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Objective hydrograph baseflow recession analysis

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SUMMARY

A streamflow hydrograph recession curve expresses the theoretical relationship between aquifer structure and groundwater outflow to a stream channel. That theoretical relationship is often portrayed empirically using a recession plot defined as a plot of $\ln(-dQ/dt)$ versus $\ln(Q)$, where Q is streamflow discharge. Such hydrograph recession plots are commonly used to estimate recession parameters, aquifer properties and for evaluating alternative hydrologic hypotheses. We introduce a comprehensive and objective approach to analyze baseflow recessions with innovations including the use of quantile regression, efficient and objective numerical estimation of dQ/dt, inclusion of groundwater withdrawals, and incorporation of seasonal effects. We document that these innovations when all combined, lead to significant improvements, over previous studies, in our ability to discern the theoretical behavior of stream aquifer systems. A case study reveals that our methodology enables us to reject the simple linear reservoir hypothesis of stream aquifer interactions for watersheds in New Jersey and results in improved correlations between low flow statistics and aquifer properties for those same watersheds.

1. Introduction

A streamflow hydrograph can be separated into a rising limb reflecting increases in discharge resulting from precipitation events, and recession limbs, which represent streamflow maintained at least in part by discharge from watershed aquifer storage. A streamflow hydrograph recession curve exhibits behavior attributed to the relationship between aquifer structure and its associated groundwater outflow to the stream channel. The theory of hydrograph recession analysis emerged from early studies of groundwater flow (Dupuit, 1863; Boussinesq, 1877; Maillet, 1905) and has since led to multiple approaches to characterize the relationship between groundwater and surface water during low flow periods (Tallaksen, 1995; Hall, 1968; Smakhtin, 2001). Increased attention has focused on both the quantity (Famiglietti and Rodell, 2013) and quality (Schirmer et al., 2012) of groundwater discharge to stream channels. This attention is due to groundwater resources being recognized as an important component of the global freshwater budget (Alley et al., 2002; Konikow, 2011) and the identification of global groundwater abstractions and depletion (Famiglietti et al., 2011). In this study, we focus on the relationship between groundwater storage and surface water because understanding the contribution of groundwater to streamflow, termed baseflow or groundwater discharge, is a fundamental focus of engineering, hydrogeologic and ecological studies.

Many investigations have studied streamflow hydrograph recession behavior to further our understanding of watershed processes. Szilagyi et al. (2007) and Shaw et al. (2013) evaluated the influence of watershed evapotranspiration on the behavior of baseflow recessions. Studies have evaluated the influence of watershed geomorphology (Biswal and Marani, 2010; Biswal and Nagesh Kumar, 2013; Biswal and Nagesh Kumar, 2014) and watershed storage on stream network dynamics. Kirchner (2009) characterized catchment behavior by deriving a sensitivity function related to nonlinear storage-discharge relationships. The consequences of an improper characterization of baseflow processes in hydrologic models were addressed by Clark et al. (2011). Lo et al. (2010) developed a parametric model of baseflow behavior to enable estimation of water table depths within a land surface watershed

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model. Carrillo et al. (2011) employed a hydrograph recession plot analysis to illustrate calibration of land surface models using groundwater/surface water behaviors. Staudinger et al. (2011) evaluated hydrologic model structures to simulate seasonal low flow; in that study, results illustrated that data clouds within the recession plot differed between models.

To study river discharge behavior at the watershed scale, Brutsaert and Nieber (1977) introduced an approach to estimate hydrograph recession parameters from a log–log plot of $-dQ/dt$ versus Q, termed the recession plot, where Q is streamflow during baseflow conditions. Despite the wide application of the recession plot approach, a theoretical characterization of watershed hydrograph recession behavior remains problematic (Rupp and Selker, 2006; Brutsaert, 2008). Vogel and Kroll (1996) demonstrated the challenge of estimating theoretical baseflow recession constants from individual hydrograph recessions. Stoelzle et al. (2013) illustrated how selection of individual recession hydrographs affects our perception of storage-outflow behavior. Further, Krakauer and Temimi (2011) employed a recession plot analysis with results suggesting that no single power law relationship represented a 'typical' recession curve.

The goal of this study is to develop and test a comprehensive scientific approach for the characterization and estimation of theoretical baseflow hydrograph models which should enable improvements in our ability to understand and predict the behavior of watershed hydrograph recessions. There is considerable controversy over the assumption that watersheds exhibit a fixed time constant, known as the baseflow recession constant, in the relation between aquifer storage and baseflow discharge (Zecharias and Brutsaert, 1988; Troch et al., 1993; Vogel and Kroll, 1996; Wittenberg, 1999; Eng and Milly, 2007; Harman and Sivapalan, 2009). Thus, another goal of our study is to improve our ability to construct hypothesis tests which can effectively evaluate whether or not watershed recessions are characterized by a time constant known as the baseflow recession constant, K_b. The following sections provide an introduction to the theoretical derivation of baseflow recession characteristics and the development of our objective methodology for evaluation of the behavior of hydrograph recessions.

