-S test is a nonparametric statistic and can be utilized to compare the probability distribution of two samples. It measures the difference between two samples by quantifying the distance between their CDFs, and the advantage of K-S test is the sensitivity to the difference in both location and shape of CDFs. The null hypothesis of test is that two tested samples do not have different distribution, as well as p-value is used to decide if rejecting or accepting null hypothesis. The critical value for rejection in this case is 0.05 (equal to 95% confidence interval). Paired watershed tests with a p-value lower than the critical value indicates that their output characteristic have significantly different distribution, and is identified with bold text in a statistic test table (e.g. Table 8).

2.8. Description of tested watersheds

Precipitation and stream discharge data used to test the toolkit were collected from four watersheds ranging in area from 3.6 to 231.0 km^2 (Table 3). Three watersheds are located in northeast Scotland and one in Yukon, Canada. The climate of Scottish watersheds is temperate and oceanic, and they received more precipitation input in winter than summer. Snow comprises about 30% and 10% of annual precipitation for Feshie and Girnock respectively, and snow cover usually has a short duration; no more than one month per year (Soulsby et al., 2004; Birkel, Soulsby and Tetzlaff, 2011). Feshie covers some of the most mountainous terrain in UK, while Girnock has relatively gentle relief. Bruntland Burn (BB) is a subcatchment of Girnock basin, therefore sharing the similar geographical setting. The precipitation and streamflow data for the Scottish watersheds were collected by the Scottish Environmental Protection Agency in different periods, and the observation period for Girnock is shorter than Feshie and BB.

Granger Creek basin is a small subarctic catchment located at south of Yukon, Canada with 70% of the basin is estimated underlying with permafrost (Carey and DeBeer, 2008). Snow accounts for approximately 40% of annual precipitation, and snow cover exists for more than 6 months a year. Peak freshet high-flows caused by snowmelt occurs between April to June. As this toolkit focuses on rainfall-caused events, the snowmelt freshet period is excluded from the analysis. The precipitation and streamflow data in Granger Creek were collected across 13 years, from 1999 to 2012 (except 2008), and only summer periods (from July 5th to October 1st) were used to test the toolkit.

According to Table 4, BB has the most complete data set, whereas other tested watersheds contains missing data in precipitation, with Feshie having a few missing data in streamflow. Missing data in precipitation can result in failure in matching runoff with a specific rainfall event. Therefore, it is possible that a number of unmatched runoff events are generated in the tested watersheds. Furthermore, the function of baseflow separation in this toolkit is unable to process null data, so before testing, the nulls in precipitation data were filled in with zero, and nulls in streamflow were interpolated by linear method.

Table 3. Watershed properties for BB, Girnock, Feshie, and Granger Creek

		Feshie	Girnock	Bruntland Burn (BB)	Granger
Area (km^2)		231.0	30.4	3.6	7.6
Elevation Range (m)		230-1115	230-861	255-542	1310-2250
Mean Elevation (m)		617	407	359	17
Monthly Temperature (˚C)	Lowest	1.2 (February)	-	-	-17.7 (January)
	Highest	10.3 (July)	-	-	14.1 (July)
Dominant Land-cover Type		Heather Moor (69%)	Heather Moor (70%)	Heather Moor (63%)	Shrub-tundra
Dominant Geology		Schist (70%)	Granite (53%)	Granite (46%)	Sediments
Mean Annual Precipitation (mm)		1598	1000	963	440
Mean Annual Runoff (mm)		-	582	600	-

Table 4. Data description for streamflow and precipitation in the tested watersheds

		Feshie	Girnock	BB	Granger
Start Date		2001 Oct. 1st	2003 Oct. 1st	2011 Jun. 2st	Jul. 5th (1999-2007, 09-2012)
End Date		2003 Jan. 1st	2004 Sep. 29th	2012 Sep. 20th	Oct. 1st (1999-2007, 2009-2012)
Observed Period (day)		457	364	476	1131 (87 × 13)
Precipitation	Time Interval	1(hr)	15(min)	1(hr)	30(min)
	Number of NAs	339	2389	0	4038
Streamflow	Time Interval	1(hr)	15(min)	15(min)	1(hr)
	Number of NAs	50	0	0	0

3. Result

3.1. Baseflow separation

The baseflow separation function partitioned the streamflow hydrograph into two components: baseflow and stormflow (also termed event runoff) using Equation 1 (Figure 7 and 8). According to Arnold and Allen (1999), watersheds often have unique filter coefficients (β), and the value of β is prescribed based on user's estimates of baseflow from pilot studies of streamflow data. In this case, the value of β was adjusted based on the degree of variation of the streamflow hydrograph, generating a baseflow pattern consistent with that typically reported in terms of appearance. In general, increasing the value of β will produce less variable baseflow and reduce the proportion of baseflow in total streamflow, with literature values ranging between 0.9-0.999 (Nathan & McMahon, 1990; Arnold and Allen, 1999; Eckhardt, 2008).A detailed analysis of the influence of β on baseflow separation is presented in the discussion section.

The separated baseflows from streamflow in Granger Creek (Figure 7) shows there is considerable inter-annual difference in appearance, suggesting the β can be adjusted on an annual basis. However, to assure objective and comparable results, β = 0.95, was applied for all years. The Scottish watersheds exhibited markedly different patterns compared with Granger Creek in terms of flow characteristics. First, the occurrences of stormflow runoff events are more frequent at Feshie than at Girnock and BB. Trial and error provided values of β that conformed closest with those expected based on patterns reported in the literature (Table 5). The β at the Scottish watersheds was higher than Granger Creek, suggesting a greater and more consistent baseflow (Figure 8).

Table 5. Values chosen as input parameters at each tested watershed.

	BB	**Girnock**	**Feshie**	**Granger**
β	0.995	0.993	0.97	0.95
PKTHR (m^3/s)	0.1	0.3	5	0.08
RR (m^3/s)	0.05	0.2	2	0.03
BSLP ($m^3 \cdot s^{-1} \cdot h^{-1}$)	0.001	0.001	0.01	0.005
ESLP ($m^3 \cdot s^{-1} \cdot h^{-1}$)	0.0001	0.0001	0.001	0.001
AT (hour)	10	10	10	12
INT (mm)	0.5	0.5	0.5	0.5

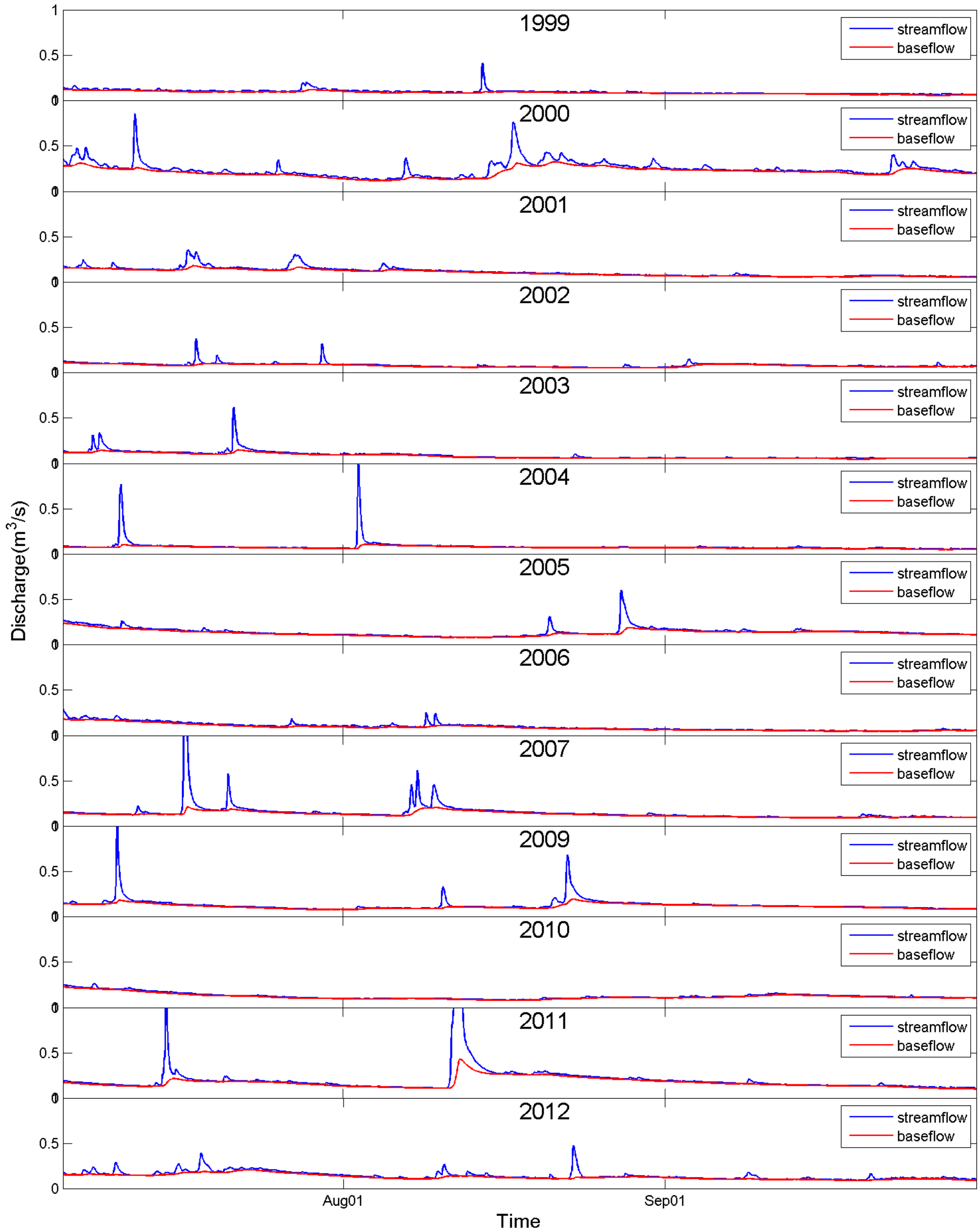


Figure 7. Baseflow separation for Granger Creek in summer period from 1999 to 2012 (except 2008).

