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Effect of catchment characteristics on the relationship between past discharge and the power law recession coefficient

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SUMMARY

This study concerns the relationship between the power law recession coefficient k (in $-dQ/dt = kQ^\alpha$, Q being discharge at the basin outlet) and past average discharge Q_N (where N is the temporal distance from the center of the selected time span in the past to the recession peak), which serves as a proxy for past storage state of the basin. The strength of the k–Q_N relationship is characterized by the coefficient of determination $R^2{}_N$, which is expected to indicate the basin's ability to hold water for N days. The main objective of this study is to examine how $R^2{}_N$ value of a basin is related with its physical characteristics. For this purpose, we use streamflow data from 358 basins in the United States and selected 18 physical parameters for each basin. First, we transform the physical parameters into mutually independent principal components. Then we employ multiple linear regression method to construct a model of $R^2{}_N$ in terms of the principal components. Furthermore, we employ step-wise multiple linear regression method to identify the dominant catchment characteristics that influence $R^2{}_N$ and their directions of influence. Our results indicate that $R^2{}_N$ is appreciably related to catchment characteristics. Particularly, it is noteworthy that the coefficient of determination of the relationship between $R^2{}_N$ and the catchment characteristics is 0.643 for $N = 45$. We found that topographical characteristics of a basin are the most dominant factors in controlling the value of $R^2{}_N$. Our results may be suggesting that it is possible to tell about the water holding capacity of a basin by just knowing about a few of its physical characteristics.

1. Introduction

One of the key features of a drainage basin is its ability to store rain water and discharge it later at a much slower late, thereby sustaining many of the biotic and abiotic activities (Botter et al., 2011; Kirchner et al., 2001; McDonnell et al., 1991; Pearce et al., 1986; Sivakumar et al., 2005; Wolock et al., 1989). Individual water particles follow various surface and subsurface flow paths to reach the basin outlet. Interestingly, the travel time distribution of individual water particles in a basin is very different from the streamflow hydrograph or the hydrologic response, owing to the difference between celerity and velocity (Botter et al., 2011, 2010; McDonnell and Beven, 2014). Nevertheless, hydrologic response represents the functional relationship between storage and discharge at basin scale. In fact, all practical hydrological models are based on the mass balance equation involving storage (S) and discharge (Q) (Anderson et al., 1997; Biswal and Nagesh Kumar, 2015; Bonell, 1998; Brutsaert and Nieber, 1977; Hooper, 2001; McGlynn et al., 2003, 2002; Rupp and Selker, 2006; Sidle et al., 2000; Thomas et al., 2013). However, the biggest challenge in implementing the mass balance equation is that it is not practically possible to observe storage due to technological limitations. An alternative avenue is to obtain information indirectly by analyzing streamflow time series. In particular, streamflow observations during recession periods or no-rain periods can give valuable information, since during these periods streamflow is sustained by drainage from subsurface storage systems only (Arnold et al., 1995; Biswal and Marani, 2014, 2010; Biswal and Nagesh Kumar, 2014a, 2014b; Brutsaert and Nieber, 1977; Marani et al., 2001; Mutzner et al., 2013; Palmroth et al., 2010; Rupp and Selker, 2006; Szilagyi et al., 1998; Tallaksen, 1995).

For recession flow analysis, Brutsaert and Nieber (1977) proposed the classical method of expressing dQ/dt as a function of Q itself, where Q is discharge at the basin outlet at time t. dQ/dt vs. Q curves generally display a power law profile as:

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$$-\frac{dQ}{dt} = kQ^{\alpha} \quad (1)$$

Biswal and Marani (2010) found that although α for a particular basin remains fairly constant, k displays considerable variation across recession events, indicating that dQ/dt–Q relationship (or storage–discharge relationship) is dynamic. Therefore, $-dQ/dt$ vs. Q curves need to be analyzed separately for the available recession events (Biswal and Marani, 2014, 2010; Biswal and Nagesh Kumar, 2014a, 2013; Mutzner et al., 2013; Shaw and Riha, 2012). The logical question, therefore, is: what controls the eventual variability of k? It appears that the coefficient k depends on initial drainable storage in the basin (Biswal and Nagesh Kumar, 2015, 2014a, 2014b). A basin accumulates water during a rainfall event and releases it gradually during the following no-rain or recession periods. Because no-rain periods are usually shorter than the time period a basin requires to drain the stored water, the basin may not drain water completely during a particular recession event. This means that the basin will still have some water left to be drained in the later recession events. Therefore, k of a recession event can be expected to be influenced by the past storage in the basin, represented by the past average discharge (Biswal and Nagesh Kumar, 2014a, 2014b; Shaw et al., 2013). Also, the effect of storage is expected to diminish with time. This means that k will be affected less by storage in the basin, say, 20 days before the recession event than by storage, say, 5 days before the event (Biswal and Nagesh Kumar, 2014a, 2014b). Essentially, the relation between k and past average discharge indicates the basin's ability to store and release water.

