Journal of Hydrology 519 (2014) 205–213

Contents lists available at ScienceDirect

Journal of Hydrology

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

Inter-seasonal variability in baseflow recession rates: The role of aquifer antecedent storage in central California watersheds

Ryan Bart *, Allen Hope

Department of Geography, San Diego State University, San Diego, CA, USA

ARTICLE INFO

Article history:
Received 18 December 2013
Received in revised form 11 July 2014
Accepted 12 July 2014
Available online 21 July 2014
This manuscript was handled by Konstantine P. Georgakakos, Editor-in-Chief, with the assistance of Marco Borga, Associate Editor

Keywords:
Baseflow
Recession curve
Inter-seasonal variability
Antecedent storage
Storage–discharge model
California

SUMMARY

Baseflow recession rates vary inter-seasonally in many watersheds. This variability is generally associated with changes in evapotranspiration; however, an additional and less studied control over inter-seasonal baseflow recession rates is the effect of aquifer antecedent storage. Understanding the role of aquifer antecedent storage on baseflow recession rates is crucial for Mediterranean-climate regions, where seasonal asynchronicity of precipitation and energy levels produces large inter-seasonal differences in aquifer storage. The primary objective of this study was to elucidate the relation between aquifer antecedent storage and baseflow recession rates in four central California watersheds using antecedent streamflow as a surrogate for watershed storage. In addition, a parsimonious storage–discharge model consisting of two nonlinear stores in parallel was developed as a heuristic tool for interpreting the empirical results and providing insight into how inter-seasonal changes in aquifer antecedent storage may affect baseflow recession rates. Antecedent streamflow cumulated from the beginning of the wateryear was found to be the strongest predictor of baseflow recession rates, indicating that inter-seasonal differences in aquifer storage are a key control on baseflow recession rates in California watersheds. Baseflow recession rates and antecedent streamflow exhibited a negative power-law relation, with baseflow recession rates decreasing by up to two orders of magnitude as antecedent streamflow levels increased. Inference based on the storage–discharge model indicated that the dominant source of recession flow shifted from small, rapid response aquifers at the beginning of the wet season to large, seasonal aquifers as the wet season progressed. Aquifer antecedent storage in California watersheds should be accounted for along with evapotranspiration when characterizing baseflow recession rates.

Published by Elsevier B.V.

1. Introduction

Baseflow recession rates represent a measure of how baseflow, or the portion of streamflow that derives from aquifers, decreases following a recharge event. They are a function of the discharge magnitude and the discharge recession rate from each watershed aquifer contributing to baseflow. Baseflow recession rates provide insight into the inner workings and storage properties of watershed aquifers (Hall, 1968) and may be used for evaluating the effects of land-cover change on baseflow (Federer, 1973), for quantifying evapotranspiration (ET) rates in a watershed (Szilagyi et al., 2007), low flow prediction (Tague and Grant, 2009), baseflow separation (Eckhardt, 2005) and hydrologic modeling (Tallaksen, 1995).

In many watersheds, the baseflow recession rate for individual recession curves varies throughout the year. This inter-seasonal variability is most commonly associated with fluctuations in ET, with a greater baseflow recession rate corresponding to higher ET (Aksoy and Wittenberg, 2011; Federer, 1973; Shaw and Riha, 2012; Szilagyi et al., 2007; Wang and Cai, 2010; Wittenberg and Sivapalan, 1999). An additional and less studied control over inter-seasonal baseflow recession rates is the effect of aquifer antecedent storage (Biswal and Kumar, 2014; Harman et al., 2009; McMillan et al., 2010; Mishra et al., 2003; Shaw et al., 2013). Harman et al. (2009) theorized that in watersheds with multiple aquifers, differences in discharge recession rates between aquifers may lead to a decrease in baseflow recession rate during wet periods, since storage levels accumulate more in aquifers with lower discharge recession rates compared to aquifers with higher discharge recession rates. However, the relation between baseflow recession rates and aquifer antecedent storage has not been well characterized for many environments, including Mediterranean-climate regions (MCRs).

* Corresponding author. Address: Department of Environmental Science, Policy and Management, University of California, Berkeley, 130 Mulford Hall, Berkeley, CA 94720, USA. Tel.: +1 510 643 7430.

E-mail address: ryanrbart@berkeley.edu (R. Bart).

http://dx.doi.org/10.1016/j.jhydrol.2014.07.020
0022-1694/Published by Elsevier B.V.

MCRs are water-limited environments that are uniquely characterized by their regime of warm, dry summers and cool, wet winters. While only occupying small parts of Australia, California, Chile, the Mediterranean Basin and South Africa, MCRs are noted for being disproportionally impacted by human development and for having limited local water resources (Rundel, 2004). The seasonal asynchronicity of precipitation and energy levels in MCRs contributes to the development of two different hydrologic regimes within MCR watersheds; an energy-limited winter wet season and a water-limited summer dry season. As storage levels differ between these two periods, baseflow recession rates at the beginning of the wet season may not be the same as those at the end of the wet season.

The effect of increases in wet season storage on baseflow recession rates in MCRs is not satisfactorily understood. Sayama et al. (2011) observed that baseflow recession rates were lower at higher levels of total watershed storage than at lower levels of total water storage for two northern California watersheds. However, the relation between baseflow recession rates and inter-seasonal changes in antecedent storage was not quantified and the watershed processes that produce this change were not investigated. Biswal and Kumar (2014) investigated the relation between baseflow recession rates and antecedent storage for a single southern California watershed, but emphasized short-term (i.e. 8-day period before the beginning of a baseflow recession curve) changes in antecedent storage, not inter-seasonal changes in antecedent storage. The primary objective of this study was to elucidate the relation between baseflow recession rates and inter-seasonal changes in aquifer antecedent storage in four central California watersheds. The secondary objective was to develop a parsimonious storage–discharge model for use as a heuristic tool to understand how inter-seasonal changes in aquifer antecedent storage may affect baseflow recession rates.

2. Controls on baseflow recession rate variability

The amount of discharge and the discharge recession rate from a single aquifer will vary as a function of storage level and aquifer physical properties such as aquifer size, geometry, porosity, and saturated hydraulic conductivity (Brutsaert and Nieber, 1977). Although the properties of a given aquifer are relatively static, they may vary greatly from aquifer to aquifer and produce a range of discharge characteristics. For a given storage capacity, high initial discharge magnitudes from the aquifer generally lead to a rapid depletion of storage and a greater aquifer discharge recession rate. Hence, recession rates from small aquifers with high saturated hydraulic conductivities and high hydrological connectivity to the stream (e.g. riparian aquifers) are generally greater than recession rates from larger aquifers that vary over seasonal time-scales and have low saturated hydraulic conductivities and low connectivity to the stream (e.g. hillslopes). In some aquifers, discharge may be threshold-based when connectivity between an aquifer and stream is not always present (Smakhtin, 2001). In watersheds containing a single aquifer, the aquifer discharge recession rate will equal the baseflow recession rate.