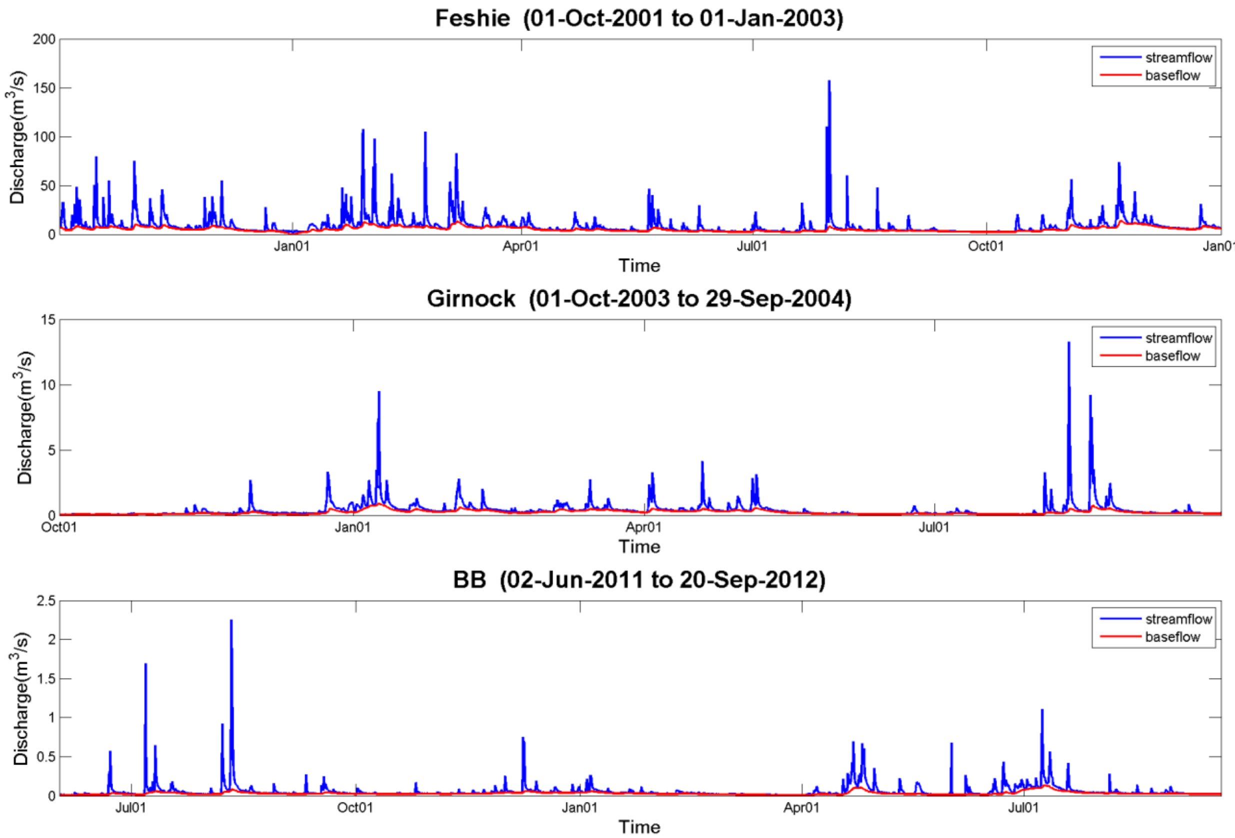


Figure 8. Baseflow separation for the Scottish watersheds

3.2. Runoff event extraction

After subtracting baseflow from streamflow, the remaining component is the baseflow-free hydrograph. The runoff events were extracted from the baseflow-free hydrograph following produces introduced in Methods Section. The baseflow-free hydrograph and extracted runoff events for Granger Creek and Scottish watersheds are shown in Figure 9 and 10. In total, 47 rainfall-runoff events were extracted from Granger Creek over 13 years, with the number of events extracted in each year varying from 0 in 2010 to 11 in 2000. Compared with Granger Creek, the runoff events on the Scottish hydrographs are more frequent, reflecting the increased occurrence of rainfall and a data-set that runs year-round. The number of runoff events extracted from BB, Girnock and Feshie over the course of a single year are 40, 43, and 71 (Table 6). The majority of the runoff events extracted from the four watersheds were single-peak event, but multiple-peak events were not uncommon. The proportion of multiple-peak events in the Scottish watersheds was considerably higher than that in Granger Creek (Table 6).

Table 6. The number of the single- and multi-peak events extracted in the tested watersheds

	BB	**Girnock**	**Feshie**	**Granger**
Single	28 (70%)	23 (54%)	39 (55%)	39 (83%)
Multiple	12 (30%)	20 (46%)	32 (45%)	8 (17%)
Total	40	43	71	47

The runoff event extraction function required a number of input parameters, including PKTHR, RR, BSLP, and ESLP (Table 2). Choosing an appropriate value of each parameter strongly influences the results, yet is subjective and based on user decisions. For each parameter, a range of values were implemented (see Discussion section for the influence of this range of the output) and for the purpose of evaluation a single value was chosen consistent with user expectation.

Through visually examination, it was found that the hydrograph at Granger Creek contained daily fluctuations, which generated peaks not associated with discrete rainfall events. In order to disregard small peaks not associated with rainfall, a PKTHR was chosen at a relative high value, resulting in only 2% of peaks selected as runoff events. Conversely, the hydrographs for Scottish watersheds exhibited less high-frequency variability, so runoff events appeared more distinct on the hydrograph, resulting in a larger proportion (approximately 15%) of local peaks selected for analysis.

Where PKTHR is the minimum requirement of peak flow for a runoff event selected for analysis, the RR determines the cessation of runoff events. Both PKTHR and RR are related to streamflow magnitude and are set by the user. The value of BSLP and ESLP depend on the requirement to the slope of hydrograph at initial rise and recession cessation. The influence of each parameter on the output is reported in the Discussion section.

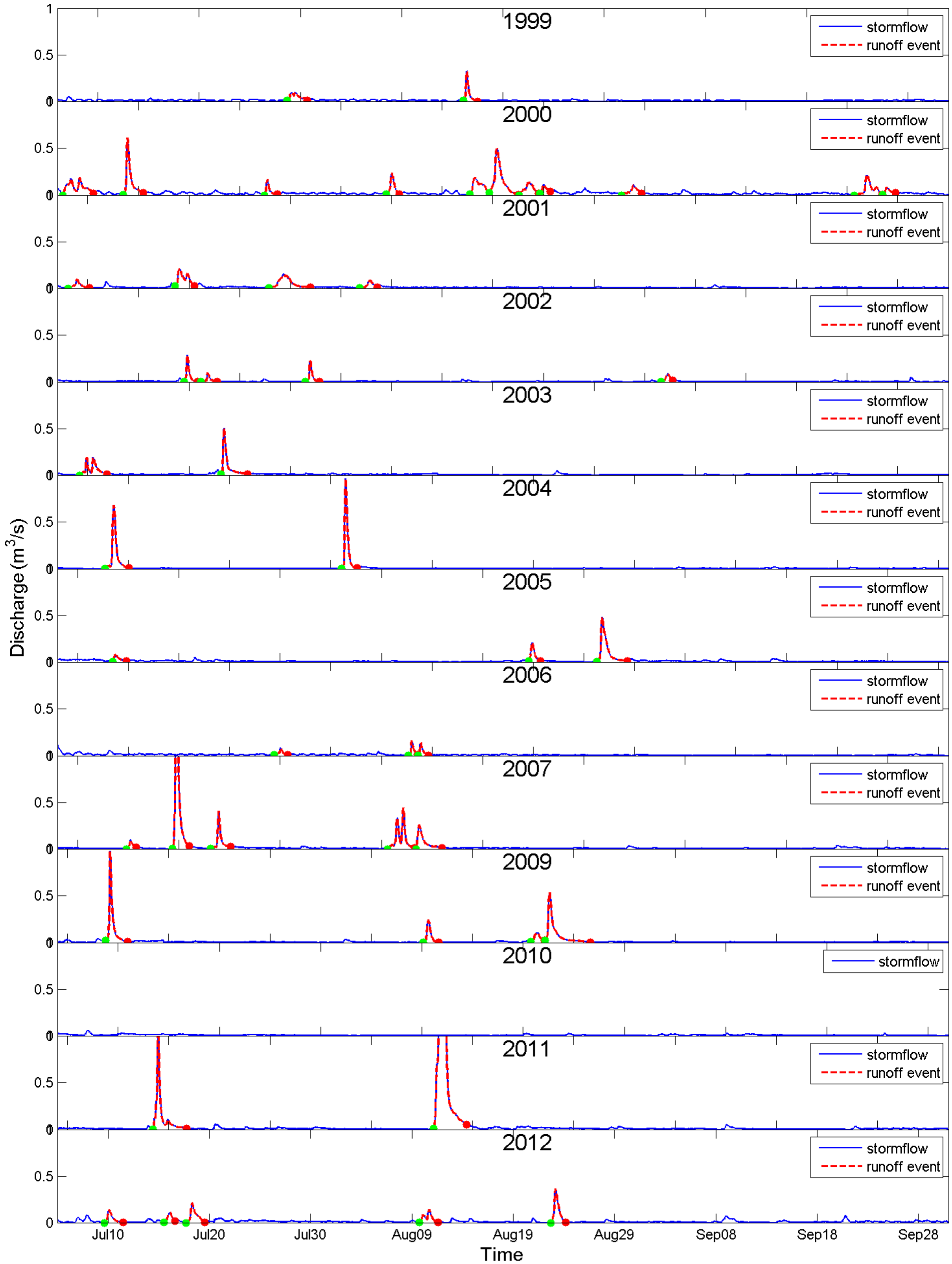


Figure 9. Extracted runoff events for Granger Creek in summer period from 1999 to 2012 (except 2008).

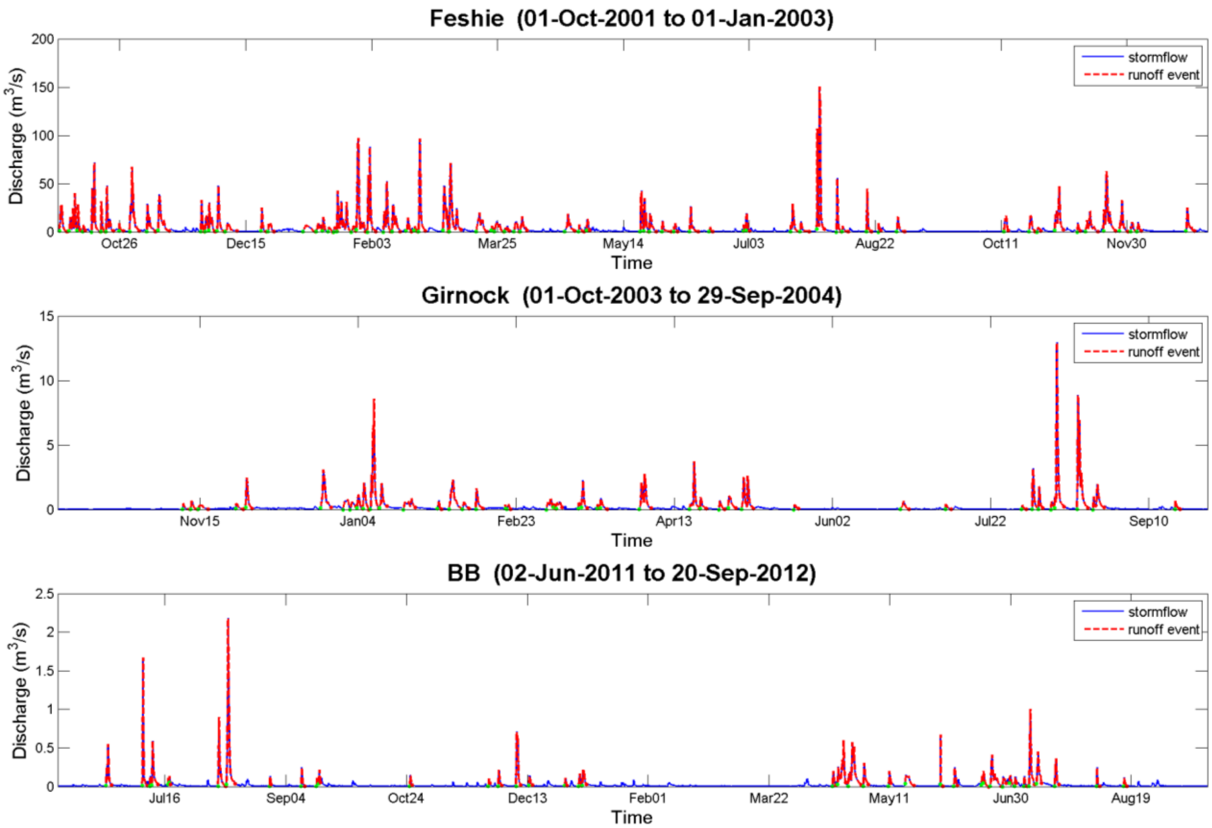


Figure 10. Extracted runoff events for the Scottish watersheds.

3.3. Rainfall-runoff event contraction

After extracting runoff events from the hydrograph, the toolkit associates each runoff event with a specific storm event to form a complete rainfall-runoff event (Figure 11). This procedure involved two parameters, AT and INT (Table 2). Considering the sparse vegetation cover of the tested watersheds, a nominal INT value of 0.5 mm was applied to all watersheds. Ideally, AT should be chosen based on the estimates of response time from pilot studies of watersheds in the same hydroclimatic region. Carey and DeBeer (2008) reported the maximum response time at Granger Creek as 11.25 hours, indicating that rainfall events unlikely appeared more than 11.25 hours before runoff. Therefore, the AT for Granger Creek in this case was set as 12 hours. However, there were no previous studies reporting the estimates of response time for the Scottish watersheds, so the AT was chosen as 10 hours as these watersheds were wetter and more responsive.

