Advances in Water Resources 88 (2016) 8–13

Contents lists available at ScienceDirect

Advances in Water Resources

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

On the transition of base flow recession from early stage to late stage

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ARTICLE INFO

Article history:
Received 22 February 2015
Revised 16 November 2015
Accepted 23 November 2015
Available online 28 November 2015

Keywords:
Base flow recession
Early stage recession
Late stage recession
Ephemeral stream
Perennial stream
Panola Mountain Research Watershed

ABSTRACT

This paper is focused on the transition of base flow recession from early stage to late stage. The volume flow rate that takes place when such a transition occurs is identified for each of the twenty-three recession events observed at the Panola Mountain Research Watershed (PMRW) in Georgia, USA, using a newly developed cumulative regression analysis method. Meanwhile, the flow at the watershed outlet, which was recorded when the discharge at the perennial stream head diminishes to zero, is identified for each recession event. As evidenced by a correlation coefficient of 0.90, these two characteristic flows are found to be highly correlated, suggesting a fundamental linkage between the transition of base flow recession from early stage to late stage and the drying up of ephemeral streams. During the early stage, the contraction of ephemeral streams largely controls the recession behavior, whereas in the late stage when perennial streams dominate the flowing streams, the contraction of flowing streams is minimal and groundwater hydraulics governs the recession behavior.

1. Introduction

Base flow recession curve in the dry period is a distinct hydrologic signature of a watershed. It provides important information to water managers for decision-making on water supply, irrigation, and management of water quality [19] and aquatic ecosystem services [30]. Baseflow recession has been extensively studied in the last few decades. By eliminating post-rainfall event time reference in hydrograph recession analysis, Brutsaert and Nieber [7] proposed a classical method to analyze the time rate of change in discharge as a function of discharge itself (i.e., $-dQ/dt=f(Q)$). Logarithmic graphs of $\ln(-dQ/dt)$ versus $\ln(Q)$ based on observed discharge demonstrate approximately linear relationships, suggesting the following power relationship [7]:

$$-\frac{dQ}{dt} = aQ^b \tag{1}$$

The value of exponent b estimated using observed discharge differs considerably between early stage of recession with high discharge and late stage of recession with low discharge. A sharp change of the exponent value from early recession to late recession has been observed for many watersheds (e.g., [17,21,22,39]).

The factors controlling the recession exponent values are complex, including groundwater hydraulics [7], the interconnection of groundwater flow systems [31], spatial heterogeneity of watershed properties [15], stream contraction [2–4], and evapotranspiration [28]. In those studies which focused on the role of groundwater hydraulics on recession behavior, the total length of stream contributing to base flow is assumed to be constant [8,32]. Based on the analytical solutions of the Boussinesq equation for a horizontal aquifer with a fully penetrating stream channel, the value of b equals 3 during early recession, and it is 1 for a linearized solution and 1.5 for a non-linearized solution during late recession [7]. Aquifer parameters at the watershed scale, including saturated hydraulic conductivity, drainable porosity and aquifer depth, were estimated based on analytical solutions for early and late recession [7,8,26,29].

The role of flowing stream contraction on recession behavior has been investigated in recent years [2,20]. The contraction of flowing stream networks is a result of geomorphological characteristics [18]. Perennial streams are active for most of the year, depending upon local climatology and basin characteristics. Ephemeral streams are intermittently active, in response to individual rainfall events [6,13,37], and gradually dry up during the recession period [10,38]. The length of active channel network is highly correlated with streamflow, and power-law relationships between flowing channel length and streamflow are usually identified [12,14]. However, the linkage between drying up of ephemeral streams and ceasing of early recession has not been fully explored in the existing literature.

We argue that the contraction rate of ephemeral streams is significant at the early stage of recession; however, at the late stage of recession when all ephemeral streams have dried up and perennial streams are the only sources for flowing streams, the contraction rate of perennial streams is negligible. The objective of this paper is to

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http://dx.doi.org/10.1016/j.advwatres.2015.11.015

identify the transition of base flow from early recession stage to late recession stage for individual recession events, and investigate the potential linkage between the transition of base flow recession and the contraction of ephemeral streams.

2. Panola Mountain Research Watershed and data

To investigate the linkage between the transition of base flow recession from early stage to late stage and the contraction of ephemeral streams, at the minimum, we need streamflow data simultaneously recorded at both the outlet and the perennial stream heads of a watershed. Such streamflow observations are rather rare to find since streamflow gauges are usually located on perennial streams. Fortunately, for the Panola Mountain Research Watershed (PMRW) streamflow observations are available at both the perennial stream head (84°10'24"W, 33°37'47"N) and the watershed outlet (84°10'20"W, 33°37'53"N) [23]. Therefore, we choose the PMRW to analyze the transitions of base flow recession from early stage to late stage.

With a drainage area of 0.41 km^2, the PMRW is located about 25 km southeast of Atlanta in the State of Georgia. It has an aridity index of 0.94, a mean annual temperature of 15.4 °C, and mean annual precipitation of 1237 mm. As shown in Fig. 1, 93% of the drainage area of PMRW is covered by forest and the rest are bedrock outcrops [11]. Bedrock outcrops and riparian zones consist of about 7 and 15% of the watershed area, respectively, and hillslopes comprise the rest of it [16]. Historically, this watershed has been the subject of much research on a variety of topics, such as the control of bedrock topography over storm runoff generation at the hillslope scale [33] and [34,35] and hydrologic modeling [24].