During the recession period, fluxes to and from an aquifer affect storage levels in an aquifer, and thus, the aquifer discharge recession rate. Fluxes to an aquifer during the recession period decrease the discharge recession rate and may occur from soil recharge or when discharge from one aquifer recharges another aquifer. Fluxes from an aquifer during the recession period, excluding discharge to a stream, include ET and losses to other aquifers. The extent to which ET affects storage levels depends on the spatial distribution of vegetation with direct access to aquifers feeding baseflow, which in turn depends on the spatial distribution of shallow groundwater and/or deep rooted vegetation within a watershed (Tallaksen, 1995). Fluxes from an aquifer increase the discharge recession rate.

In watersheds with more than one aquifer, differences in the relative discharge magnitude from each aquifer may produce variability in baseflow recession rates (Moore, 1997). The source of these differences largely stems from variability in aquifer discharge recession rates, though differences in recharge, aquifer size, and discharge-thresholds may also be factors. Aquifers with high discharge recession rates have the greatest impact on baseflow during initial periods following a recharge event, but rapid depletion of storage levels supports little sustained discharge. Aquifers with low discharge recession rates, on the other hand, have a more muted response to recharge events. The slow release of water from these aquifers allows storage to accumulate during extended periods of recharge (Harman et al., 2009), shifting the dominant control on baseflow from aquifers with higher discharge recession rates to aquifers with lower discharge recession rates.

3. Watersheds

The watersheds in this study were selected from US Geological Survey (USGS) streamflow gauges in central and southern California and evaluated for inclusion based on the absence of major diversions or regulations, lack of persistent winter snow cover, little urbanization or agriculture, and data record. Four watersheds were found to be suitable for investigation; Arroyo Seco, Big Sur River, Nacimiento River, and San Antonio River (Table 1). The watersheds are all located in the Santa Lucia Mountains along the Central Coast region of California (Fig. 1). The Santa Lucia Mountains are characterized by steep topography with peak elevations exceeding 2000m asl. The mountains are underlain primarily by late-Cenozoic marine sediments with a basement of pre-Cenozoic granite rock from the Salinian Block (Ducea et al., 2003). Most rainfall is generated by frontal systems and spatial variation in rainfall amounts is largely controlled by orographic effects. Big Sur is located on the windward side of the Santa Lucia Mountains and is smaller and wetter than the other three watersheds, which are located on the leeward side of the mountain. Streamflow was gauged at calibrated cross-sections of the stream channel and streamflow records (in mm/day) ranged from 40 to 69 years (Table 1). Vegetation is a mosaic of grasslands, coastal sage scrub, chaparral, oak woodlands, and forests (Callaway and Davis, 1993), though chaparral vegetation dominates the higher elevations of the watersheds and woodland and grassland are most prevalent in the lowland areas.

The wet season in central California generally falls within the period from October to April, with large inter-annual variability in precipitation amounts. Fig. 2 shows mean monthly precipitation totals (wateryears 1976–2005) for the four watersheds. These values were derived from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) gridded product produced by the Climate Group at Oregon State University (http://prism.oregonstate.edu). Watershed mean monthly precipitation totals vary for each of the four watersheds, though seasonal patterns show great similarity. The majority of annual precipitation falls during December, January, February and March. Very little precipitation occurs during the summer and summer streamflow frequently ceases for Arroyo Seco, Nacimiento and San Antonio (Table 1).

Mean monthly potential ET totals (wateryears 1994–2011) from a California Irrigation Management Information System (CIMIS) (www.cimis.water.ca.gov) meteorological station located to the east of the Santa Lucia Mountains is displayed in Fig. 2. Potential ET in central California follows the seasonal energy cycle. During the summer dry period, cumulative potential ET exceeds precipitation. This extended period of seasonal water-deficit in central California creates very low soil moisture and storage levels at the end of the dry season (Miller et al., 1983). During the winter wet period, precipitation exceeds potential ET, allowing storages to be recharged.

4. Approach

4.1. Derivation of baseflow recession rates

To investigate inter-seasonal changes in baseflow recession rates, baseflow recession curves need to be comparable from one baseflow recession curve to another. Baseflow recession rates along a single baseflow recession curve often vary with baseflow magnitude. In order to normalize baseflow recession rates for magnitude, Brutsaert and Nieber (1977) proposed eliminating the time variable from the baseflow recession curve and comparing the change in baseflow magnitude dQ/dt to the observed baseflow Q, such that

$$-\frac{dQ}{dt} = f(Q) \quad (1)$$

where Q is baseflow discharge in mm and t is time (daily). This relationship is referred to as the recession slope curve (Rupp and Selker, 2006a). The recession slope curve has often been observed to be approximately linear when plotted graphically on a $\log(-dQ/dt) - \log(Q)$ plot, which implies a power-law relation;

$$-\frac{dQ}{dt} = aQ^b \quad (2)$$

where a is the value of $-dQ/dt$ when $Q = 1$ and b is the slope of the $\log(-dQ/dt) - \log(Q)$ relation (Clark et al., 2009). When the exponent b is equal to one, the recession slope curve simplifies to a linear relation between $-dQ/dt$ and Q, whereas an exponent other than one indicates a nonlinear relation, or power-law nonlinearity. If the recession slope curve is not linear on a $\log(-dQ/dt) - \log(Q)$ plot, the recession slope curve may be considered to be concave nonlinear (Wang, 2011). dQ/dt was computed as the difference between two consecutive points on the recession curve,

$$\frac{dQ}{dt} = \frac{Q_i - Q_{i-1}}{\Delta t}, \quad (3a)$$

while Q was computed as the mean of two consecutive recession points;

$$Q = \frac{Q_i + Q_{i-1}}{2}. \quad (3b)$$

Baseflow recession curves were defined as segments of the streamflow hydrograph where there was a consecutive decline in streamflow for at least seven days after a stormflow peak. The first two days were excluded from the analyses to account for storm-related flows. Each individual recession slope curve was analyzed visually for anomalous reductions in dQ/dt that were likely associated with precipitation events that were large enough to reduce the baseflow recession rate but not increase the magnitude of baseflow. These points were not considered in the analysis.

To isolate the effect of storage differences on baseflow recession rates, the influence of ET must be accounted for or minimized. Only recession curves during the period from November to February were included for examination of inter-seasonal changes since both potential ET rates (Fig. 2) and actual ET rates (Luo et al., 2007) are at their annual minimum during this period.

When the magnitude of baseflow change is smaller than the precision of the stream gauge, the recession slope curve may display discretization errors on a $\log(-dQ/dt) - \log(Q)$ plot (Rupp and Selker, 2006b). This problem is exacerbated in gauge networks

Table 1
Summary of watershed characteristics.