The extracted runoff event can have either a single peak (Figure 11a) or multiple peaks (Figure 11b). In some cases, runoff events were not matched with rainfall events in the searching window (Figure 11c). This occurred most often in the Feshie, followed by Girnock, Granger Creek and BB and was attributed to the precipitation gauge missing the rainfall event, which increases in possibility as catchment scale increases. In addition, occasional snowmelt events in the Scottish watersheds may also generate a response where no precipitation is recorded, whereas this period has been removed for Granger Creek. Lastly, there are some events (Figure 11d) where runoff occurred prior to the identified rainfall, calling into question the representativeness of a single precipitation gauge.

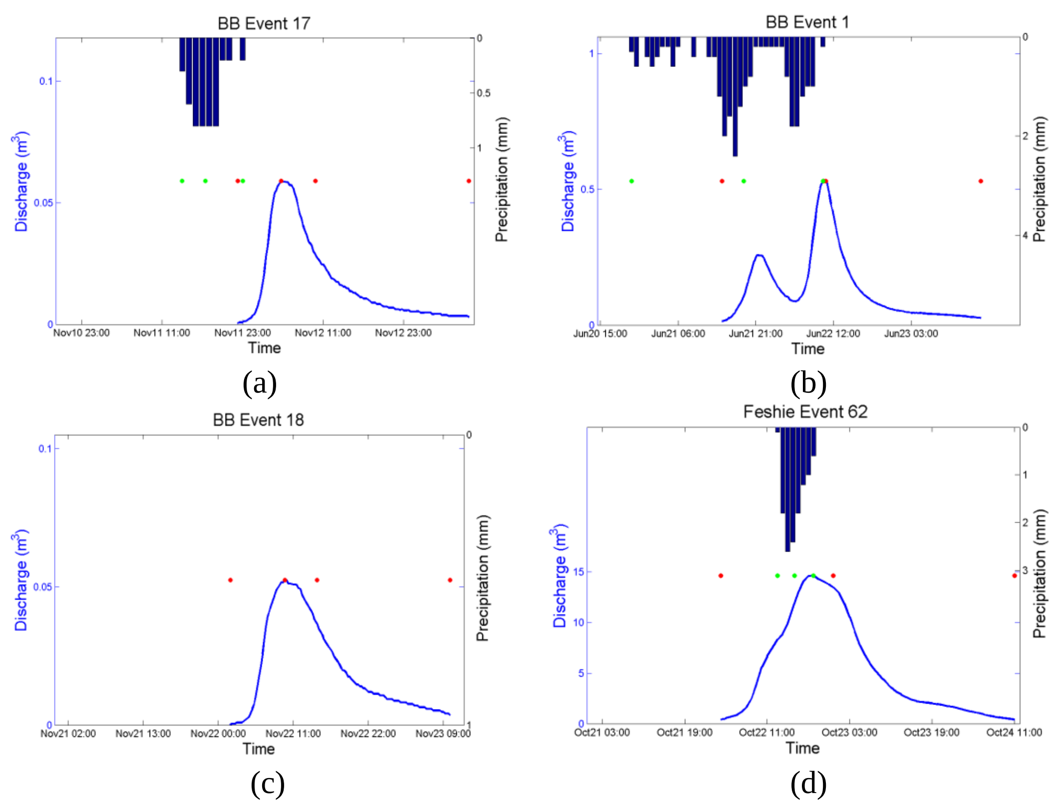
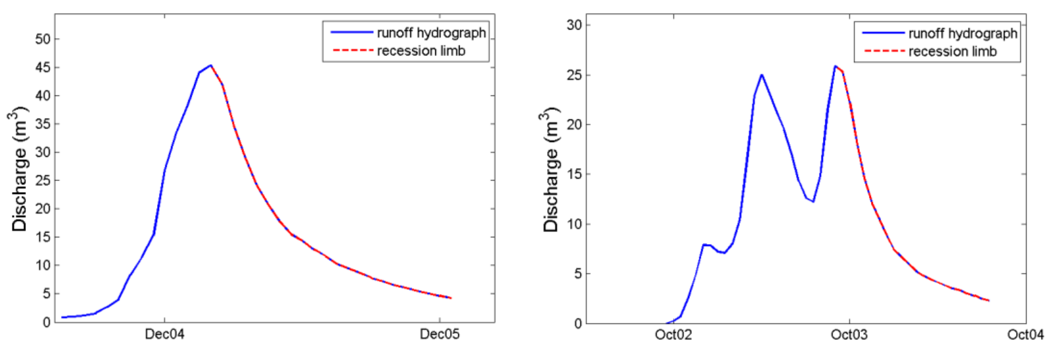


Figure 11. Examples of rainfall-runoff events (extracted from BB and Feshie watersheds). Green points represent time instants for precipitation, and red points are for runoff.

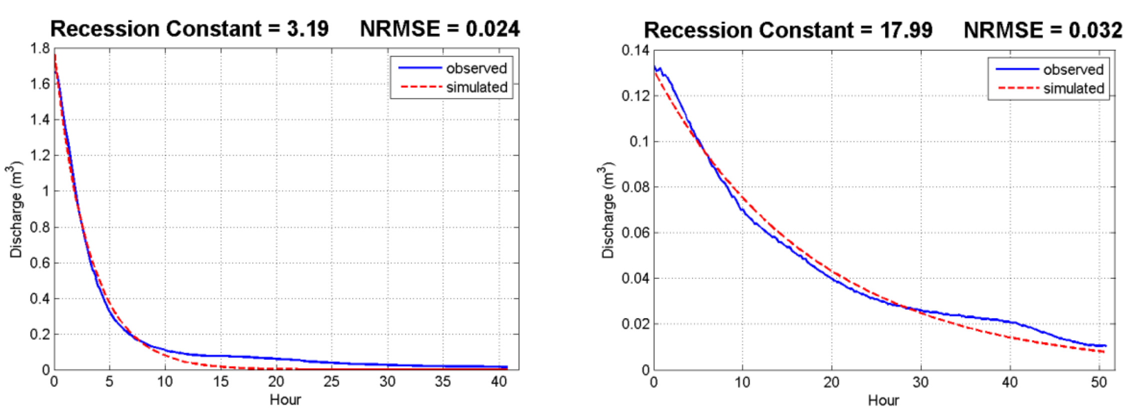
3.4. Recession Constant

Following the identification of runoff events, recession limbs were extracted (Figure 12a,b). For multiple-peak events, the recession limb was assessed following the last peak (Figure 12b). Once extracted, the recession limbs were modeled using Equation 6, and both recession constant and NRMSE were determined. A high recession constant indicates a slow decline, whereas a low recession constant represents a fast recession to pre-event flows (Figure 13). NRMSE was used as a measure of goodness of fit between modeled and observation flows. An example of model fit (Figure 14) indicates the appropriateness of the exponential model for recession parameter estimation.



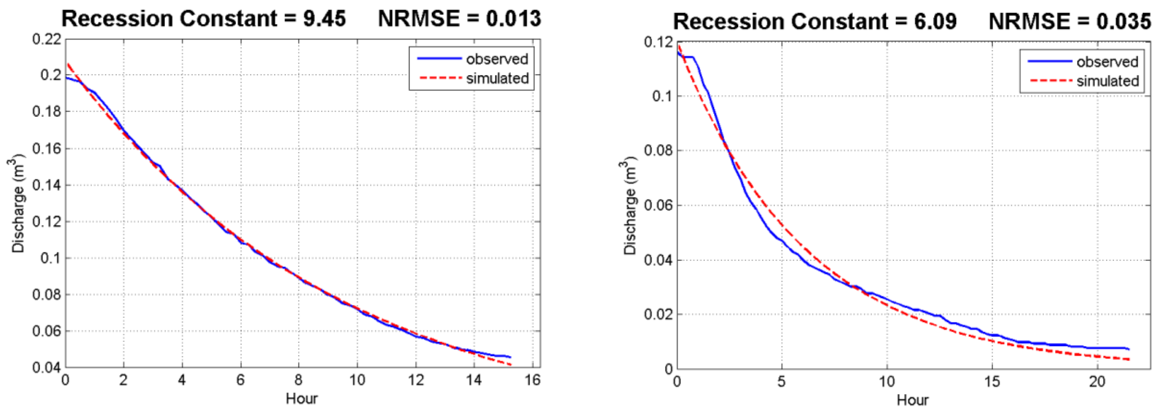
(a) (b)

Figure 12. Example of recession limb for single-peak event (a) and multiple-peak event (b).



(a) (b)

Figure 13. Comparison of recession constant for recession limbs derived from BB (a) and Girnock (b).



(a) (b)

Figure 14. Comparison of NRMSE of recession limbs derived from BB.

The CDFs of recession constant for the four tested watersheds show the variability in recession constant within and among sites (Figure 15). The mean recession constant for Granger Creek was 9.2 hours (Table 7), with BB having a similar mean value of 9.1 hours. The mean for Feshie (10.1 hours) is close to BB and Granger Creek, while Girnock has longer mean recession constant (12.5 hours) than other watersheds. According to the CDF graph, the longer mean for Girnock can be partially attributed to a single large value (36.5 hours), which was much higher than the maximum for the other watersheds. In addition to the mean, the standard deviation for Girnock was largest, indicating greater variability of recession constants. A rank-sum K-S test indicates that the distributions of recession constant in Granger Creek and BB are not significantly different from each other, but are significantly different from other two watersheds, particularly Girnock (Table 8).

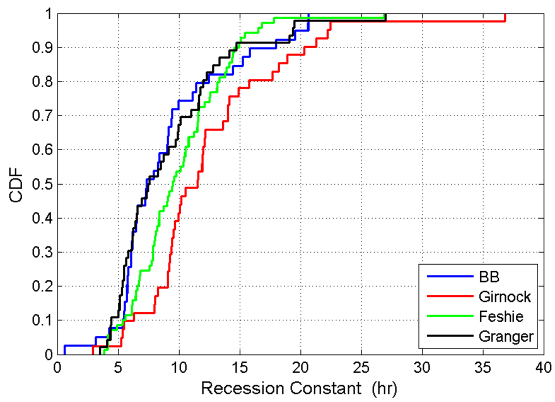


Figure 15. CDF of recession constant for the tested watersheds.

Table 7. Summary of recession constant for the tested watersheds.

	BB	Girnock	Feshie	Granger
Mean	9.1	12.5	10.1	9.2
Median	7.4	11.5	9.5	7.5
Min.	0.6	2.9	3.8	3.5
Max.	20.7	36.8	26.9	27.0
Std.	4.8	6.1	4.0	4.9

Table 8. The P-value for KS test performed on recession constant.

Site	BB	Girnock	Feshie	Granger
BB	-	**0.00**	**0.05**	0.73
Girnock	-	-	0.06	**0.00**
Feshie	-	-	-	**0.04**
Granger	-	-	-	-

3.5. Runoff ratio

Runoff ratio was calculated for each extracted rainfall-runoff event. The runoff ratio is the ratio of total discharge to total precipitation measured in a single rainfall-runoff event, and its value should range from > 0 to 1. However, the absence of rainfall for some runoff event resulted in an infinite value of runoff ratio as the total precipitation was zero. In addition, runoff ratios greater than one were also identified, which could be explained by precipitation gauge under-estimation and/or the potential for snowmelt contribution to flow. Both infinite values and the values larger than one are considered anomalous and were excluded from further analysis. Over half of the runoff events extracted from Feshie and Girnock had invalid runoff ratios (whose value > 1), whereas BB and Granger had only to 20 % invalid events (Table 11 – 14). Therefore, it was speculated that the runoff ratios extracted from small watersheds were likley more reliable due to the higher valid rate.