The basic objective of this study is to investigate the physical controls over the relationship between the coefficient k and past average discharge considering data from 358 basins situated in the United States. More specifically, we attempt to identify the dominant parameters (Sivakumar, 2004) that govern the power law relationship between k and past average discharge. The main intention is to provide a first order understanding of recession flow processes from catchment characteristics.

2. Data and analysis

2.1. Streamflow data collection and preliminary analysis

Daily average streamflow data were collected for 358 basins from the USGS database (http://waterwatch.usgs.gov/) (Table S1 of the supplementary material provides the basin ids). Satellite images (courtesy of Google Earth) were used to select the basins that are relatively less influenced by human activities. Since we were particularly interested in analyzing streamflows contributed by subsurface storage systems, we did not consider basins that contain relatively large natural or artificial lakes. Any streamflow time series in which discharge was observed to be declining continuously for at least 5 days was considered as a recession curve (Biswal and Marani, 2010; Biswal and Nagesh Kumar, 2014b). $-dQ/dt$ and Q were computed as (Brutsaert and Nieber, 1977):

$$-dQ/dt = (Q_t - Q_{t+\Delta t})/\Delta t, \text{and} \quad (2a)$$

$$Q = (Q_t + Q_{t+\Delta t})/2 \quad (2b)$$

The time step Δt is 1 day in this study. Note that for computation of α and k recession peaks were not considered as they are supposed to be influenced by surface flows (Biswal and Nagesh Kumar, 2014a). For each study basin, the available recession curves were collected and the corresponding values of α were computed. The median of the values of α was considered to be the representative α (α_r) for the basin (Biswal and Marani, 2010). Then, for each recession curve of the basin, k was computed by fixing α at its α_r (Biswal and Marani, 2014). Subsequently, we analyzed the power law relationship between k of a recession event and Q_N, expressed in a more general form:

$$k \propto Q_N^{-\delta_N} \quad (3)$$

where Q_N is the average discharge observed from N'' to N' days before the peak of the recession event, and $N = (N'' + N')/2$ and δ_N is the exponent. The main difference between our analysis and the analysis of Biswal and Nagesh Kumar (2014b) is that while Biswal and Nagesh Kumar (2014b) considered only the case of $N'' = 2$, we considered different values of N'' (Fig. 1). We noted the values of $R^2{}_N$ (coefficients of regression) for power law relationship between k and Q_N for four combinations of (N'', N'): (2, 10), (10, 30), (30, 60) and (60, 120), as shown in Fig. 2 for USGS gauging station #01586610 (Morgan Run, MD).

2.2. $R^2{}_N$ and catchment characteristics

To investigate how different catchment characteristics affect $R^2{}_N$, we used the hydrologic database of Falcone et al. (2010), which gives various physical properties for the selected basins. The coefficient of determination of the relationship between each of the selected catchment parameter and $R^2{}_N$ for each N was found out by employing the least square linear regression method. We denote $R^2{}_{NPi}$ as the coefficient of determination of the relationship between $R^2{}_N$ and the ith parameter, P_i. In total, 18 catchment characteristics were selected for the rest of the analysis (Table 1) that were statistically significant (see the p-values in the table), although a few parameters not satisfying the criterion were also added since we thought that they are important catchment characteristics.

The catchment parameters were normalized by subtracting the respective mean and dividing it by the standard deviation. Then, the dataset (catchment variables) was transformed into a set of principal components, as we found that many of the selected parameters are not mutually independent (Abdi and Williams, 2010; Brown, 1993). The procedure makes use of orthogonal transformation method to convert a set of mutually-dependent variables into a set of principal components that are independent of one another. PC_i is referred here as the ith principal component.

Multiple linear regression analysis was performed between ($R^2{}_N$) (dependent variable) and the first Z principal components (independent variables) for each N. The general relationship is represented as:

$$R_N^2 = \beta_0 + \sum_{i=1}^{Z} \beta_i PC_i \quad (4)$$

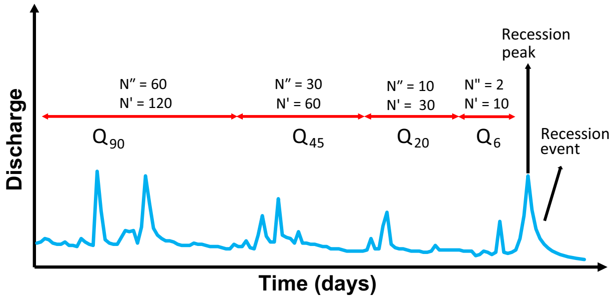

Fig. 1. An illustration of the analysis of streamflow time series data as done in this study. Q_N is the average discharge from N'' to N' days before the recession peak, where $N = (N'' + N')/2$. The relationship between the recession flow parameter k and Q_N is investigated by considering four values of N (N = 6, 20, 45 and 90) as shown in the figure.