Name	USGS ID	Area (km^2)	MAP (mm)	MAQ (mm)	Zero flow days (%)	Geology (% sedimentary)	Mean soil depth (cm)	Soil porosity	Mean slope	Main channel length (km)	Drainage density	Mean LAI	Streamflow record
Arroyo Seco	11152000	632.0	708	231	12.3	44.0	56	0.46	24.17	48.1	0.36	2.44	1943–2011
Big Sur	11143000	119.1	1073	763	0	7.9	53	0.31	29.29	19.8	0.35	3.54	1952–2011
Nacimiento	11148900	419.6	568	386	30	85.5	64	0.55	16.97	50.5	0.36	2.02	1972–2011
San Antonio	11149900	562.0	587	170	44.8	76.4	81	0.78	15.55	50.7	0.40	1.83	1966–2011

MAP: mean annual precipitation; MAQ: mean annual streamflow; LAI: leaf-area index.

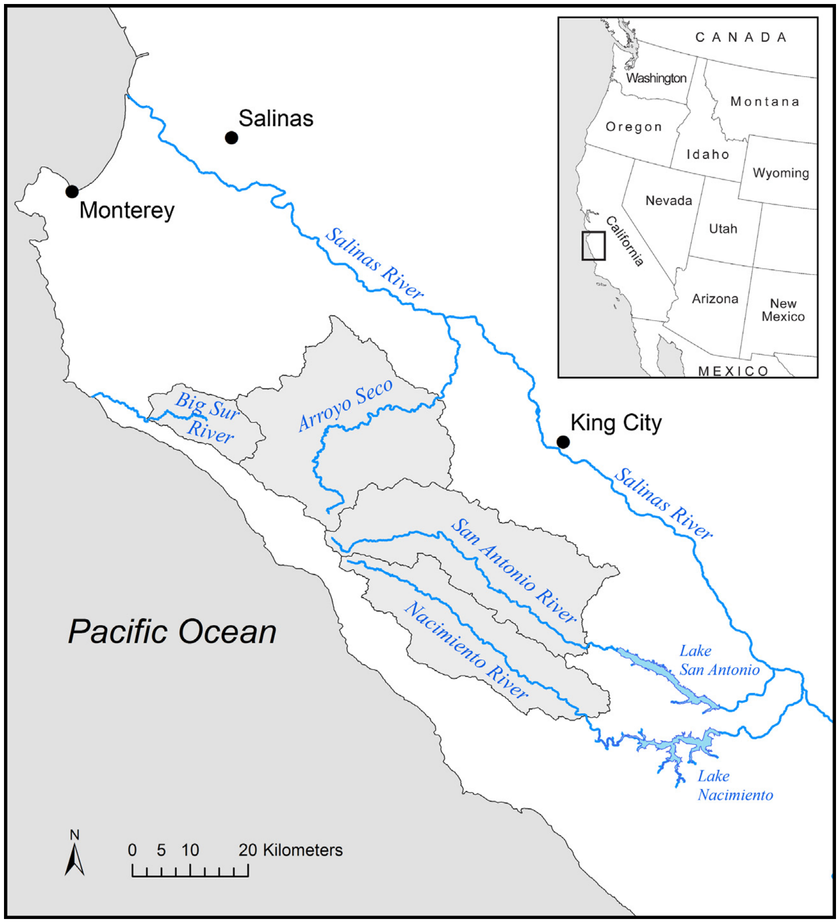

Fig. 1. Map of study watersheds.

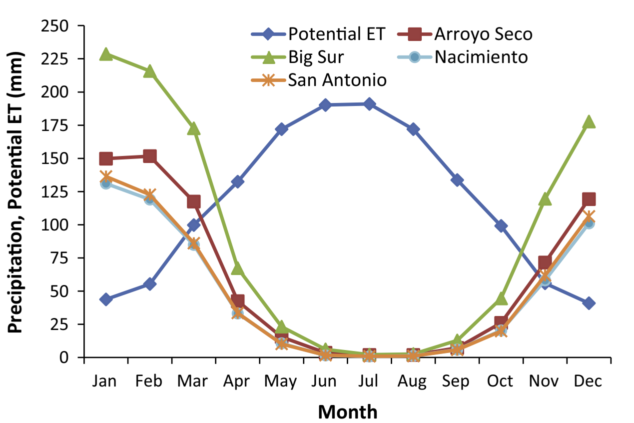

Fig. 2. Mean monthly precipitation for each watershed and mean monthly potential ET.

such as USGS, where precision for low flows may be very poor (Archfield and Vogel, 2009). Following the recommendation by Rupp and Selker (2006b), the time interval Δt in Eq. (3a) was increased for flows below the expected precision of the gauge until the change in baseflow ΔQ exceeded a critical precision threshold ΔQ_{crit}. The value of ΔQ_{crit} for each watershed (0.1 mm for Arroyo Seco, 0.25 mm for Big Sur, 0.1 mm for Nacimiento, 0.12 mm for San Antonio) was determined empirically by visual inspection.

Baseflow recession rates for each individual recession curve were represented by the a parameter (Eq. (2)) by fixing the exponent b at a common value for each watershed, similar to Biswal and Marani (2010), Shaw and Riha (2012), and Mutzner et al. (2013). A linear regression model with log-transformed data (Xiao et al., 2011) was fitted to each individual recession slope curve and the fixed value of b was derived from the median b value from among all the curves in a watershed. The median values of b for Arroyo Seco, Big Sur, Nacimiento and San Antonio were calibrated as 1.98, 2.10, 1.99 and 1.85, respectively. The value of a was then recomputed for all values along the recession slope curve using Eq. (2) with the fixed value of b. The median value of a from each individual recession slope curve was used to represent the baseflow recession rate for that recession slope curve.

4.2. Quantifying aquifer antecedent storage

The watersheds in this study are large, non-research watersheds and direct measurements of aquifer antecedent storage are not available. Estimates of aquifer antecedent storage based on continuous hydrologic models require an a-priori or calibrated estimate of the baseflow recession rate, making modeling approaches unsuitable for estimating antecedent storage in this study. An alternative approach for estimating aquifer antecedent storage that does not require a-priori knowledge of baseflow recession rates is to use antecedent streamflow cumulated for a designated period prior to the baseflow recession curve of interest. Although cumulative antecedent streamflow cannot account for storage depletion during inter-storm periods, it does provide an objective estimate of aquifer antecedent storage at watershed scales. Antecedent streamflow has previously been used to predict inter-seasonal changes in recession rates by Mishra et al. (2003) for the Nile River in Ethiopia and by Biswal and Kumar (2014) for watersheds in the United States.