The mean runoff ratio for Granger Creek was 0.25, which was less than BB (0.31) and Girnock (0.35). The Feshie has a much higher mean runoff ratio (0.61) than other watersheds (Table 9), and a distinct CDF of runoff ratios extracted (Figure 16). The p-values in K-S test indicate that there are significant differences in runoff ratio between Feshie and the other watersheds (Table 10). In addition, it is also found that Girnock is significantly different from Granger Creek.

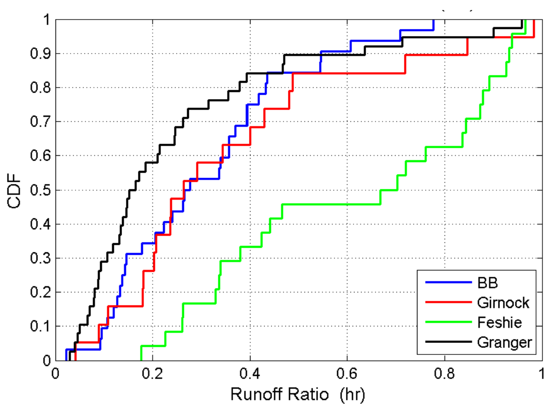


Figure 16. CDF of runoff ratio for the tested watersheds.

Table 9. Summary of runoff ratio for the tested watersheds.

	BB	Girnock	Feshie	Granger
Mean	0.31	0.35	0.61	0.25
Median	0.27	0.26	0.69	0.16
Min.	0.02	0.04	0.18	0.03
Max.	0.78	0.98	0.97	0.96
Std.	0.19	0.26	0.28	0.23

Table 10. The P-value for KS test performed on runoff ratios.

Site	BB	Girnock	Feshie	Granger
BB	-	0.72	**0.00**	0.12
Girnock	-	-	**0.04**	**0.03**
Feshie	-	-	-	**0.00**
Granger	-	-	-	-

3.6. Time characteristics

The seven time instants were identified on the hydrograph and hyetograph for each event (see green and red points on Figure 11), and time characteristics observed. Normally, time characteristics should be positive, but null and negative values were calculated. The null values result from absence of rainfall, as well as the negative values resulting from runoff features appearing before rainfall features. For example, the start of runoff in some cases occurred earlier than the start of rainfall, which results in negative values for T_{LR}. Both null and negative values were considered anomalous and excluded from analysis.

Valid rate refers to the proportion of valid values in for the total number time characteristics determined from rainfall-runoff events. The valid rates were variable for different time characteristics and among the watersheds (Table 11 – 14). T_b and T_r had a valid rate of 100% for all watersheds, yet other time characteristics had invalid values, with T_{LR} always lower than others (Table 11 – 14). Moreover, the valid rates of time characteristics for Girnock and Feshie were on average lower than those for BB and Granger Creek. Therefore, it suggested that this toolkit probably provided more reliable results when working on small-scale watersheds.

Table 11. The total number and valid number of characteristics at BB

	Runoff Ratio	Recession Constant	T_w	T_{LR}	T_r	T_{LP}	T_{LPC}	T_{LC}	T_b	T_c
Total	40	40	40	40	40	40	40	40	40	40
Valid	32	40	38	37	40	38	37	38	40	38
Valid Rate (%)	80.0	100	95.0	92.5	100.0	95.0	92.5	95.0	100.0	95.0

Table 12. The total number and valid number of characteristics at Girnock

	Runoff Ratio	Recession Constant	T_w	T_{LR}	T_r	T_{LP}	T_{LPC}	T_{LC}	T_b	T_c
Total	43	43	43	43	43	43	43	43	43	43
Valid	19	43	31	21	43	30	30	27	43	31
Valid Rate (%)	44.2	100	72.1	48.8	100.0	69.8	69.8	62.8	100.0	72.1

Table 13. The total number and valid number of characteristics at Feshie

	Runoff Ratio	Recession Constant	T_w	T_{LR}	T_r	T_{LP}	T_{LPC}	T_{LC}	T_b	T_c
Total	71	71	71	71	71	71	71	71	71	71
Valid	24	71	57	33	71	52	46	54	71	57
Valid Rate (%)	33.8	100	80.3	46.5	100.0	73.2	64.8	76.1	100.0	80.3

Table 14. The total number and valid number of characteristics at Granger Creek

	Runoff Ratio	Recession Constant	T_w	T_{LR}	T_r	T_{LP}	T_{LPC}	T_{LC}	T_b	T_c
Total	47	47	47	47	47	47	47	47	47	47
Valid	38	47	40	37	47	40	38	40	47	40
Valid Rate (%)	80.9	100	85.1	78.7	100.0	85.1	80.9	85.1	100.0	85.1

The means of duration of net rainfall (T_w) for Granger Creek is 14.2 hours, whereas the means for the Scottish watersheds are slightly longer than Granger Creek, ranging from 16.5 hours at Girnock to 18.7 hours at Feshie (Table 15). Moreover, Granger Creek has a much smaller standard deviation than other watersheds. The CDFs of the tested watersheds are relatively similar before 90%, but the last 10% values of T_w in Scottish watersheds are much more variable than those in Granger Creek (Figure 17). In other words, Scottish watersheds have more extensive ranges of T_w than Granger Creek. In addition, the p-values in K-S test indicate that T_w in Granger Creek and Girnock are significantly different from each other (Table 16).

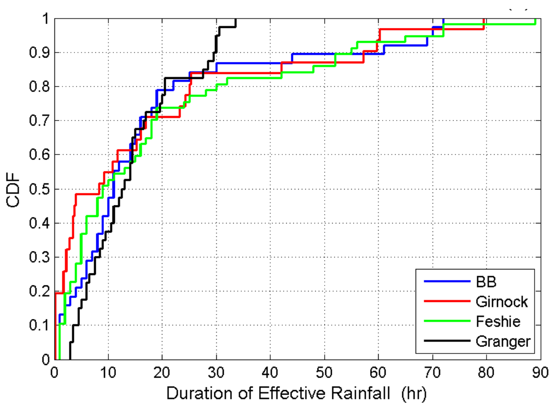


Figure 17. CDF of T_w for the tested watersheds.

Table 15. Summary of T_w for the tested watersheds.

	BB	Girnock	Feshie	Granger
Mean	17.4	16.5	18.7	14.2
Median	11.0	8.2	9.0	12.8
Min.	1.0	0.2	1.0	3.0
Max.	72.0	79.5	89.0	33.5
Std.	19.7	21.4	21.6	8.9

Table 16. The P-value for KS test performed on T_w.

Site	BB	Girnock	Feshie	Granger
BB	-	0.09	0.62	0.72
Girnock	-	-	0.27	**0.01**
Feshie	-	-	-	0.20
Granger	-	-	-	-

The time characteristic of time base (T_b) represents the duration of a runoff event. The mean of T_b for Granger Creek is 45 hours (Table 17). BB has a similar mean (43.3 hours) with Granger Creek, while the mean for Girnock (53.2 hours) and Feshie (64.5 hours) are longer. Among the Scottish watersheds, T_b exhibits a trend that the means increase with the watershed area (Table 17). On the CDF graph, the majority of Girnock is on the right of BB and Granger Creek, as well as the line for Feshie is constantly on the right of Girnock (Figure 18). A series of KS tests show that T_b in Feshie is significantly different from other three (Table 18). In addition, a significant difference was also detected between BB and Girnock.

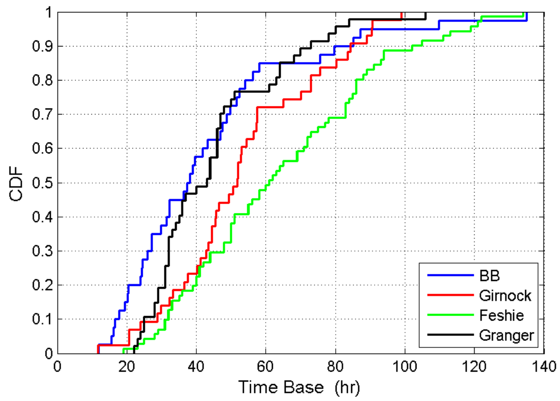


Figure 18. CDF of T_b for the tested watersheds.

Table 17. Summary of T_b for the tested watersheds.

	BB	Girnock	Feshie	Granger
Mean	43.3	53.2	64.5	45.1
Median	37.8	51.8	61.0	43.0
Min.	12.0	11.8	19.0	22.0
Max.	135.0	99.0	134.0	106.0
Std.	26.7	21.0	27.4	18.7

Table 18. The P-value for KS test performed on T_b.

Site	BB	Girnock	Feshie	Granger
BB	-	**0.02**	**0.00**	0.15
Girnock	-	-	**0.04**	0.06
Feshie	-	-	-	**0.00**
Granger	-	-	-	-

Response lag (T_{LR}) refers to the delay between the start of rainfall and the start of runoff. In general, it is the shortest time characteristic. Mean T_{LR} for the tested watersheds ranged from 2.5 hours at Feshie to 4.5 hours at BB (Table 19). The pattern of CDF for T_{LR} is distinct from other time characteristics (Figure 20). It is interesting to note that a significant number of T_{LR} values at Granger Creek and Feshie are zero. The upper limit of value (maximum) was directly controlled by the value chosen for parameter AT. Although tested watersheds exhibit very different patterns on the CDF graph, the Feshie and Girnock is the only pair with p-value under critical value (0.05), suggesting they are significantly different form each other (Table 20).

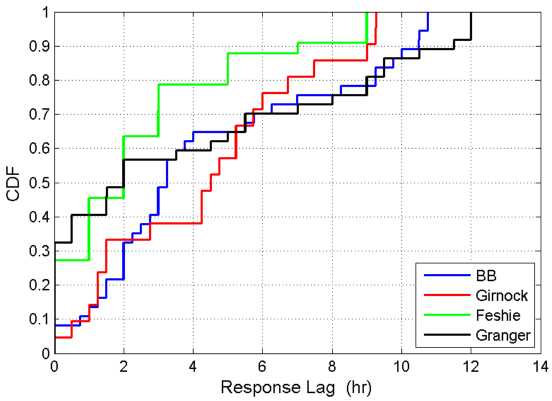


Figure 19. CDF of T_{LR} for the tested watersheds.

Table 19. Summary of T_{LR} for the tested watersheds.

	BB	Girnock	Feshie	Granger
Mean	4.5	4.4	2.5	3.9
Median	3.2	4.5	2.0	2.0
Min.	0.0	0.0	0.0	0.0
Max.	10.7	9.3	9.0	12.0
Std.	3.5	3.0	2.7	4.4

Table 20. The P-value for KS test performed on T_{LR}.

Site	BB	Girnock	Feshie	Granger
BB	-	0.29	0.06	0.04
Girnock	-	-	**0.03**	0.15
Feshie	-	-	-	0.31
Granger	-	-	-	-

Similar to T_{LR}, time of concentration (T_c) is the time delay between the end of rainfall and the end of runoff. The mean of T_c for Granger Creek was 34.6 hours, and BB has a shorter mean (30.3 hours) than Granger Creek, while Girnock and Feshie have longer mean, at 37.6 hours and 44.8 hours respectively (Table 21). Similar with T_b, there is a trend for T_c at Scottish watersheds that the mean increased with watersheds area. The p-values in KS tests indicate that the distribution of the T_c values at Feshie is significantly different from that at BB and Granger Creek (Table 22).

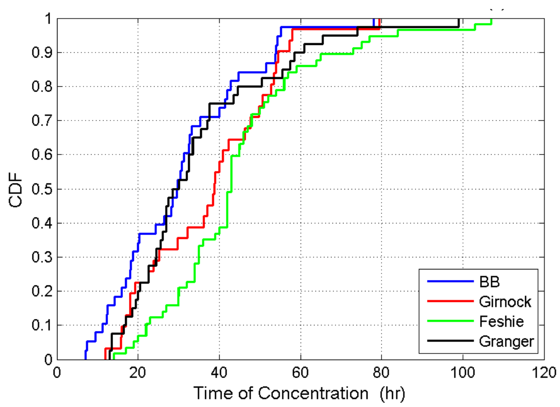


Figure 20. CDF of T_c for the tested watersheds.