Rainfall and streamflow observations exist for the period from October 1, 1985 to September 30, 2007 [23]. Rainfall data were recorded at one-minute time intervals at several tipping bucket gauges within or adjacent to PMRW, and were recorded weekly at several standard Tenite rain gauges. Comparing the weekly rainfall totals at tipping bucket gauges with those at standard rain gauges, the tipping bucket rainfall series in the week that best reproduced the totals from the standard gauges are combined to generate the rainfall data by average [24]. Streamflow data of PMRW were computed with a stage-discharge rating curve and, the stage record was obtained from a data logger at 5-minute intervals except during rainstorms when data was collected at 1-minute intervals [24]. Streamflow data are available at two gauge stations as shown in Fig. 1. One gauge station is located at the outlet of the watershed, of which the streamflow is denoted as Q_p. The other gauge, with a drainage area of 0.1 km^2, is located in the transition zone between the ephemeral and perennial riparian aquifers, approximately at the perennial stream head as shown in Fig. 1 [9]; and its streamflow is denoted as Q_e. In this paper, the 5-minute streamflow series at both gauges at the outlet and the perennial stream head in PMRW were aggregated to hourly time series. To be consistent with other studies, these hourly discharge data were converted to mm/day (e.g., [36]). In a recession, the outlet discharge Q_p, that occurred at the moment when discharge at the perennial stream head Q_e diminishes to zero, is denoted as Q_{p0}.

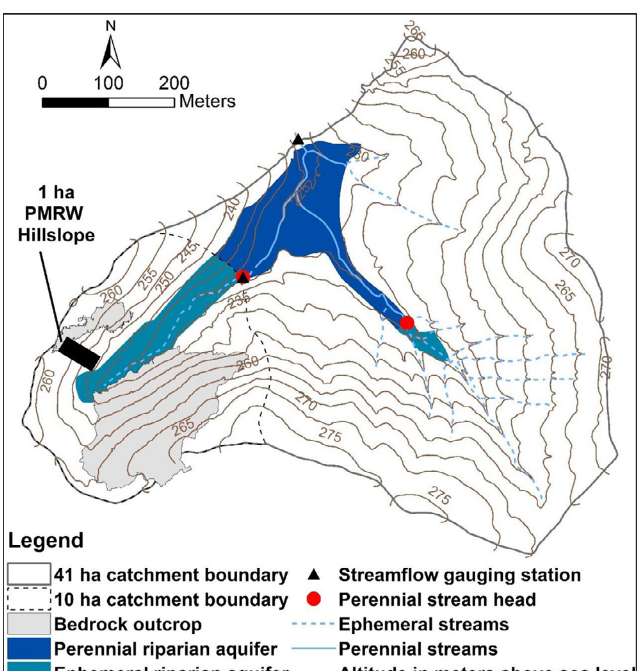

Fig. 1. Spatial distribution of perennial and ephemeral streams, two streamflow gauge stations, and two major perennial stream heads at the PMRW (adopted from [9]).

3. Methodology

3.1. Contraction of flowing stream to perennial stream head

The streamflow observations at the upstream gauge in the PMRW provide an opportunity to identify the time when flowing stream contracts to the perennial stream head. Using discharge time series of the upstream gauge, we identified the moment when the ephemeral streams dry up ($Q_e \to 0$) and the corresponding discharge at the watershed outlet Q_{p0}. Another major ephemeral tributary is located in the southeastern side of the watershed. The drainage areas for both perennial stream heads are about 0.1 km^2. The topographic index [1] for the gauged perennial stream head is 14.2, which approximately equals to the topographic index at the other perennial stream head, 13.8. Therefore, it is reasonable to assume that the two tributaries contract to their perennial stream heads at approximately the same time.

3.2. Identification of the transition of base flow recession from early stage to late stage

The first step for identifying the transition point of base flow recession is to select base flow recession events from streamflow time series, and to determine the starting time of the recession analysis. The starting time of recession is typically determined according to rainfall events or the peak discharge after a rainfall event. In order to eliminate quick flows in the recession analysis, Brutsaert and Nieber [7] selected recession data that were collected at least 5 days after rainfall events. Brutsaert and Lopez [8] found that the early recession analysis is sensitive to the number of days after storms. To determine the earliest onset of base flow, uninterrupted recession flow data starting from the second day after the cessation of rainfall were selected for analysis in some studies [8,32,22].

In this paper, the following criteria were applied to determine base flow recession segments from the hourly discharge data: (1) recession segments after rainfall events with precipitation depth greater than 55 mm are selected for recession analysis [9], as 55 mm rainfall is typically required to fill the depressions in the bedrock of PMRW [33,34]; (2) no rainfall events occur during the recession period; (3) the first six hours of discharge data following a peak discharge should be discarded; (4) with all the above three criteria being met, discharge at the perennial stream head must be larger than zero at the starting time of recession analysis; and (5) in order to capture the late recession behavior, the discharge at the outlet should keep decreasing for at least three hours after the discharge at the perennial stream head diminishes to zero.

For each selected recession event, we computed the data pair of $-dQ/dt = (Q_{i+1}-Q_i)/\Delta t$ and $Q = (Q_i+Q_{i+1})/2$. On a recession curve, the