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

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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.

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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).

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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 precipita-