Table 21. Summary of T_c for the tested watersheds.

	BB	Girnock	Feshie	Granger
Mean	30.3	37.6	44.8	34.6
Median	29.6	38.8	43.0	29.3
Min.	7.0	12.0	14.0	13.0
Max.	78.0	79.5	107.0	99.0
Std.	16.1	16.3	18.9	18.4

Table 22. The P-value for KS test performed on T_c.

Site	BB	Girnock	Feshie	Granger
BB	-	0.06	**0.00**	0.64
Girnock	-	-	0.25	0.09
Feshie	-	-	-	**0.00**
Granger	-	-	-	-

Centroid lag (T_{LC}) represents the time between the centroid of mass of the water input to the centroid of mass of runoff. The mean of T_{LC} for the tested watersheds are quite similar, ranging from 12.5 hours at BB to 14.8 hours at Girnock (Table 23). However, the standard deviation at BB is much smaller than others, indicating that the values of T_{LC} at BB were less variable. The pattern of CDFs for tested watersheds are quite similar (Figure 21), and the results of KS tests indicated that there was a significant difference between BB and Girnock (Table 24).

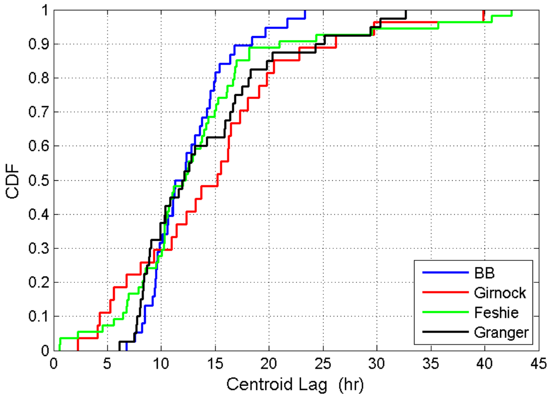


Figure 21. CDF of T_{LC} for the tested watersheds.

Table 23. Summary of T_{LC} for the tested watersheds.

	BB	Girnock	Feshie	Granger
Mean	12.5	14.8	13.5	14.1
Median	11.7	15.2	12.1	12.0
Min.	6.8	2.2	0.6	6.1
Max.	23.3	39.8	42.5	32.7
Std.	3.8	8.5	8.3	6.7

Table 24. The P-value for KS test performed on T_{LC}.

Site	BB	Girnock	Feshie	Granger
BB	-	**0.05**	0.69	0.27
Girnock	-	-	0.24	0.47
Feshie	-	-	-	0.68
Granger	-	-	-	-

Centroid lag-to-peak (T_{LPC}), similar with T_{LC}, represents the time between the centroid of mass of rainfall and peak of runoff. Typically, runoff events have longer recession limb than rising limb, resulting in their centroid later than their time of peak flow. For that reason, the T_{LPC} for a certain runoff event is typically shorter than the corresponding T_{LC}, and this can be used to verify the correctness of calculated time characteristics. In this case, it was found that mean T_{LPC} for each watershed was shorter than their mean T_{LC} (Table 23 and 25). The mean of T_{LPC} at Granger Creek is 10.3 hours (Table 25). Among the Scottish watersheds, BB has the shortest mean (8.0 hour), and the means for Feshie and Girnock are almost the same (9.5 and 9.3 hours respectively). No significant difference in centroid of lag-to-peak was detected in KS tests (Table 26).

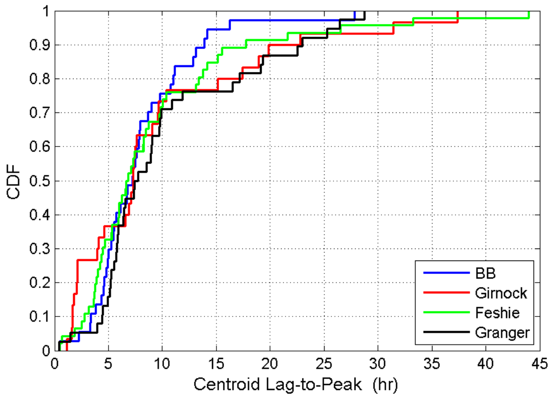


Figure 22. CDF of T_{LPC} for the tested watersheds.

Table 25. Summary of T_{LPC} for the tested watersheds.

	BB	Girnock	Feshie	Granger
Mean	8.0	9.5	9.3	10.3
Median	7.3	7.3	6.7	7.6
Min.	0.5	1.1	0.5	0.4
Max.	27.8	37.4	44.0	28.8
Std.	4.9	9.0	8.3	7.3

Table 26. The P-value for KS test performed on T_{LPC}.

Site	BB	Girnock	Feshie	Granger
BB	-	0.30	0.70	0.30
Girnock	-	-	0.45	0.23
Feshie	-	-	-	0.30
Granger	-	-	-	-

Lag-to-peak (T_{LP}) is the delay between the start of rainfall to the peak of runoff. The means of T_{LP} for the tested watershed are very close to each other, ranging from 15.2 hours at Feshie to 16.9 hours at Girnock (Table 27). In addition, the watersheds show similar patterns on CDF graph, but Granger Creek has a shorter range in the value of T_{LP}, which is corroborated by the smaller deviation at Granger Creek (Figure 23 and Table 27). No significant difference was detected in KS tests (Table 28).

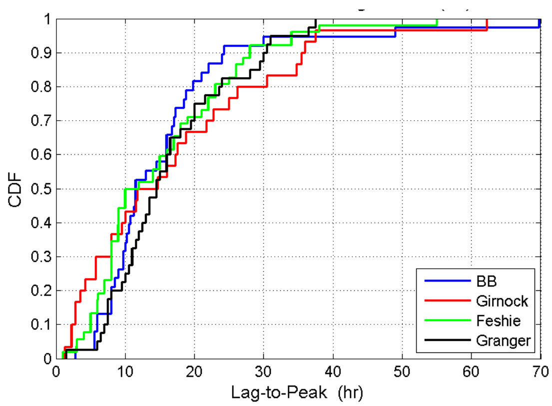


Figure 23. CDF of T_{LP} for the tested watersheds.

Table 27. Summary of T_{LP} for the tested watersheds.

	BB	Girnock	Feshie	Granger
Mean	15.7	16.9	15.2	16.5
Median	11.5	13.2	11.0	14.5
Min.	2.7	1.3	1.0	1.5
Max.	69.8	62.3	55.0	37.5
Std.	12.3	14.3	10.7	8.8

Table 28. The P-value for KS test performed on T_{LP}.

Site	BB	Girnock	Feshie	Granger
BB	-	0.39	0.48	0.41
Girnock	-	-	0.68	0.15
Feshie	-	-	-	0.12
Granger	-	-	-	-

The mean of time of rise (T_r) at Granger Creek is 13.3 hours, and it has the smallest standard deviation (7.8 hours) among tested watersheds (Table 29). Besides, BB has the shortest mean (11.4 hours), which is consistent with the comparison in T_b. Although the means for Feshie (16.9 hours) and Girnock (16.3 hours) are very similar, their p-value in KS test indicated that their CDFs were significantly different (Figure 24 and Table 30). In addition, significant differences were also detected between BB and Feshie and between BB and Granger. This can be corroborated by the CDF of BB that shows a dissimilar pattern with other CDFs (Figure 24).

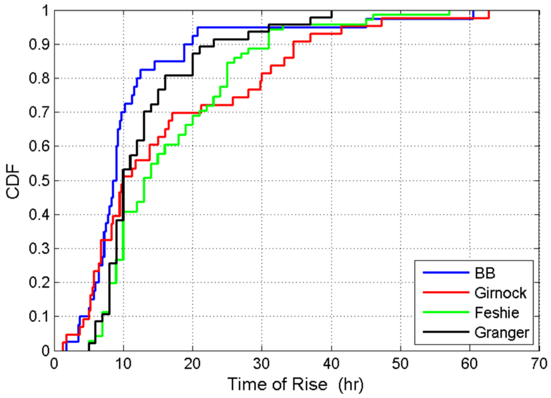


Figure 24. CDF of T_r for the tested watersheds.

Table 29. Summary of T_r for the tested watersheds.

	BB	Girnock	Feshie	Granger
Mean	11.4	16.6	16.9	13.3
Median	8.8	10.0	13.0	10.0
Min.	1.7	1.2	5.0	5.0
Max.	60.5	62.8	57.0	40.0
Std.	10.7	14.0	10.3	7.8

Table 30. The P-value for KS test performed on T_r.

Site	BB	Girnock	Feshie	Granger
BB	-	0.11	**0.00**	**0.03**
Girnock	-	-	**0.03**	0.15
Feshie	-	-	-	0.20
Granger	-	-	-	-

4. Discussion

4.1. Sensitivity Analysis

The performance of this toolkit is largely dependent on the selection of input parameter values, as outputs are variable depending upon the selection of key parameters by the user. Therefore, finding a set of parameter values appropriate for the target watersheds is extremely important to produce reliable, accurate and comparable output characteristics. In this toolkit, most input parameters are 'graphical' rather than 'physical' parameters, indicating they do not in most cases have specific physical (or hydrological) meaning. Accordingly, detailed information regarding watershed conditions (e.g. geology, soil type, and land cover type) are not required for using this toolkit, although they may be considered. The first way to determine if the value of an input parameter is appropriate is through visual examination. With the appropriate input parameters, the extracted runoff events should appear in accordance or similar to the user's expectation. If the appearance of extracted runoff differed greatly from the user's expectation, it suggested that adjusting the input parameters is necessary. As such, it is important to understand how every input parameter affects the appearance and characteristics of the extracted runoff events. To assess the influence of input parameter selection on the results, a sensitivity analysis to each input parameter was implemented, aiming to provide basic understanding to the effect of each parameter on appearance of runoff and the value of output characteristics. The conclusions from the sensitivity analysis provide a useful reference for deciding the value of input parameters.

The performance of this hydrograph toolkit varied among the tested watersheds. A primary indicator for evaluating the performance was the valid rate of the output characteristics. Valid characteristics referred to the characteristics with a value within the reasonable range (for example, the reasonable range of runoff ratio is from >0 to 1), and valid rate was the proportion of valid characteristics. For a test watershed, the valid rates of different output characteristics differed, and the same output characteristic had different valid rates among the tested watersheds (Table 11-14). Recession constant, T_b, and T_r maintained at 100% valid rate, whereas the valid rates for other characteristics, particularly runoff ratio and T_{LR}, were variable among the watersheds. For example, Feshie and Girnock had a poor valid rate for runoff ratio, both less than 50%.

Comparing the tested watersheds, BB in general had a higher valid rate than the other three watersheds, suggesting that the toolkit performed better there. Therefore, BB was selected as the target watershed to implement sensitivity test for the input parameters. Each input parameter in this toolkit was tested separately to understand how the input parameter affects the appearance of rainfall and runoff events as well as the output characteristics.

In each sensitivity test, the value of a select input parameter was varied in a plausible range (Table 31), and other parameters remained constant at their default setting (see Table 5 in Results section). Then, the variation of runoff appearance and output characteristics were related to the input parameter changes, and the effects of each input parameter on output characteristics were identified.

Table 31. The tested values of input parameters in sensitivity analysis

	Range	Interval (ratio)	Number of tested values
β	0.990-0.999	0.001	10
PKTHR (m^3/s)	0.08-0.25	0.01	18
RR (m^3/s)	0.01-0.1	0.005	19
BSLP ($m^3 \cdot s^{-1} \cdot h^{-1}$)	10^{-6}-10^{-2}	10	5
ESLP ($m^3 \cdot s^{-1} \cdot h^{-1}$)	10^{-6}-10^{-2}	10	5
AT (hour)	1-24	1	24
INT (mm)	0-5	0.2	25

4.1.1. Filter coefficient (β)

β was the only user-defined parameter for separating baseflow, and it largely controlled the partitioning of baseflow and stormflow from the streamflow record. In general, the proportion of baseflow in streamflow decreased with an increased β. Based on values reported in the literature (Nathan & McMahon, 1990; Arnold and Allen, 1999; Eckhardt, 2008) and those deemed most appropriate for the test watersheds, the value of β was selected within the range from 0.900 to 0.999. In the case of BB, the optimal value for of β was considered 0.995. In the sensitivity analysis, 10 values of β within the range from 0.990 to 0.999 were tested, and the variations of the output characteristics were associated with the change of β (Figure 25).