Biswal and Kumar (2014) examined the relation between baseflow recession rates and antecedent streamflow measured over several different time spans (8, 28 and 118 days) for a watershed with a year-round precipitation regime. They observed that shorter time spans of antecedent streamflow were a better predictor of baseflow recession rates than longer time spans. A similar approach was replicated for this study, with antecedent streamflow (mm) cumulated over three time spans; from 10 to 2 days prior to the start of each baseflow recession curve (Q_{P8}), from 30 to 2 days prior to the start of each baseflow recession curve (Q_{P28}), and from the beginning of the wateryear (October 1) to 2 days before the start of each baseflow recession curve (Q_{PWY}). The two days immediately before a recession event were excluded so that streamflow associated with the current rainfall event was not incorporated into the antecedent streamflow metric. The first two time spans Q_{P8} and Q_{P28} are equivalent to the time spans examined in Biswal and Kumar (2014). The last time span is similar to Q_{P118} (120 to 2 days before start of baseflow recession curve) but uses wateryear instead of a fixed period. The time span from the beginning of the wateryear to the months of November through February ranges from 31 to 151 days. However, since the conditions prior to the start of the wateryear in California are extremely dry, Q_{PWY} is analogous to Q_{P118} for all months except February, when the time span for antecedent streamflow may exceed 120 days prior to the start of the baseflow recession curve. Differences between Q_{P118} and Q_{PWY} were found to be minimal.

4.3. Storage–discharge model

Simple storage–discharge models conceptualize recession flows as originating from a single homogeneous store. A relation linking storage and baseflow can be represented as a power-law function:

$$Q_s = cS^d, \tag{4}$$

where Q_s is discharge from storage, S is aquifer storage in mm, and c ($\mathrm{mm}^{1-d}\ \mathrm{t}^{-1}$) and d (–) are defined in terms of a and b from Eq. (2) (Clark et al., 2009):

$$c = [a(2-b)]^{1/(2-b)} \tag{5a}$$

$$d = 1/(2-b). \tag{5b}$$

The storage–discharge relation in Eq. (4) reduces to a linear reservoir when d is equal to one. The continuity equation for a single store during a recession period may be represented as:

$$-\frac{dS}{dt} = Q_s, \tag{6}$$

with the assumption that fluxes to storage (e.g. recharge) and from storage (e.g. ET, discharge to other stores) are negligible during the recession period.

The behavior of a single store model with no additional fluxes besides discharge to a stream is invariant, and consequently, inadequate for replicating inter-seasonality of baseflow recession rates (McMillan et al., 2010; Sloan, 2000). Inter-seasonality implies different controls on recession flows at different times of the year. The effect of multiple stores configured in parallel may be represented by

$$Q = \sum_j^J Q_{s_j} \tag{7}$$

where Q is baseflow at the streamflow gauge, Q_{s_j} is discharge to the stream from the jth store, and J is the total number of stores.

5. Relation between baseflow recession rates and aquifer antecedent storage

The relation between baseflow recession rates (a) from Eq. (2) and cumulative streamflow for three antecedent time spans (8 days, 28 days and wateryear) is displayed in Fig. 3 for Arroyo Seco. Baseflow recession rates exhibited a negative relation with cumulated antecedent streamflow for each of the time spans. A linear regression model with log-transformed a and cumulative antecedent streamflow (Xiao et al., 2011) revealed that the relation improved as the time span increased, with coefficient of determination (R^2) values increasing from 0.64 for Q_{P8} to 0.93 for Q_{PWY}. This improvement of model fit with increasing antecedent streamflow time span was also observed in Big Sur, Nacimiento and San Antonio. The relation between baseflow recession rates and Q_{PWY} for these latter watersheds is shown in Fig. 4. For all four watersheds, baseflow recession rates decreased with higher antecedent streamflow, with a decreasing by up to two orders of magnitude following initial baseflow events.

The improvement in model fit with increasing time spans of antecedent streamflow that was observed in this study contrasts the results of Biswal and Kumar (2014). This difference may be due to the greater inter-seasonal range of aquifer storage in California compared to regions with precipitation that is more evenly distributed throughout the year. At the beginning of the central California wet season, watersheds are characterized by maximum soil moisture and aquifer storage deficits (Miller et al., 1983). Following the first precipitation events of the season, baseflow response is likely to originate from small, low-threshold aquifers that can be quickly recharged and have high aquifer discharge recession rates. At the same time, channel losses to groundwater may be considerable in many central California watersheds, particularly for intermittent and ephemeral streams where the water table is located below the stream (Pilgrim et al., 1988). As channel losses increase baseflow recession rates relative to conditions with no channel losses, baseflow recession rates at the beginning of the central California wet season are likely be relatively rapid.

As the wet season progresses, the primary source of baseflow is likely to shift from aquifers with higher discharge recession rates to aquifers with lower discharge recession rates as the latter aquifers become progressively filled and release larger volumes of water (Harman et al., 2009). These aquifers may also be subject to varying amounts of recharge during the recession period from other aquifers. Channel losses at this time are likely to be minimal in all but the most ephemeral watersheds and/or driest years. The cumulative effect of these processes should be a continual decrease in baseflow recession rates heading toward the end of the wet season. The good fit of Q_{PWY} to baseflow recession rates strongly suggests that accounting for these inter-season differences in storage is critical for characterizing baseflow recession rates in central California watersheds.

6. Evaluating inter-seasonal variability in baseflow recession rates using a storage–discharge model

The empirical results outlined above indicated that baseflow recession rates decreased with inter-seasonal increases in cumulative antecedent streamflow and it was postulated that this decrease may be due to an increase or change in the number of active aquifers discharging to baseflow from the beginning of the wet season to the end of the wet season. In this section, a two-store storage–discharge model was used as a heuristic tool to explore how inter-seasonal changes in aquifer antecedent storage may produce inter-seasonal changes in baseflow recession rates.

6.1. Modeling approach

A parsimonious storage–discharge model consisting of two nonlinear stores in parallel was selected to isolate the role of storage on baseflow recession rates. Conceptually, the faster of the two stores was considered to represent low-threshold aquifers that were responsive throughout the wet season and had high hydrological connectivity to the stream and high discharge recession rates (e.g. shallow riparian aquifers). The slower of the two stores was considered to represent seasonal aquifers located further up hillslopes with lower saturated hydraulic conductivity and lower discharge recession rates. It was assumed that only the fast store was active at the beginning of the wet season since the contribution from aquifers with low discharge recession rates is likely to be negligible due to low storage levels. Both the fast and slow stores were assumed to contribute to recession flows under high storage levels.

