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An analysis of trends in baseflow recession and low-flows in rain-dominated coastal streams of the pacific coast

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SUMMARY

The work presented here centers on the identification and calculation of indices representative of annual low-flow conditions and baseflow recession form, and the evaluation of trends in these indices with time for rain-dominated streams of the Pacific coastal mountain ranges. Two different baseflow recession analysis techniques are employed, which when combined are capable of modeling the varied dry-season flow conditions that exist over the broad range of catchments included in the study area. Results indicate that over the past 40–80 years widespread trends of increasing rates of baseflow recession and decreasing annual low-flow conditions exist throughout the region. Of streamgages analyzed, 44% were identified as having a statistically significant trend in either low-flow conditions or recession form with time. While spring flow conditions show little change over the study period, trends of decreasing late-summer flow conditions and increasing rates of recession are particularly common. Northern California and Oregon are especially impacted locations, with upwards of 60% of study gages exhibiting decreasing trends in late summer flow conditions. Detailed conceptual explanations for the connections between trends in recession form and indices of low-flow are also presented.

1. Introduction

In the coastal mountain ranges of the Western United States, groundwater-derived discharge (baseflow) is typically the primary source of streamflow during the precipitation-free summer dry season. As the dry season progresses, groundwater reservoirs drain and the contribution of subsurface water to streams typically decreases. The resulting decline in stream discharge is referred to as baseflow recession (Tallaksen, 1995). The culmination of the annual baseflow recession process is marked by the point of minimum discharge just prior to the arrival of the first significant precipitation event of the wet season. Because of the distinct wet–dry-season climate of the region, the end of the annual baseflow recession also consistently coincides with the point of minimum annual streamflow. Previous studies of regional streams have documented trends in these annual minimum flow statistics with time (Lins and Slack, 1999; Lins, 2005); however, none to date have looked at changes with time in the form of the annual baseflow recession, representative of the processes that lead to the annual minimum flow. In the work presented here, we analyze historic streamflow records to evaluate trends in annual baseflow recession form, annual low-flow statistics, and the relationship between the two.

Observed trends in the climate of the Pacific Coast region during the 20th century are well documented. Widespread increases in both wet- and dry-season air temperatures with time have been reported (Mote et al., 2005; Hamlet et al., 2007; Hamlet and Lettenmaier, 2007). Trends in precipitation have been more variable, with localized regional trends, but not the extensive or consistent changes seen in temperatures (Cayan et al., 1998; Mote, 2003; Hamlet and Lettenmaier, 2007). Recent climate models suggest that these trends in temperature and precipitation are likely to persist and evolve during the 21st century (Meehl et al., 2007; Cayan et al., 2008; Mote and Salathé, 2010). Determining how these climatic changes will affect terrestrial hydrologic systems and the ecosystems that depend on them is a pertinent endeavor (Mote et al., 2003; Battin et al., 2007). Identifying how dry-season streamflows have already been modified by changes in climate and development will help to better predict how future precipitation and temperature changes will further affect these systems.

Although numerous studies have previously identified significant trends in dry-season streamflow characteristics in the Pacific states of California, Oregon, and Washington, the majority of these studies focused on streamflow records from snowmelt-dominated

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watersheds located in the Sierra Nevada and Cascade mountain ranges (Lins and Slack, 1999; Lins, 2005; Luce and Holden, 2009). Changes in snow accumulation and melt timing due to changes in spring and winter air temperatures have been shown to directly control the snowmelt recession curve and late summer low-flows (Stewart et al., 2004, 2005; Stewart, 2009; McCabe and Clark, 2005; Hamlet et al., 2005). The combination of long precipitation-free dry seasons and rain-dominated wet-season precipitation make the watersheds of the Pacific coastal ranges excellent locations for the study of the linkages between baseflow and low-flows in non-snowmelt systems. The hydrology of the coastal ranges is also of relevance because of the ecosystems and keystone species it supports. Roughly 50% of the habitat area currently accessible to anadromous Pacific salmon and steelhead within California, Oregon, and Washington lies in the coastal mountains of the Pacific Coast (Augerot and Foley, 2005). Although wild salmonids are well-adapted to the regional wet–dry climate, low streamflow discharge during the dry season has been identified as one of the primary factors limiting the health of federally threatened and endangered salmon and steelhead populations in the area (Boughton et al., 2007). Increased rates of baseflow recession could not only result in lower annual streamflows, but also potentially lengthen the duration of exposure of salmonids to stressful low-flow conditions.

The principal goals of this study center on the identification of trends in, and relationships between, dry-season flow and baseflow recession conditions with time. Two different methods are employed to analyze and characterize annual baseflow recession conditions (Sections 4.1–4.3). Annual dry-season flow conditions are quantified using a variety of common low-flow indices (Section 4.4). Trend analyses (methods discussed in Section 3) are then performed on the annual time-series of low-flow and recession indices. The geographical distribution of, and relationships between, statistically significant trends in low-flow and recession indices are then analyzed.