As previously mentioned, β predominantly controls the proportions of baseflow in streamflow. With increased β, the baseflow dropped to a lower level on hydrograph (Figure 25), as well as its volume showed a persistent reduction (Figure 26). Consequently, the volumes of stormflow increased as compensation to baseflow reduction, resulting in the increase in the mean runoff ratio from 28.2% to 33.4% (Figure 27). In addition, the mean of recession constant rose from 7.8 to 12.9 hours (Figure 28), which is attributed to the delay in the end point of runoff events and it was determined that runoff events had longer recession limb after increasing β (Figure 29). With the end point of runoff extended, T_b and T_c, showed a marked growth, while other time characteristic remained largely unchanged (Figure 30).

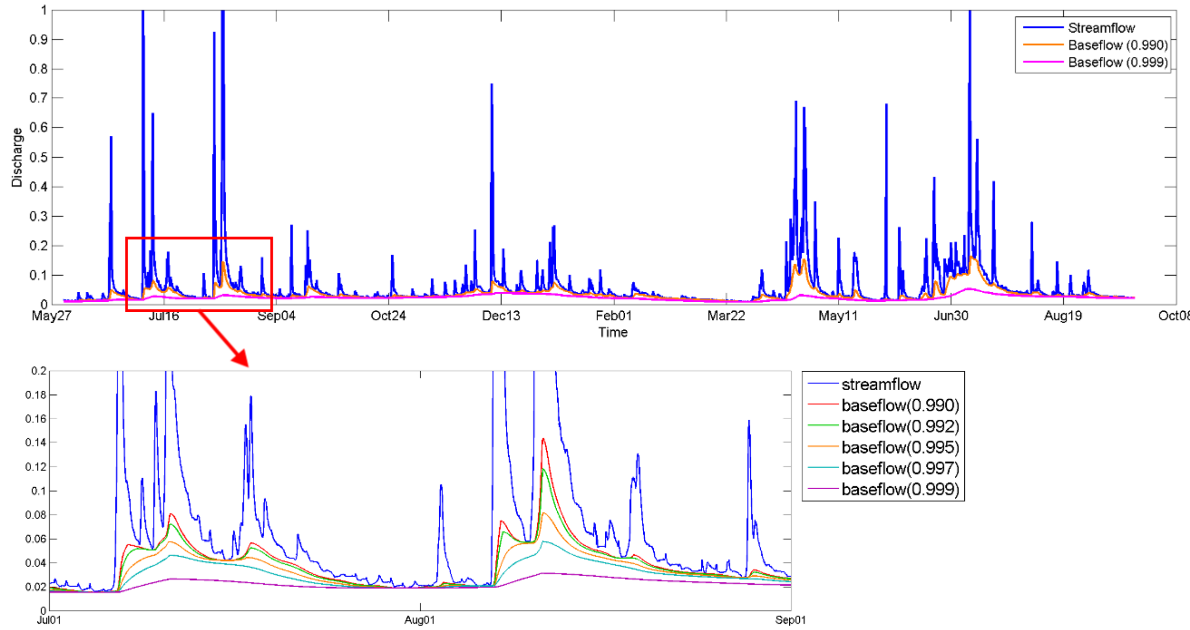


Figure 25. The baseflows generated by the β of 0.990 and 0.999 for BB

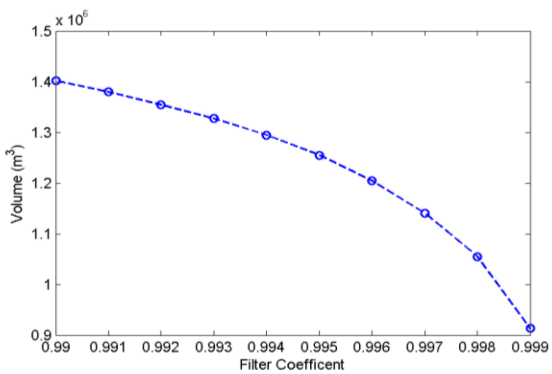


Figure 26. The variation of baseflow volume with the change of β

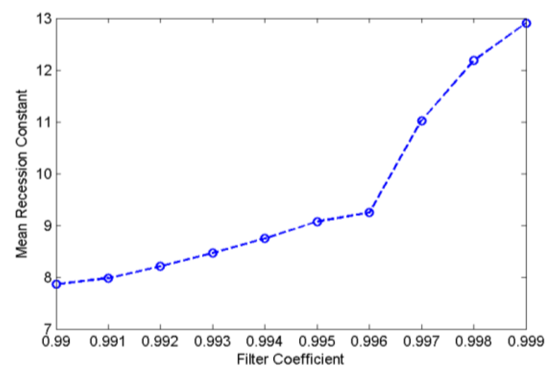


Figure 28. The variation of mean recession constant with the change of β

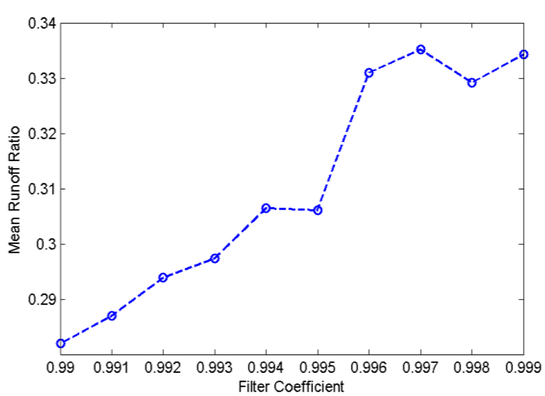


Figure 27. The variation of mean runoff ratio with the change of β

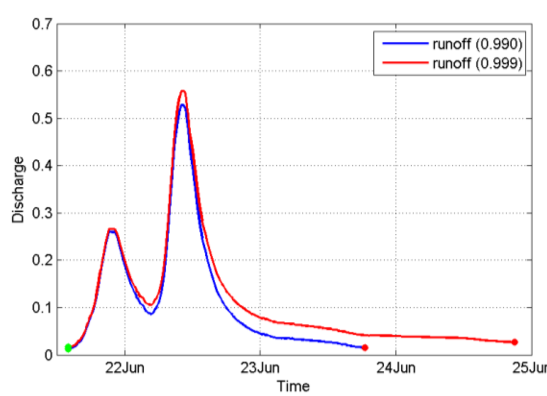


Figure 29. Comparison of runoff events extracted by β of 0.990 and 0.999

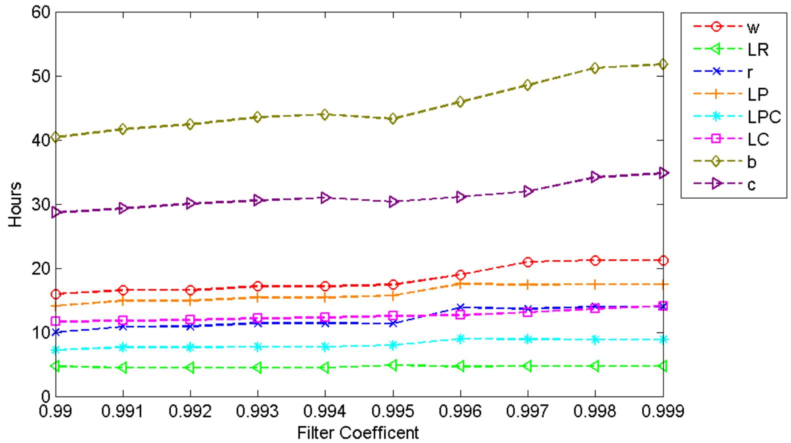


Figure 30. The variation of means of time characteristics with the change of β

4.1.2. Peak discharge threshold (PKTHR)

PKTHR ensures the runoff events selected in analysis with a distinct peak. In general, with increased PKTHR, there were less runoff events identified and extracted for analysis. In this sensitivity test, values of PKTHR were selected within the range from 0.08 to 0.25 (m^3/s). A reasonable value for PKTHR should be higher than RR. Considering RR in default setting is 0.05 (m^3/s), the minimum test values for PKTHR was selected slightly higher than that, as 0.08 (m^3/s). It is important to note that the PKTHR applies to the baseflow-free hydrograph, not the original streamflow hydrograph. With increased PKTHR, the number of extracted events showed a persistent decrease, from 46 to 14 (Figure 31). Meanwhile, the mean peak flow of runoff events unsurprisingly increased from 0.34 to 0.78 (m^3/s) (Figure 32). In addition, runoff ratio increased by up to 16.8%, suggesting that high-magnitude runoff events had a higher runoff ratio. On the other hand, the recession constant remained virtually unchanged in the test. Furthermore, the increase in T_w and T_b (Figure 33) indicated that high-magnitude runoff events tended to be caused by long storm events and last longer than low-peak events. The extension of runoff duration also explained the increase in T_r and in T_c. In addition, as the searching window was extended with runoff duration, more rainfall records could be included in events, resulting in the increase of T_w. No notable change was detected from other time characteristics.

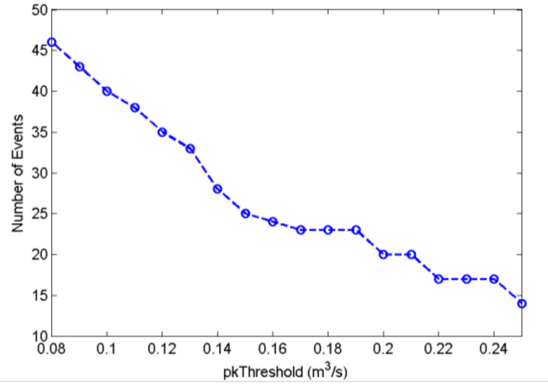


Figure 31. The variation of number of extracted runoff events with PKTHR.

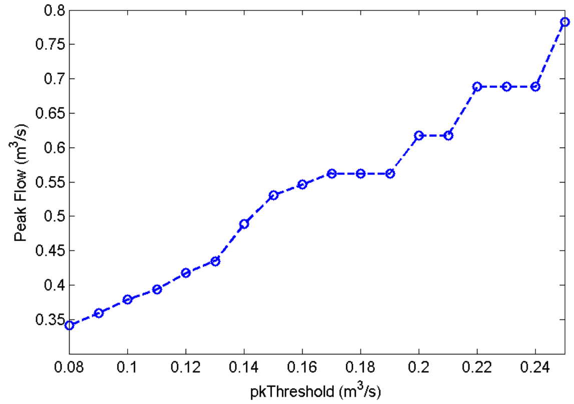


Figure 32. The variation of mean peak flow with PKTHR.