The storage–discharge model was calibrated against recession slope curve data binned by cumulative antecedent streamflow. Bin sizes were selected to provide sufficient data for calibrating the model while minimizing the variability of baseflow recession rates within each bin. Bins representing early season and late season conditions were selected from the decile (10%) of recession slope curves with the lowest and highest Q_{PWY}, respectively. The Q_{PWY} decile limits for each watershed are shown in the legend of Fig. 5. The recession slope curves for both cumulative antecedent streamflow bins approximated a power law function (Eq. (2)) and a linear least-squares regression on log-transformed values of Q

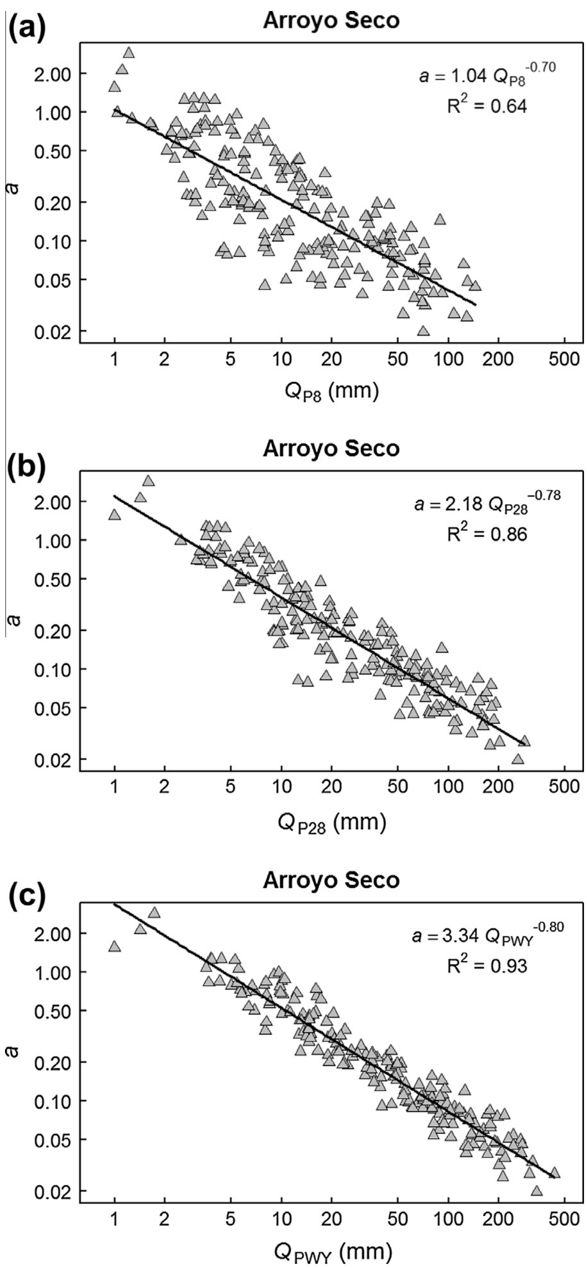

Fig. 3. Plot of a against antecedent streamflow cumulated (a) from 10 to 2 days prior to the start of the baseflow recession curve (Q_{P8}), (b) from 30 to 2 days prior to the start of the baseflow recession curve (Q_{P28}), and (c) from the beginning of the wateryear to 2 days prior to the start of the baseflow recession curve (Q_{PWY}) for Arroyo Seco.

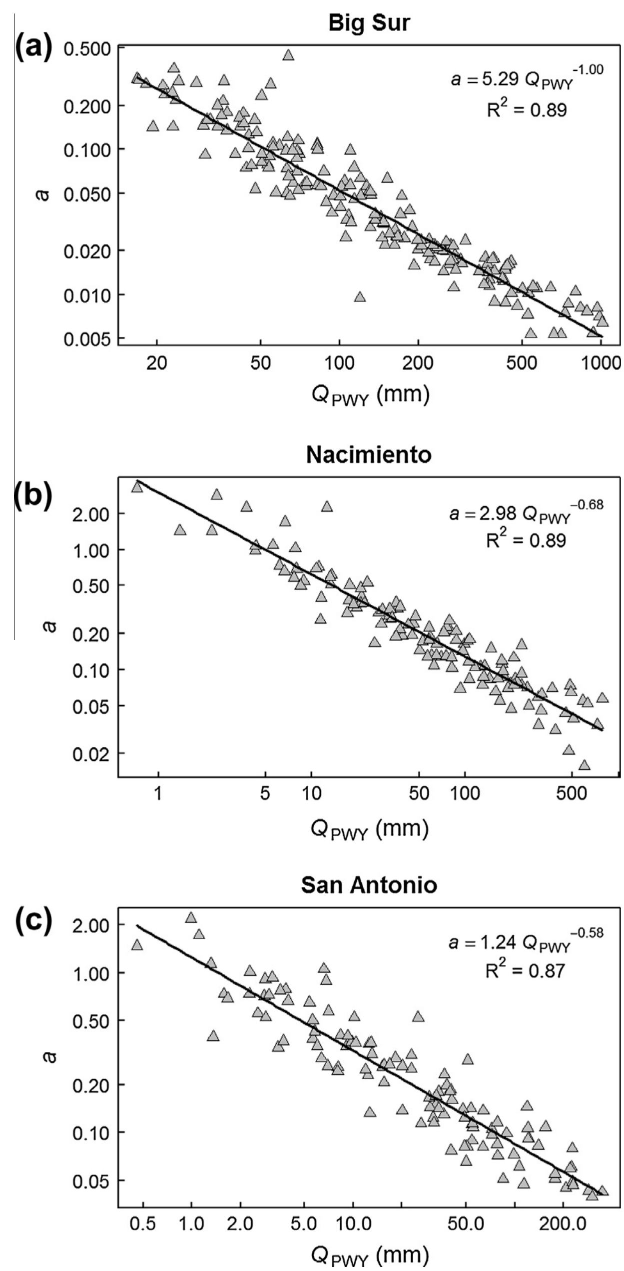

Fig. 4. Plot of a against antecedent streamflow cumulated from the beginning of the wateryear to 2 days prior to the start of the baseflow recession curve (Q_{PWY}) for (a) Big Sur, (b) Nacimiento and (c) San Antonio.