2. Data

Our primary intent is to identify changes to streamflow conditions caused by non-point source alterations to the hydrologic cycle, such as changing meteorological conditions, land use practices, or minor dispersed withdrawals (e.g., small scale diversions and groundwater pumping) within watersheds. This work is not intended to analyze the effects of large accountable point-source diversions and storage (i.e., dams and reservoirs) on streamflow conditions. The U.S. Geological Survey's (USGS) Hydro-Climatic Data Network (HCDN) is an excellent dataset for such an analysis. The HCDN (1988, 2009) consists of USGS streamgages with mean daily streamflow primarily reflecting prevailing meteorological conditions with minor direct influences of human activity, and with datasets of sufficient length to perform analyses of patterns in streamflow over time (Slack and Landwehr, 1992; Lins, 2012). Combined, the 1988 and 2009 HCDN total 274 gages in California, Oregon, and Washington. We further refined the list of HCDN gages to remove basins with large-scale regulation or diversion projects using the GAGES database (Falcone et al., 2010). A subset of gages was then selected based on climate, length of record, and degree of water resource development (see supplementary section for a table of selected gages). Because our focus is on rain-fed systems, selected gages are primarily limited to the coastal mountain ranges of the Pacific states. Gages on streams draining the Sierra Nevada, Cascade, and Olympic mountain ranges are excluded because of their snowmelt-dominated nature. We further limit the set of gages to be analyzed by requiring a record length of greater than or equal to 40 years, and that gages still be active. Datasets of this length have been shown in past work to be sufficient for the trend analyses performed (Lins, 2012). Upstream drainage basins of the selected gages were inspected (typically using Google Earth™) to ensure that no new or undocumented hydrograph-altering water resource projects existed. Following these selection criteria, the original set of 274 HCDN gages was reduced to a subset of 54 gages for study (Fig. 1). Of the study gages selected, 40 (74%) are located in California (19 (35%) north of San Francisco Bay, 21 (39%) south), 9 (17%) in Oregon, and 5 (10%) in Washington. Basin sizes range from 9 to 1200 km^2.

3. Time-series trend analysis methods

The work presented here is based on the analysis of indices representative of annual low-flow statistics and baseflow recession form, and the evaluation of trends in these indices with time. The specific indices and methods of calculation are discussed in detail in the following Section 4. For time-series analysis, the non-parametric Mann–Kendall trend test is used to calculate Kendall's *tau* and a corresponding p-value (Lins and Slack, 1999; Burn and Hag Elnur, 2002; Helsel and Hirsch, 2002; McCabe and Wolock, 2002). Results with p-values $\leqslant 0.05$ are identified as time-series with statistically significant trends. Sen's slope and a corresponding Kendall-Theil Robust Line fit are calculated for datasets identified by the Mann–Kendall test as having statistically significant trends (Helsel and Hirsch, 2002). To test for potential false positive outcomes caused by serial correlation, Ljung–Box tests using the residuals from the Kendall-Theil Robust Line fit are performed (Ljung and Box, 1978; von Storch and Navarra, 1995; Burn and Hag Elnur, 2002). In cases where serial correlation is identified, time-series are re-sampled omitting a subset of regularly-spaced data points in an attempt to form a set of observations that are sufficiently separated temporally to reduce autocorrelation (Helsel

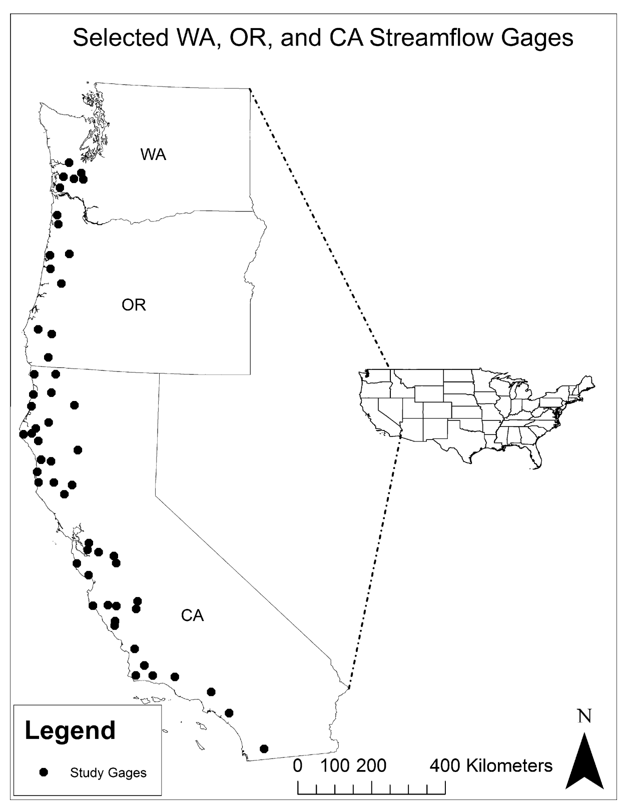

Fig. 1. Map of USGS streamflow gages in WA, OR, and CA selected for analysis from the 1988 and 2009 Hydro-Climatic Data Networks based on location, length of record, and level of water extraction within watersheds.