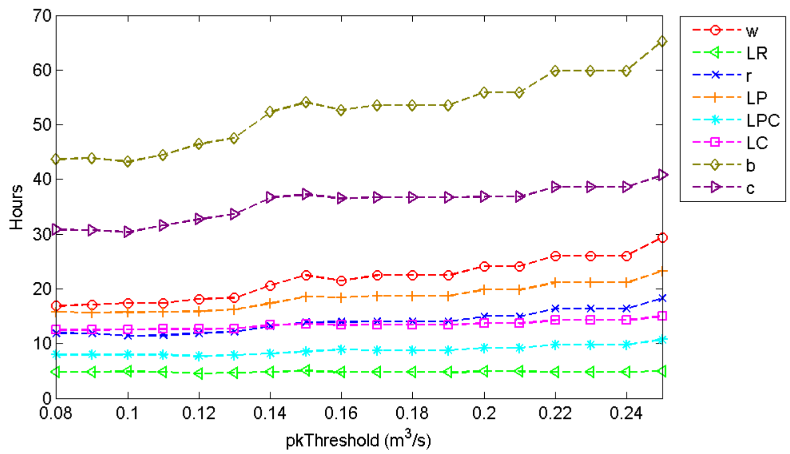
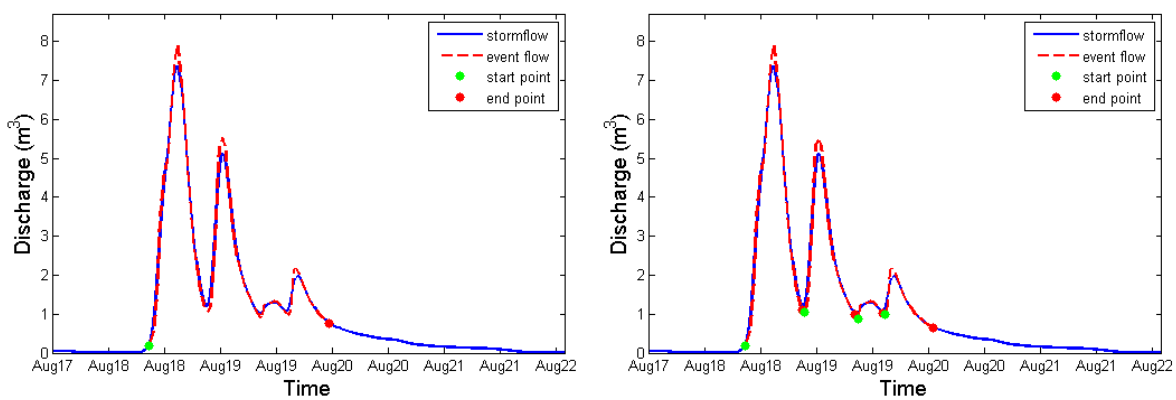


Figure 33. The variation of means of time characteristics with the change of PKTHR

4.1.3. Return ratio (RR)

The value of RR strongly affected the appearance of extracted runoff events. More specifically, it controlled whether events were a single multiple peak or a several single peak event, as only below the chosen value of RR will a local minimum be selected as the end point of runoff. Therefore, increasing the value of RR resulted in more local minimums being included, and consequently this increased the number of runoff events generated. An example of breaking down multiple-peak into several single-peak events by increasing the value of RR is provided in Figure 34. In this sensitivity test, a growth in the number of extracted runoff events, from 33 to 46, was observed with increased RR. At the same time, the ratio of the proportion of single-peak events rose considerably from 16.7% to 82.8%, as well as the average number of peaks in an individual event decreased from 4.7 to 1.2. As many longer events were broken down into shorter events, the values for most time characteristics substantially declined (Figure 35), yet an increase in T_{LR} was observed. It was assumed that breaking down multiple-peak events could generate many adjacent runoff events, whose corresponding rainfall events were also close to each other. Therefore, it was possible that the rainfall records in the previous rainfall event were included in the searching window of the later runoff event, resulting in the start of rainfall mistakenly advanced. Consequently, advancement in start of rainfall increased the T_{LR}. In addition, the mean recession constant showed a slight decrease. However, runoff ratios remained largely the same in the test, indicating that it was insensitive to the change of RR.



(a) (b)

Figure 34. Breaking down a runoff event by increasing RR from 0.1 (a) to 0.25 (b), at Girnock.

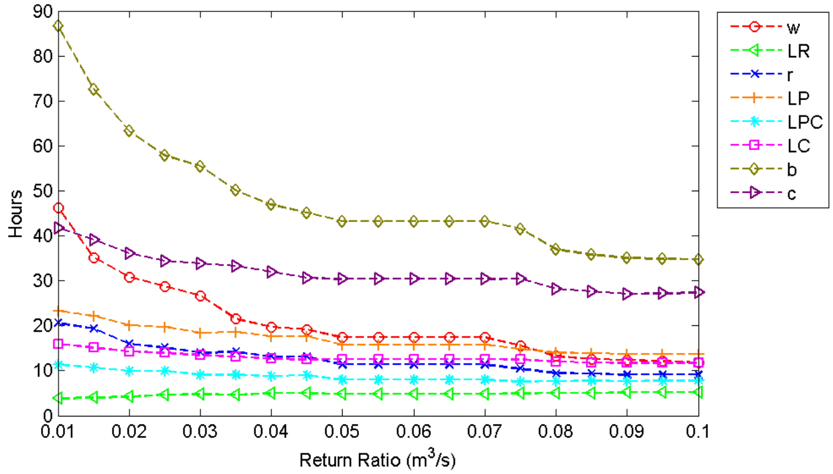


Figure 35. The variation of means of time characteristics with the change of RR

4.1.4. Beginning slope (BSLP) and ending slope (ESLP)

The BSLP was used to move a start point of runoff from a local minimum to a more exact (or objective) position. In this case, the appropriate position was defined where hydrograph exhibited a significant rise. The ESLP had a similar procedure for the end point of runoff. Therefore, the increase of BSLP postponed the start of runoff, as well as increasing ESLP advanced the end of runoff.

In this sensitivity test, the change of BSLP only affected the time characteristics related with the start of runoff, such as T_b and T_r (Figure 36). Their values showed a moderate decrease with increased BSLP. In addition, it was of note that the mean T_w and T_{LP} also slightly decreased. The delay of start point forward resulted in the searching window for rainfall event moving backward, so the start of rainfall was postponed. Furthermore, runoff ratio appears to be insensitive to the change of BSLP, with a change of only 0.8%. Recession constant was not influenced by the BSLP.

Although ESLP was tested by the same values with BSLP, the change of ESLP more strongly influenced output characteristics. The time characteristics directly associated with the end of runoff, such as T_b and T_c, decreased considerably with increased ESLP (Figure 37). In addition, advancing end of runoff also affected the runoff centroid, resulting in a moderate decrease in T_{LPC}. Moreover, as the searching window shrank with runoff duration, there was a slight decrease in T_w. Furthermore, the mean recession constant decreased from 9.2 to 7.4 hours. Additionally, the mean runoff ratio showed a greater change than it did in the test of BSLP, decreasing ~ 2.5%.

Through comparing the sensitivity test for BSLP and ESLP with the same change, the output characteristics responded more notably to the change of ESLP. As the falling limb of the hydrograph is typically more gradual than the rising limb, it was more sensitive to a change in slope.

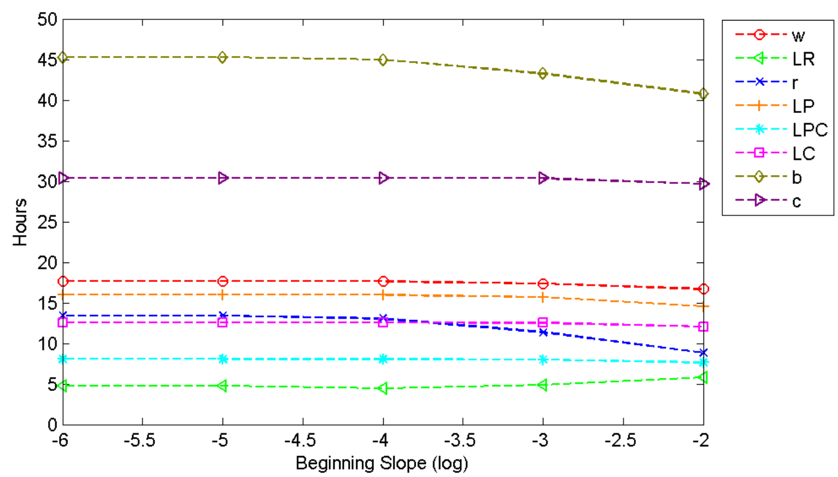


Figure 36. The variation of means of time characteristics with the change of BSLP

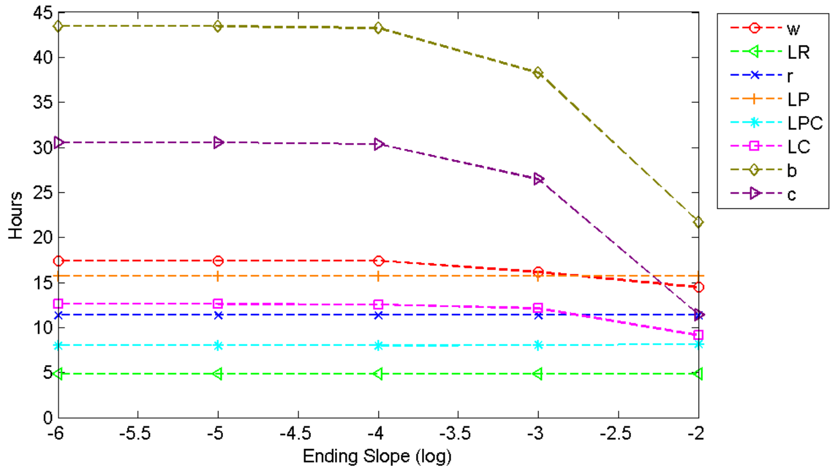


Figure 37. The variation of means of time characteristics with the change of ESLP

4.1.5. Advancing time (AT)

AT predominantly controlled the size of searching window for a rainfall event. In this method, the searching window was defined spanning from *n* (AT) hours before the start of runoff to the last peak flow of runoff. Therefore, increasing AT directly resulted in increase of searching widow size. When the searching window was expanded, the possibility exists for detection of more rainfall, so the generated rainfall event consequently grew in both duration and volume.

In the sensitivity test, with increased AT, the runoff ratio decreased from 36.6% to 26.9%. This is explained by the increased volume of rainfall. In addition, the time characteristics relevant to the time features of rainfall, such as T_w, T_{LR}, T_{LP}, T_{LC} and T_{LPC} exhibited a significant increase when AT increased (Figure 38). On the other hand, as AT did not affect runoff, the runoff characteristics, such as T_b, T_r and recession constant had no response to the change of AT.

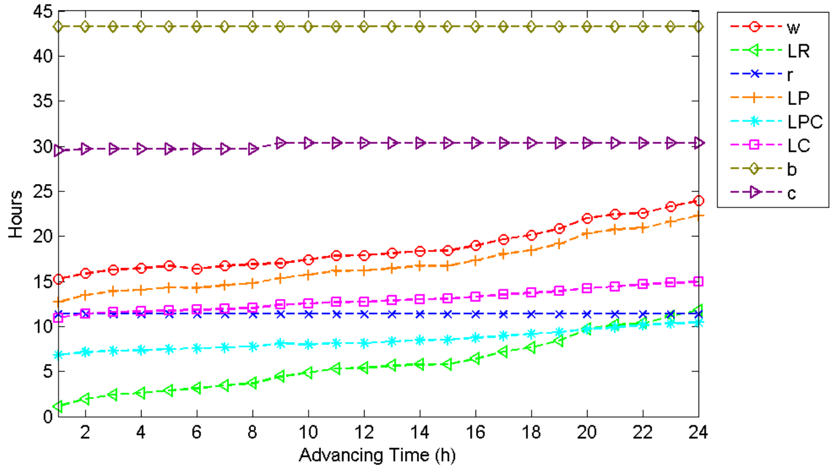


Figure 38. The variation of means of time characteristics with the change of AT

4.1.6. Interception (INT)

The parameter of INT is defined the amount of assumed interception from vegetation and abstracted from precipitation. As interception is removed from precipitation at the start of the story, a change of interception affects the start of rainfall events. In general, a large value of INT would postpone the start of rainfall event. In addition, the mean volume of rainfall persistently decreased when increasing INT (Figure 19), which directly resulted in the growth of runoff ratio from 29.7% to 48.1% (Figure 40). Among the time characteristics, T_w and T_{LR} were the most sensitive to the change of INT (Figure 41). In addition, T_{LC} and T_{LPC} exhibited a slight decline in the test. On the other hand, other runoff time characteristics, like in the sensitivity test of AT, remained the same with change of INT.