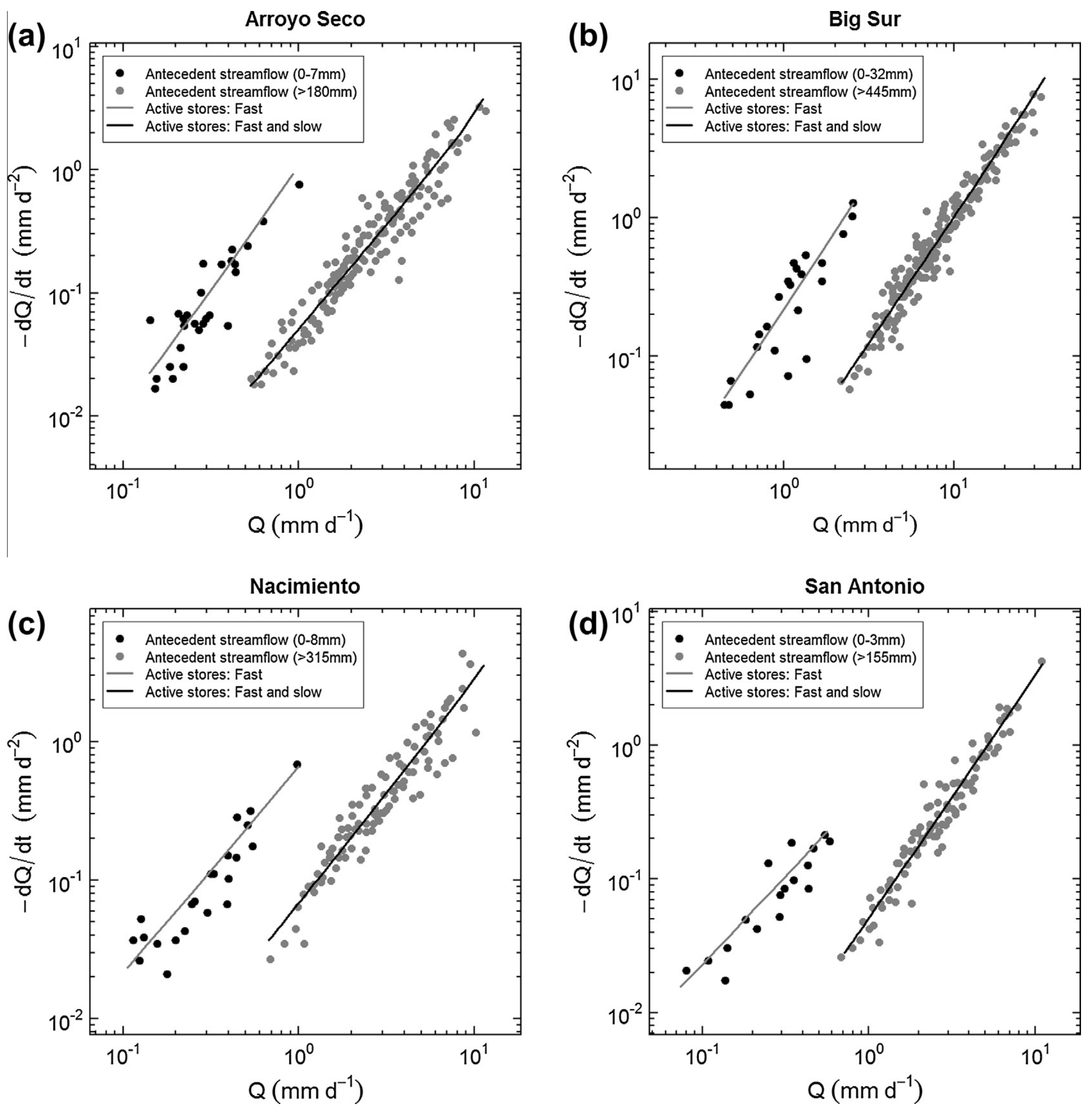

Fig. 5. Fit of a storage–discharge model with two stores in parallel to recession slope curves binned by the lowest and highest decile of Q_{PWY} values. For low Q_{PWY} conditions, the fast store was assumed to be initially full and the slow store initially empty. For high Q_{PWY} conditions, both stores were assumed to be initially full.

Table 2
Simulated store characteristics.

Name	Store	c	d	S_{max} (mm)	dQ/dt at $Q = 2$ mm	dQ/dt at $Q = 0.5$ mm
Arroyo Seco	Fast	1.63E−06	6.30	9	2.727	0.212
	Slow	3.82E−06	3.05	134	0.162	0.016
Big Sur	Fast	3.10E−06	4.17	28	0.672	0.059
	Slow	1.62E−12	4.77	627	0.056	0.005
Nacimiento	Fast	1.24E−01	1.71	4	1.345	0.189
	Slow	2.83E−04	2.30	101	0.196	0.022
San Antonio	Fast	1.73E−01	1.40	3	0.965	0.163
	Slow	9.34E−10	4.59	160	0.171	0.014

and dQ/dt was found to best characterize the recession slope curves (Xiao et al., 2011).

To evaluate inter-seasonal changes in baseflow recession rates, parameters c, d, and the maximum size of active storage S_{max} needed to be calibrated for both the fast and slow model store (Eq. (4)). The parameters of the fast store were identified by fitting a power-law function to the recession slope curve of the lowest cumulative antecedent streamflow bin in each watershed and using Eqs. (5a) and (5b) to derive c and d, respectively. S_{max} for the fast store was calculated using Eq. (4) and assuming that the maximum observed baseflow value (herein referred to as Q_{max}) for the lowest cumulative antecedent streamflow bin corresponded to discharge from the maximum active storage size, S_{max}.

During periods of high cumulative antecedent streamflow, both the fast and slow stores were assumed to be active. The parameters of the slow store were obtained using the following procedure. (1)

A slow store value of *c* was selected using a grid search of the probable parameter space. (2) The *d* parameter of the slow store was derived from the *b* parameter of the modeled recession slope curve from the highest cumulative antecedent streamflow bin. (3) S_{max} for the slow store was calculated by first computing Q_{max} for the slow store, which was assumed to be the difference between the maximum observed recession flow value produced in the watershed and Q_{max} of the fast store. This value, along with the *c* and *d* parameters, was used to derive S_{max} of the slow store using Eq. (4). (4) Discharge from the slow store was simulated simultaneously with discharge from the fast store and the combined flow was compared to the regression-derived recession slope curve of the highest cumulative antecedent streamflow bin using the root mean square error (RMSE) on logged variables. The initial storage level for both the fast and slow store was assumed to be at S_{max}. (5) The value of *c* associated with the lowest RMSE was selected for the model.

6.2. Modeling results

The fit of the modeled recession slope curve to the observed recession slope curve for the lowest and highest cumulative antecedent streamflow bins is shown in Fig. 5. Under low cumulative antecedent streamflow conditions when only a single power-law store was active, the modeled recession slope curve plotted as a linear line on a $\log(-dQ/dt) - \log(Q)$ plot and closely matched the observed recession slope curve. Similarly, at high cumulative antecedent streamflow levels, when both power-law stores were active, the modeled recession slope curve also maintained characteristics of a power-law function, but at a slower rate of recession. Power-law behavior was maintained in the latter case, even though both stores were active, because discharge from the slow store was much larger than discharge from the fast store, such that the modeled recession slope curve approximated the power-law behavior of the slow store. At high cumulative antecedent streamflow levels, the influence of the fast store, if observable, was small and short-lived. An example of this influence can be seen in Arroyo Seco, where the modeled recession slope curve becomes concave upwards for high magnitude flows, reflecting the brief influence of fast-store discharge on baseflow when storage levels were high.