1.1. Theoretical background

To characterize relationships between groundwater and surface water systems, we employ the method introduced by Brutsaert and Nieber (1977) which assumes a power law relationship ($Q = \alpha S^n$) between watershed aquifer storage (S) and baseflow discharge (Q) (Hall, 1968; Dooge, 1973) combined with the watershed continuity equation under baseflow conditions which yields $dS/dt = I - Q = -Q$ because there is no inflow ($I = 0$) during a hydrograph recession. Combining these two expressions leads to $dQ/dt = -n\alpha^{1/n}Q^{(2n-1)/n}$ which can be further simplified as a power law relationship between dQ/dt and Q using $dQ/dt = -aQ^b$ where the exponent $b = (2n - 1)/n$ and $a = n\alpha^{1/n}$. Although the value of n in the power law model can take on any value in the range $[0, \infty]$, it is often assumed that $n = b = 1$ which implies that the aquifer behaves as a linear reservoir with a fixed time constant. Note that Brutsaert and Nieber (1977) also derived solutions to the Boussinesq equation for conditions where the exponent $b = 1.5$ and $b = 3.0$. Brutsaert and Nieber (1977) graphically illustrate that on a recession plot of $\ln(dQ/dt)$ versus $\ln(Q)$, the log of parameter a is the intercept while b is the slope of the fitted envelope to the streamflow recession data. Brutsaert and Nieber (1977) recommended fitting a lower envelope to data points created by the recession plot when employing the graphical estimation method. The justification for using the lower envelope arises from the assumption that, for any given streamflow Q, the lowest change in flow per time (dQ/dt) represents flow originating solely from groundwater storage. In our analysis, we fit a lower envelope as described by Brutsaert and Nieber (1977) to mitigate large dQ/dt values attributed to surface runoff or small recharge events.

There are numerous challenges to the approach suggested by Brutsaert and Nieber (1977) for estimation of recession parameters. Vogel and Kroll (1992, 1996), Biswal and Marani (2010) and Shaw and Riha (2012) assess baseflow recessions using individual events rather than the cloud of points in the recession plot. Kirchner (2009) assessed watershed behavior using mean values of binned streamflow to estimate recession parameters within a recession plot framework. Other studies (Rupp and Selker, 2006; Wang and Cai, 2009; Thomas et al., 2013) advance numerous different approaches to characterize the relationship between streamflow and dQ/dt. Several studies document seasonal effects on the baseflow response due to changes in evapotranspiration (ET) (Szilagyi et al., 2007; Wang and Cai, 2009).

Wang and Cai (2010) and Thomas et al. (2013) derive similar equations to Brutsaert and Nieber (1977) that account for the impact of groundwater withdrawals on hydrograph recessions, which we consider in Section 3.4. Rupp and Selker (2006) address estimation of dQ/dt given various Δt; for this study, we use $\Delta t = 1$ day to match the averaging period of the most commonly available U.S. Geological Survey streamflow data. Initially we assume groundwater withdrawals are negligible and ET is either constant or has a negligible impact during baseflow events. These assumptions are consistent with numerous previous studies (Brutsaert, 2008; Szilagyi and Parlange, 1988; among many others).

Brutsaert (2008) notes that, at the watershed scale, streamflow measurement error and inconsistent parameter estimation methods result in additional concerns over the interpretation and relevance of estimated baseflow parameters. Given the findings summarized above, combined with concerns raised by Brutsaert (2008), we conjecture that there are numerous issues concerning hydrography recession analysis which could have an impact on our ability to interpret, model, understand and attribute watershed behavior. It is difficult to decipher the true relationship in the power law model ($Q = \alpha S^n$) since one never knows the true value of n. We introduce several innovations in this study with the goal of developing a more objective approach to the analysis of baseflow recessions. Our purpose is to show, by making the analysis more objective, that our analyses lead to a more complete scientific understanding of watershed hydrograph recession behavior. Our overall methodology includes several innovations including: (1) a rigorous quantile regression approach to fit the power law model to the lower envelope of the relationship between $-dQ/dt$ vs. Q (Thomas, 2012; Stoelzle et al., 2013), (2) an efficient and reproducible approach for estimation of the numerical derivative (dQ/dt) and evaluation of the influence of both (3) seasonality and (4) the degree of groundwater withdrawals in the watershed on hydrograph recession characteristics. After introduction of these four innovations, we employ them together to test the hypothesis that groundwater outflow responds as a linear reservoir and is thus characterized by a fixed time constant.

2. Database description

We apply our baseflow estimation schemes to daily streamflow hydrographs for watersheds in New Jersey, USA, because it is currently one of the only regions we are aware of in which time series of monthly groundwater withdrawals are readily available in an electronic format. A total of 45 watersheds were selected for this study because (1) these watersheds are within high density population areas which meets the challenge of Sivapalan et al. (2012) and Vogel (2011) to study anthropogenic impacts on hydrologic