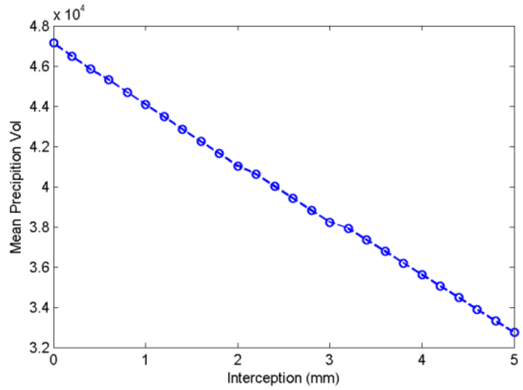


Figure 39. The variation of mean rainfall volume with the change of INT

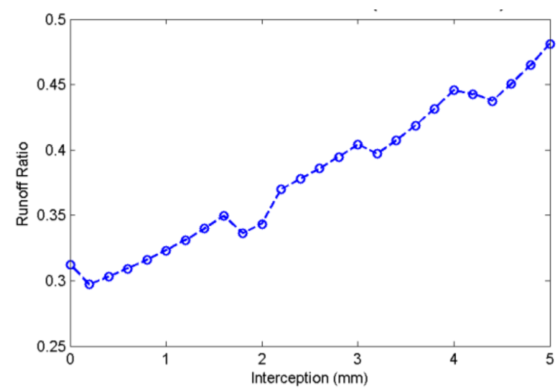


Figure 40. The variation of mean runoff ratio with the change of INT

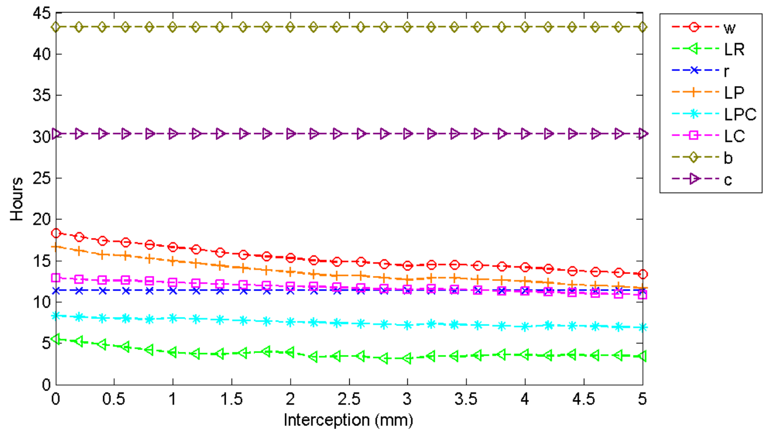


Figure 41. The variation of means of time characteristics with the change of INT

4.1.7. Summary for sensitivity analysis

All input parameters affected the output characteristics by controlling the basic features of runoff and/or rainfall, such as start and end point and peak flow. According to their objective, input parameters can be classified in two categories: runoff parameters and rainfall parameters. The runoff parameters included β, PKTHR, RR, and BSLP and ESLP, as well as the rainfall parameters were AT and INT. In some cases, the runoff parameters had some influence on specific rainfall features (e.g. increasing the value of RR led to a significant decrease in rainfall duration) as the rainfall events were extracted in the basis of runoff events. However, no influence of rainfall parameters were detected on runoff features.

Among the runoff parameters, β, PKTHR, and RR exerted the greatest control on the appearance of extracted runoff. β was considered the most comprehensive and influential parameter in this toolkit because it affected almost all output characteristics, although the significance of the effect varied with the characteristics. However, its impact on output characteristic was subtle because it exerted its influence on baseflow, rather than directly altered the runoff features. On the other hand, PKTHR and RR affect the output more directly. PKTHR was considered an effective parameter to select a distinct parameter. However, there was a negative relationship between PKTHR and the number of extracted runoff events. Therefore, the value of PKTHR should be chosen carefully in order to generate a sufficient number of runoff events for analysis. RR significantly affected the appearance of extracted runoffs (single-peak or multiple-peak event). Most time characteristics, particularly time T_b and T_w, were very sensitive to the change of the value of RR. Due to the complexity of runoff appearance, it is very difficult to find a value of RR that was appropriate for every event. Typically, the decision of the value of RR had to be made after examining the hydrograph and having a general understanding of the characteristics of the local minimums. Furthermore, a reasonable value of RR should be lower than the value chosen for PKTHR. Comparing with previous β, PKTHR and RR, the influence of BSLP and ESLP was less significant, but each focused on one runoff feature, which made their effect on output characteristics more specific. As the runoff hydrograph typically had more gradual recession than rising limb it is recommend that the value of ending should be chosen lower than the value of BSLP.

The influence of AT and INT was limited to rainfall features. The selection of their value should be based on the understanding of the target watershed and could be facilitated by the information regarding the watershed properties relating to stream response, and climate characteristics (e.g. frequency of storm event). The choice of the values of AT and INT are important as they affected the match of rainfall with the runoff event. Mismatching rainfall and runoff could result in a significant decrease of the valid rate of output characteristics, particularly for runoff ratio and T_{LR}. Therefore, the value of AT and INT must be chosen appropriately in order to ensure the quality of output characteristics.

4.2. Comparison of automated technique and manual approach

Carey and DeBeer selected 49 rainfall-runoff events at Granger Creek during a 5-year study period (1999-2003) and calculated runoff ratio, recession constant, and time characteristics manually (Table 32). Comparing with those derived by manual approaches, the time characteristics generated by this toolkit tend to have longer means. The mean of T_w and T_{LR} obtained in this study agree reasonably well with the previous study, which only increased 2 and 1.4 hours respectively. On the other hand, T_b and T_c exhibit a substantial growth by using the automated technique, where T_b increased from 25.2 hours to 45.1 hours as well as T_c soared 139.2%, from 15.3 hours to 36.6 hours. The rest of time characteristics show moderate increases, from 3.7 hours for T_r to 6 hours for T_{LC}. The extension in time characteristics can be accounted for by utilizing the parameter of PKTHR. This toolkit merely selected runoff events with peak flow higher than the value of PKTHR, which increases the average magnitude of runoff events in analysis. In addition to time characteristics, runoff ratio shows an increase of 177.8 %, from 0.09

to 0.25. It is speculated that the considerable increase in runoff ratio also resulted from the increase in the average magnitude of runoff events. On the other hand, a substantial decrease was observed in the recession constant. The mean recession constant calculated by this toolkit is 32.5 hours shorter than that derived in Carey and DeBeer's study, which again is related to the selection of different events in the manual analysis. .

Table 32. Comparison of output characteristics derived from automated toolkit and manual approach in Carey and DeBeer's study (2008)

	Mean (automated technique)	Mean (manual approach)	Difference in value	Difference in percent
Runoff Ratio	0.25	0.09	0.16	177.8 %
Recession Constant (h)	9.2	41.7	-32.5	-77.9 %
T_w (h)	14.2	12.2	2	16.4 %
T_{LR} (h)	3.9	2.5	1.4	56.0 %
T_r (h)	13.3	9.6	3.7	38.5 %
T_{LP} (h)	16.5	11.8	4.7	39.8 %
T_{LPC} (h)	10.3	5.8	4.5	77.6 %
T_{LC} (h)	14.1	8.1	6	74.1 %
T_b (h)	45.1	25.2	19.9	79.0 %
T_c (h)	36.6	15.3	21.3	139.2 %

5. Conclusion

This study attempts to automate the process of extracting individual rainfall-runoff event from long-term precipitation and streamflow data and compute a number of hydrological characteristics based on the extracted events. A toolkit has been developed in the MATLAB environment to fulfill this objective. This toolkit contains a number of independent but inter-related functions, including separating baseflow, extracting runoff event, recession analysis, matching rainfall and runoff event, compute runoff ratio and time characteristics.

The baseflow separation function is based on the digital filter method proposed by Nathan and McMahon (1990). According to previous studies (Nathan and McMahon, 1990; Arnold et al, 1995; Arnold and Allen, 1999), the digital filter method produces realistic results if the filter coefficient is chosen appropriately. The methodology also has advantages in performance on long-term, continuous streamflow data because of its nature of signal processing (Chapman, 1999). This is the reason of adopting digital filter method in this toolkit.

The original and most fundamental function in this toolkit is runoff extraction because its product is the basis for other functions. Providing a number of input parameters in this function enhances the flexibility of using the toolkit. The user is able to control the appearance of the extracted runoff events through adjusting the values of parameters. It was found that this automated method of extracting runoff events agreed reasonably well with user's expectation when the appropriate input parameters are applied. Based on the extracted runoff event, the corresponding storm event is identified within a pre-defined searching window. The size of window is flexible and is determined by a user-defined parameter, AT. It was recommended that the value of AT should be chosen based on the estimates of response time on target watershed(s).

The estimates should come from guidance in previous studies conducted on the same or similar watersheds and/or be deduced based on watershed properties and climate conditions.

After obtaining a rainfall-runoff event, runoff ratio and time characteristics are calculated and then used for subsequent analysis. In addition, recession analysis was also performed for the extracted runoff events to acquired recession constants. It is very difficult to evaluate the absolute accuracy of outcomes because the true values of the time characteristics are unknown. However, the output characteristics at Granger Creek derived by this toolkit were compared with those obtained by manual approaches in Carey and DeBeer's study (2008), in order to check the consistency between the automated method and manual approaches. It was found that time characteristics calculated in this study were generally longer than those reported by Carey and DeBeer (2008). As this toolkit has a requirement for the peak flow when selecting runoff events, it increases average magnitude of runoff events selected for analysis. Therefore, it was speculated that the longer time characteristics was accounted for by the higher magnitude of runoff event. However, this speculation has not been confirmed as the peak flows of runoff events were not provided in Carey and DeBeer's study (2008). Although this toolkit generated longer time characteristics, the sequence of time characteristics in terms of length agrees with those derived by manual approaches. Runoff ratios are larger and recession constants much shorter than those derived by Carey and DeBeer (2008).

In addition to Granger Creek, this toolkit was also applied on three Scottish watersheds with very different areas. Results suggest that the toolkit performs better on small-scale watersheds based on the higher valid rates of output characteristics. As rainfall distribution is nearly homogenous over a small area such as BB, the precipitation data, usually a point measurement, can well represent for the whole watershed rather than a certain region in watershed. Consequently it increases the probability of successfully associating runoff with storm event on precipitation data. The valid rates of output characteristics are improved through reducing risk of mismatching rainfall and runoff events.

The choice of input parameters is extremely important because it affects the performance of the toolkit and the accuracy and reliability of output characteristics. The parameters of β, PKTHR, RR, BSLP and ESLP are 'graphical' parameters, and their values should be based on visual examination to streamflow and baseflow-free hydrograph. An appropriate value of parameter is designed to generate results meeting user's expectation. Therefore, an effective way to identify the optimal parameter is to adjusting its value until the output meet user's expectation. The initial value of parameter should be based on user's understanding on shape features.

Conversely, due to the complexity of hydrograph appearance, it is extremely difficult to find a set of parameters that generate all rainfall-runoff events that perfectly agree with user's expectation. Although output characteristics with unreasonable values will be automatically excluded, visual control may still be required in order to further improve reliability of extracted rainfall-runoff events. This toolkit is able to generate hyetograph-hydrograph sets for individual events. The hyetograph-hydrographs enable the user to exercise visual control to select the most representative events and exclude events deemed unacceptable. For example, some runoff events may contain several equally significant peaks, which lead to difficulty and confusion in deciding the time of peak. Users can record the event number and manually remove them from analysis.

In future studies, the accuracy and reliability of the output characteristics should be further investigated by comparing with manual approaches. Although the accuracy of results remains uncertain, this toolkit is considered objective and reproducible. More importantly, it greatly improves the efficiency of rainfall-runoff event extraction and hydrological characteristics calculation. It is believed that this toolkit will benefit hydrograph analysis and other relevant research, such as watershed response to storm event and water resource management.

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