The modeled store characteristics are displayed in Table 2. To facilitate direct comparisons of baseflow recession rates between the fast and slow store, the baseflow recession rate dQ/dt was calculated at two fixed baseflow magnitudes equal to 2 mm and 0.5 mm (Table 2). The baseflow recession rate of the slow store ranged from 5.6 to 16.8 times slower than the fast store at 2 mm of baseflow and from 8.5 to 13.3 times slower than the fast store at 0.5 mm of baseflow. Baseflow recession rates for the slow stores mirrored the percentage of zero flow days in a watershed, with the lowest rate occurring in the perennial watershed Big Sur and the highest rates occurring in Nacimiento and San Antonio, which are dry for 30% and 44.8% of the year, respectively (Tables 1 and 2). The maximum active storage size S_{max} ranged from 3 to 28 mm for the fast stores and from 101 to 627 mm for the slow stores (Table 2). This corresponded to a slow store capacity that is 14.9–53.3 times larger than the fast store. These storage values appear physically plausible, as the aquifers represented by the fast store are likely localized in very small areas of the watershed (e.g. riparian zones) and actual aquifer depths are likely much deeper.

The storage–discharge model with two stores in parallel replicated both the power-law characteristics of the recession slope curve under low cumulative antecedent streamflow conditions when the fast store was the dominant control on baseflow and under high cumulative antecedent streamflow conditions when the slow store was the dominant control on baseflow (Fig. 5). However, as the wet season progressed, the controls on the recession

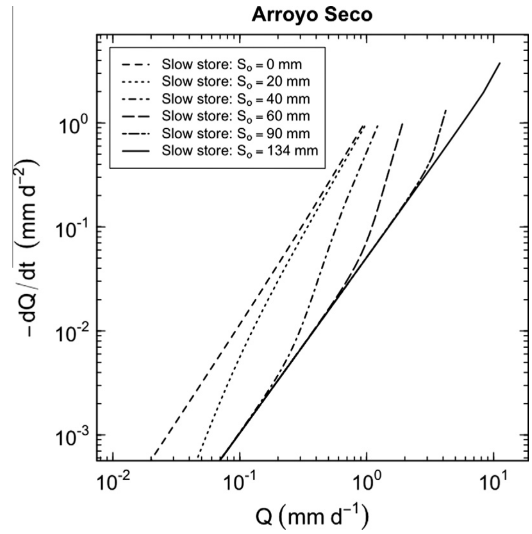

Fig. 6. Transition of a recession slope curve from a dominant fast store to a dominant slow store for Arroyo Seco using a storage–discharge model with two stores in parallel. Initial storage S_o of the fast store was fixed at S_{max}, while S_o of the slow store was varied between 0 mm (empty) and 134 mm (full).

slope curve could be expected to transition between these two end-member conditions. The simulated transition of the recession slope curve from a dominant fast store to a dominant slow store is demonstrated for the Arroyo Seco watershed (Fig. 6). The initial storage value (herein referred to as S_o) of the fast store was assumed equal to S_{max} (9 mm) for each of the curves generated, while S_o of the slow store was varied from empty (0 mm) to S_{max} (134 mm). While the recession slope curve displayed power-law characteristics when the slow store was either empty or full, the transition between these two levels introduced concave nonlinearity in the recession slope curve (Fig. 6). This concave nonlinearity occurred when discharge from the fast and slow stores were similar in magnitude. In addition, recession slope curves transitioning from a dominant fast store to a dominant slow store had a steeper slope (i.e. larger *b* value) than either of the two end-member recession slope curves (Fig. 6). This inter-seasonal variability in the exponent *b* suggests that the common practice of fixing *b* at a single value, as done in this study, may not always be appropriate for watersheds with multiple aquifers.

7. Conclusions

This study investigated the effects of inter-seasonal changes in aquifer antecedent storage on baseflow recession rates in four central California watersheds. Antecedent streamflow cumulated from the beginning of the wateryear was found to be the best surrogate measure of aquifer antecedent storage. Baseflow recession rates and cumulative antecedent streamflow displayed a negative power-law relation, with baseflow recession rates decreasing by up to two orders of magnitude with increasing levels of cumulative antecedent streamflow.

Inter-seasonal reductions in baseflow recession rates were well-represented by a storage–discharge model with two nonlinear stores in parallel. The model showed that at the beginning of the central California wet season, the baseflow recession curve could be replicated by a small, fast store. Physically, this store likely corresponds to shallow, quickly-recharged riparian aquifers with high hydrological connectivity to the stream, allowing for rapid responses following precipitation events. As the wet season progresses, a much larger and much slower store, which is initially empty at the onset of the wet season, is recharged. This slow store, which represents seasonal aquifers within the watershed, becomes the dominant control on baseflow as discharge from the slow store eventually overwhelms discharge from the fast store.

The results of this study have clearly shown that accounting for aquifer storage conditions is important for properly characterizing baseflow recession rates, particularly in MCRs that are typified by large inter-seasonal differences in aquifer storage levels. Many previous studies of inter-seasonal baseflow recession rate change in MCRs have focused solely on the role of ET on baseflow recession rates (Aksoy and Wittenberg, 2011; Wittenberg and Sivapalan, 1999). Future work on inter-seasonal variability in MCRs needs to address the relative role of both storage and ET on baseflow recession rates. Further, the effect of other storage–discharge related processes such as channel losses and storage losses also need to be examined.

Finally, there has been recognition in recent years that the controls on recession flows in many watersheds are dynamic (Biswal and Kumar, 2014; McMillan et al., 2010; Mishra et al., 2003; Shaw et al., 2013; Wang and Cai, 2009). This study adds to this understanding by demonstrating how changes in storage can be used to explain inter-seasonality of baseflow recession rates in central California watersheds. This study also demonstrates that the frequent assumption of a single storage–discharge relation for representing baseflow may not be appropriate in some watersheds, which has implications for hydrologic applications ranging from baseflow separation (Eckhardt, 2005) to rainfall-runoff modeling (Jakeman and Hornberger, 1993).

Acknowledgements

We would like to acknowledge the helpful comments and suggestions provided by Trent Biggs, Christina Tague, Oliver Chadwick and three anonymous reviewers.

References

Aksoy, H., Wittenberg, H., 2011. Nonlinear baseflow recession analysis in watersheds with intermittent streamflow. Hydrol. Sci. J. 56, 226–237. http://dx.doi.org/10.1080/02626667.2011.553614.
Archfield, S.A., Vogel, R.M., 2009. The implications of discretizing continuous random variables: an example using the U.S. Geological Survey reporting standards for streamflow data. In: Proceedings of the American Society of Civil Engineers World Environmental and Water Resources Congress. Kansas City, Missouri. doi:10.1061/41036(342)519.
Biswal, B., Kumar, D.N., 2014. Study of dynamic behaviour of recession curves. Hydrol. Process. 28, 784–792. http://dx.doi.org/10.1002/hyp.9604.
Biswal, B., Marani, M., 2010. Geomorphological origin of recession curves. Geophys. Res. Lett. 37, L24403.
Brutsaert, W., Nieber, J.L., 1977. Regionalized drought flow hydrographs from a mature glaciated plateau. Water Resour. Res. 13, 637–643.
Callaway, R.M., Davis, F.W., 1993. Vegetation dynamics, fire, and the physical environment in coastal central California. Ecology 74, 1567–1578. http://dx.doi.org/10.2307/1940084.
Clark, M.P., Rupp, D.E., Woods, R.A., Tromp-van Meerveld, H.J., Peters, N.E., Freer, J.E., 2009. Consistency between hydrological models and field observations: linking processes at the hillslope scale to hydrological responses at the watershed scale. Hydrol. Process. 23, 311–319.
Ducea, M., House, M.A., Kidder, S., 2003. Late Cenozoic denudation and uplift rates in the Santa Lucia Mountains, California. Geology 31, 139–142.
Eckhardt, K., 2005. How to construct recursive digital filters for baseflow separation. Hydrol. Process. 19, 507–515. http://dx.doi.org/10.1002/hyp.5675.
Federer, C.A., 1973. Forest transpiration greatly speeds streamflow recession. Water Resour. Res. 9, 1599–1604.
Hall, F.R., 1968. Base-flow recessions – a review. Water Resour. Res. 4, 973–983.
Harman, C.J., Sivapalan, M., Kumar, P., 2009. Power law catchment-scale recessions arising from heterogeneous linear small-scale dynamics. Water Resour. Res. 45, W09404.
Jakeman, A.J., Hornberger, G.M., 1993. How much complexity is warranted in a rainfall-runoff model? Water Resour. Res. 29, 2637–2650.
Luo, H., Oechel, W.C., Hastings, S.J., Zulueta, R., Qian, Y., Kwon, H., 2007. Mature semiarid chaparral ecosystems can be a significant sink for atmospheric carbon dioxide. Global Change Biol. 13, 386–396.
McMillan, H., Clark, M., Woods, R., Duncan, M., 2010. Improving perceptual and conceptual hydrological models using data from small basins. In: Status and Perspectives of Hydrology in Small Basins. IAHS Publ. 336-08, pp. 1–6.
Miller, P.C., Poole, D.K., Miller, P.M., 1983. The influence of annual precipitation, topography, and vegetative cover on soil moisture and summer drought in Southern California. Oecologia 56, 385–391.
Mishra, A., Hata, T., Abdelhadi, A.W., Tada, A., Tanakamaru, H., 2003. Recession flow analysis of the Blue Nile River. Hydrol. Process. 17, 2825–2835. http://dx.doi.org/10.1002/hyp.1436.
Moore, R.D., 1997. Storage-outflow modelling of streamflow recessions, with application to a shallow-soil forested catchment. J. Hydrol. 198, 260–270.
Mutzner, R., Bertuzzo, E., Tarolli, P., Weijs, S.V., Nicotina, L., Ceola, S., Tomasic, N., Rodriguez-Iturbe, I., Parlange, M.B., Rinaldo, A., 2013. Geomorphic signatures on Brutsaert base flow recession analysis. Water Resour. Res. 49, 5462–5472.
Pilgrim, D.H., Chapman, T.G., Doran, D.G., 1988. Problems of rainfall-runoff modelling in arid and semiarid regions. Hydrol. Sci. J. 33, 379–400.
Rundel, P.W., 2004. Mediterranean-climate ecosystems: defining their extent and community dominance. In: Arianoutsou, Papanastasis (Eds.), Proceedings 10th MEDECOS Conference, Proceedings 10th MEDECOS Conference. Presented at the 10th MEDECOS Conference, Rhodes, Greece, pp. 1–12.
Rupp, D.E., Selker, J.S., 2006a. On the use of the Boussinesq equation for interpreting recession hydrographs from sloping aquifers. Water Resour. Res. 42, W12421.
Rupp, D.E., Selker, J.S., 2006b. Information, artifacts, and noise in $dQ/dt - Q$ recession analysis. Adv. Water Resour. 29, 154–160. http://dx.doi.org/10.1016/j.advwatres.2005.03.019.
Sayama, T., McDonnell, J.J., Dhakal, A., Sullivan, K., 2011. How much water can a watershed store? Hydrol. Process. 25, 3899–3908. http://dx.doi.org/10.1002/hyp.8288.
Shaw, S.B., McHardy, T.M., Riha, S.J., 2013. Evaluating the influence of watershed moisture storage on variations in baseflow recession rates during prolonged rain-free periods in medium-sized catchments in New York and Illinois, USA. Water Resour. Res. 49, 6022–6028. http://dx.doi.org/10.1002/wrcr.20507.
Shaw, S.B., Riha, S.J., 2012. Examining individual recession events instead of a data cloud: Using a modified interpretation of $dQ/dt - Q$ streamflow recession in glaciated watersheds to better inform models of low flow. J. Hydrol. 434–435, 46–54. http://dx.doi.org/10.1016/j.jhydrol.2012.02.034.
Sloan, W.T., 2000. A physics-based function for modeling transient groundwater discharge at the watershed scale. Water Resour. Res. 36, 225–241.
Smakhtin, V.U., 2001. Low flow hydrology: a review. J. Hydrol. 240, 147–186.
Szilagyi, J., Gribovszki, Z., Kalicz, P., 2007. Estimation of catchment-scale evapotranspiration from baseflow recession data: numerical model and practical application results. J. Hydrol. 336, 206–217.
Tague, C., Grant, G.E., 2009. Groundwater dynamics mediate low-flow response to global warming in snow-dominated alpine regions. Water Resour. Res. 45, W07421, doi: 200910.1029/2008WR007179.
Tallaksen, L.M., 1995. A review of baseflow recession analysis. J. Hydrol. 165, 349–370. http://dx.doi.org/10.1016/0022-1694(94)02540-R.
Wang, D., 2011. On the base flow recession at the Panola Mountain Research Watershed, Georgia, United States. Water Resour. Res. 47, W03527, doi: 201110.1029/2010WR009910.
Wang, D., Cai, X., 2009. Detecting human interferences to low flows through base flow recession analysis. Water Resour. Res. 45, W07426.
Wang, D., Cai, X., 2010. Recession slope curve analysis under human interferences. Adv. Water Resour. 33, 1053–1061.
Wittenberg, H., Sivapalan, M., 1999. Watershed groundwater balance estimation using streamflow recession analysis and baseflow separation. J. Hydrol. 219, 20–33.
Xiao, X., White, E.P., Hooten, M.B., Durham, S.L., 2011. On the use of log-transformation vs. nonlinear regression for analyzing biological power laws. Ecology 92, 1887–1894.